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AUTOMATIC GAIN CONTROL FOR SEMICONDUCTOR LASER AMPLIFIERS

BY

RUSSELL ARCHIE MORRIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **AUTOMATIC GAIN CONTROL FOR SEMICONDUCTOR LASER AMPLIFIERS** submitted by **Russell Archie Morris** in partial fulfillment of the requirements for the degree of **Master of Science**.

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To My Parents,

For their help, encouragement, and patience over the years.

ABSTRACT

This thesis examines the design objectives and presents the performance of an automatic gain control circuit capable of stabilizing the gain or output power of a semiconductor laser amplifier to within 0.1 dB of a desired operating point. This level of accuracy is achieved by dynamically controlling the amplifier bias current using a closed loop feedback system.

The theory of semiconductor laser amplifiers is introduced in order to demonstrate the physical mechanisms responsible for changes in laser amplifier gain that are induced by variations in input signal polarization, laser amplifier chip temperature, or system wavelength. Measurements are presented indicating the sensitivity that a real laser amplifier exhibits towards these parameters. These results provide the motivation for the implementation of a laser amplifier gain control system.

The operation of the entire control system is examined, as well as the function and performance of the individual building blocks. Test results are presented, demonstrating the ability of the system to stabilize the gain or output power of a laser amplifier. These results indicate that the system is capable of compensating for laser amplifier gain or output power fluctuations which occur at speeds up to approximately 6 kHz. The control circuit achieves this high speed amplifier stabilization independent of the transmission bit rate of the fiber optic system within which it operates. In addition, the control system operates over a wide input signal dynamic range, functioning correctly for input optical powers ranging from -20 dBm to -40 dBm.

The tight control provided by the system allows it to be used in many fiber optic applications, several of which are introduced in this work. Two optimal laser amplifier control system configurations are also proposed as an outcome

of this project. These systems are capable of performing laser amplifier gain or output power stabilization, while at the same time reducing interchannel crosstalk created when several channels are simultaneously amplified by a laser amplifier. Implementation and testing of these optimum systems indicates one of several directions along which further gain control circuit work may proceed.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AGC	Automatic Gain Control
AR	AntiReflection (coating)
DC	Direct Current
DFB	Distributed Feedback (laser)
InGaAsP	Indium Gallium Arsenide Phosphide
Gbit/s	Gigabits per second (1 Gbit/s = 10^9 bits/second)
LED	Light Emitting Diode
Mbit/s	Megabits per second (1 Mbit/s = 10^6 bits/second)
NRZ	Non-Return to Zero
PIN	P-I-N junction photodiode
PRBS	PseudoRandom Bit Sequence
RF	Radio Frequency
SNR	Signal to Noise Ratio
SONET	Synchronous Optical NETwork
TE	Transverse Electric
TM	Transverse Magnetic
WDM	Wavelength Division Multiplexing

LIST OF SYMBOLS

$a(T)$	Temperature dependent gain coefficient
α	Laser amplifier active region material loss coefficient
b	Gain constant
β	Linewidth broadening factor
c	Speed of light
c_λ	Wavelength shift coefficient
d	Laser amplifier active region thickness
E	Energy of a photon of light
E_c	Conduction band energy level
E_g	Energy gap of the material in the laser amplifier active region
E_v	Valence band energy level
g_O	Laser amplifier material gain coefficient
G	Laser amplifier resonant optical power gain
G_B	Laser amplifier resonant backward travelling optical power gain
G_s	Laser amplifier single pass optical power gain
Γ	Laser amplifier active region optical confinement factor
h	Planck's constant
L	Laser amplifier active region length
λ	Optical wavelength
λ_O	Center wavelength of the laser amplifier spontaneous emission spectrum, when biased at the original laser threshold current
λ_p	Peak gain wavelength
n	Laser amplifier active region carrier density

n_{th}	Active region carrier density, when biased at the original laser threshold current
$n_O(T)$	Active region transparency density
P_{out}	Laser amplifier optical output power
P_{sat}	Laser amplifier gain saturation optical output power
θ	Laser amplifier single pass phase shift
R_1, R_2	Input and output facet residual power reflectivities
ρ	Refractive index of the material in the laser amplifier active region
T	Laser amplifier device temperature
τ	Spontaneous carrier lifetime within the laser amplifier active region
w	Laser amplifier active region width

1. INTRODUCTION

Optical amplifiers are devices which may be used to amplify optical signals directly in fiber optic communication systems. Two types of optical amplifiers exist, semiconductor laser amplifiers and active fiber amplifiers. Semiconductor laser amplifiers have a structure based upon a semiconductor laser, modified by the addition of antireflection coatings to the end facets. Active fiber amplifiers, on the other hand, are similar in structure to single mode fiber; however, the core region is doped with a rare earth material such as Erbium, in order to produce the desired gain characteristic [1]. Both devices are transformed into an amplifying state by a process called pumping. Pumping is performed by injecting a bias current into the active region of a semiconductor laser amplifier, or by the injection of a high power optical pump signal in the case of an active fiber amplifier. In both cases the result of pumping is the formation of an active region capable of directly amplifying an externally injected optical signal. Although these two devices are quite different in structure and excitation method, both perform the same basic operation. There are additional differences, however, in their amplification properties such as bandwidth, signal coupling, and sensitivity to environmental conditions, as well as amplifier complexity, reliability, and cost.

The following two sections introduce some of the fiber optic system architectures which are presently used, together with some that are currently under study. These systems are aimed at meeting the ever present demand for higher and higher transmission capacity. This discussion indicates some of the directions in which future fiber systems may proceed, and presents the role that optical amplifiers may play in these systems. In addition, some of the hurdles which must be overcome before these devices can find widespread use in the communication industry are introduced.

The aim of the research reported in this thesis was to build and test a gain control circuit capable of stabilizing the gain of an optical amplifier in a fiber optic system, thereby reducing the sensitivity amplifier gain exhibits with respect to environmental conditions. Although the control system which has been implemented was tested using a semiconductor laser amplifier, the control concept applies equally well to active fiber amplifiers. The final section of this chapter presents an outline of the overall approach that will be taken to explain the operational principles of semiconductor laser amplifiers, together with their inherent sensitivities and the control technique which has been used to combat several of these properties.

1.1 Fiber Optic System Architectures

One of the main methods that has been used to date to satisfy the demand for increased system capacity in digital communication systems has been to time-division multiplex several lower bit rate channels onto one higher bit rate stream, creating systems with increased baseband transmission rates. These systems generally operate by intensity modulating the input optical signal and directly detecting the time varying intensity at the receiver using a photodetector device. An example of this type of system is the recently announced product line from Northern Telecom called Fiber World™. This system byte interleaves 48 SONET channels, each transmitting data at 51.85 Mbits/s, onto a single 2.488 Gbit/s data stream.

The concept of time-division multiplexing is illustrated in Figure 1.1. This scheme involves reading n lower speed input data streams and writing them to a single output bit stream at a rate nominally n times higher than that of the input channels [2]. For example, in Figure 1.1 there are four input data streams, each at a bit rate of 1/t. The output stream is generated by interleaving data from the four input streams, resulting in an output data stream at a bit rate 4/t. In this way, the transmission capacity of the system is increased, at the expense of increased baseband bandwidth. Most of the presently installed systems use this method to expand system capacity. Usually, intensity modulation and direct photodetection are used to transmit the high speed data stream.

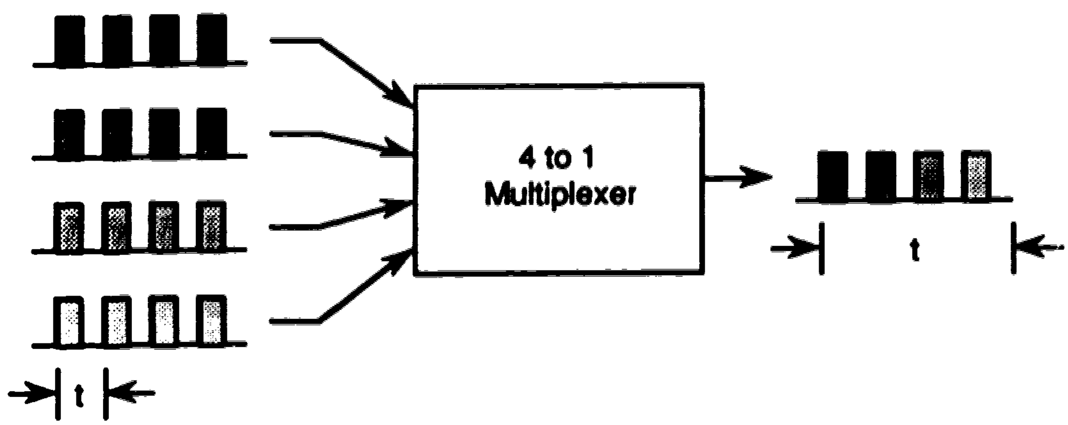

Figure 1.1 Time-Division Multiplexing

The signal must usually be amplified along the transmission path in order to compensate for splitting and attenuation losses. This is required in order that the optical signal present at the receiver is strong enough to allow direct detection by a photodetector and receiver amplifier. Installed systems use regenerative repeaters to perform signal retransmission and effectively achieve signal amplification. These devices contain a photodetector and electronic amplifier in order to detect the input intensity modulated signal. The received electrical signal is reshaped and clocking information is extracted to allow complete signal regeneration. The electrical signal is then retransmitted by directly modulating a semiconductor laser contained within the regenerative repeater. The disadvantage of this type of system is the cost involved, as an entire transmitter and receiver pair is included in the repeater, along with circuitry for clock recovery and signal regeneration. Also, as a consequence of regeneration, the repeater must contain a phase locked loop which inherently only locks to clock rates over a relatively narrow range, indicating bit rate sensitivity on the part of the repeater. However, if an optical amplifier were used in place of a regenerative repeater, the input optical signal could be amplified directly, independent of the transmission bit rate. Changes in system bit rate would thus be transparent if an optical amplifier were used, whereas they are not if a regenerative repeater is used. It should be noted, however, that if the system is limited by dispersion and intersymbol interference rather than signal power, the signal must be regenerated at the repeater, precluding the use of an optical amplifier repeater in such systems. Most installed systems operate at or near the dispersion minimum at 1300 nm, and are not limited by dispersion but rather by signal intensity. The main point here is that, as time-division multiplexed intensity modulated direct detection systems move to higher and higher bit rates in order to increase transmission capacity, optical amplifier repeaters become more attractive because of their bit rate insensitivity and the increasing difficulty of implementing regenerative repeaters.

One of the alternatives to time-division multiplexing is subcarrier multiplexing, shown in Figure 1.2 [3]. In a subcarrier multiplexed system there are n input channels, either analog or digital, which are modulated onto n different subcarrier frequencies. The modulation format may be any type, such as some form of amplitude or phase modulation. The n streams are summed and may be used to modulate the laser, again in any selected format. At the receiver, the combined signal is detected, using a suitable method given the laser modulation format, and the individual channels are recovered using a bank of n bandpass filters, tuned to the frequencies f_1, f_2, ..., f_n in order to select the desired channel. The main advantage of this method of transmission over a time-division multiplexed system is the ability of the system to maintain the same overall transmission capacity, while at the same time requiring each individual channel to process signals at speeds n times lower than is required in a time-division multiplexed system. In addition, a subcarrier multiplexed system is particularly well suited to broadband distribution applications, supplying each channel on a separate subcarrier.

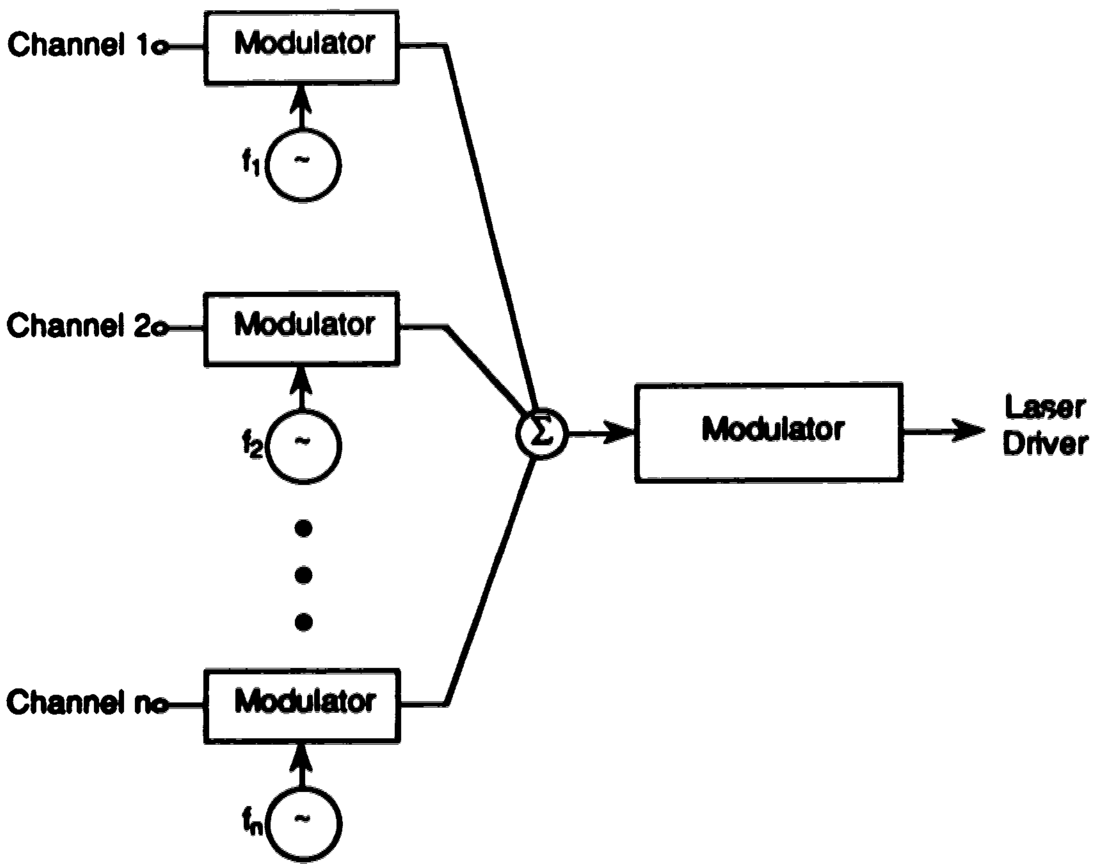

Figure 1.2 Subcarrier Multiplexing

A subcarrier multiplexed transmission scheme illustrates the general applicability of optical amplifiers, as the optical signal generated by the source laser could easily be amplified using an optical amplifier, independent of the modulation format used to drive the laser diode. Use of a regenerative repeater is not only more costly, but is much more complex as the repeater must include an entire receiver and transmitter system. These operations become more and more complex as more channels are transmitted using a subcarrier multiplexing scheme.

An alternative to a subcarrier multiplexed system is a wavelength division multiplexed system. A system of this type is shown in Figure 1.3. This system involves modulating n different lasers using any desired method, for example intensity modulation, frequency modulation, or phase modulation [4]. The lasers operate at slightly different wavelengths, with their optical outputs summed using an n-input optical power coupler. At the receiver, the n individual channels can be detected by one of two methods, depending on the wavelength spacing which is used. If the channels are spaced by 1 to 2 nm, the individual channels may be extracted using narrowband optical filters. The individual channel data may be recovered using a suitable method, given the modulation format of the selected channel. If dense wavelength division multiplexing is used, also called frequency division multiplexing [4], the channels are spaced by approximately 6 to 10 times the baseband bandwidth of an individual channel. Until very recently, coherent detection has been necessary in this situation. Coherent detection requires a local oscillator at the receiver which is tuned to the wavelength of the selected channel, or alternatively some other scheme such as self-heterodyne detection. Signal detection of an individual channel then proceeds according to the modulation format of the chosen channel.

This system architecture is an example of a system which would benefit greatly from the use of optical amplifiers, as the bandwidth of a semiconductor laser amplifier is approximately 30 to 50 nm. Considering a bandwidth of 30 nm and a channel spacing of 1.5 nm, an optical amplifier may be used to amplify 20 channels simultaneously. Further, assuming that these channels each contain 2.488 Gbit/s data streams, such as in FiberWorld™, the total transmission capacity is approximately 50 Gbits/s. Moving to systems with a 1 nm channel spacing and a 50 nm laser amplifier bandwidth, the effective transmission capacity reaches almost 125 Gbits/s. This demonstrates the incredible amount of information which may be transmitted through a laser amplifier, and the real applicability of these devices. Considering dense wavelength division multiplexing the achievable transmission rates are even higher.

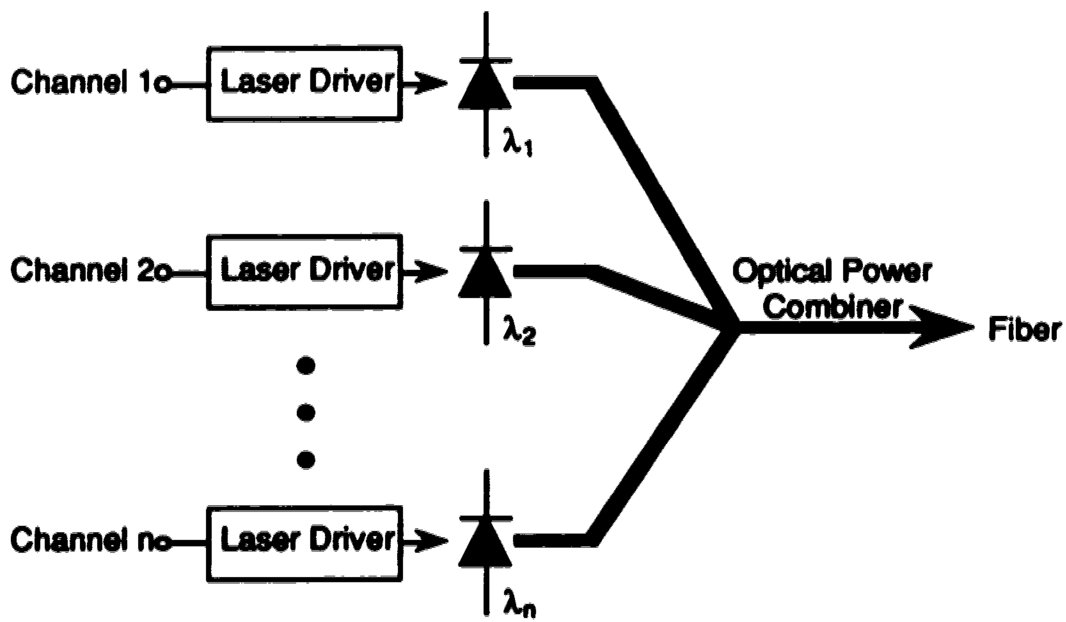

Figure 1.3 Wavelength Division Multiplexing

The main point of this discussion has been to demonstrate the applicability of optical amplifiers to present and future fiber optic transmission systems, and to indicate the immense amount of information which may be transmitted through an optical amplifier. These devices, however, have inherent deficiencies which have prohibited their installation in fiber optic systems to date. These problems will be discussed in the following section, along with the role that optical amplifiers may play in future fiber optic systems.

1.2 Role of Optical Amplifiers

One of the possible applications of optical amplifiers in each of the system architectures discussed above would be use as an inline amplifier or signal booster. In particular, optical amplifiers show promise as all optical repeaters in trunk lines and undersea communication systems, where the wide bandwidth of optical amplifiers may be used to handle the great amount of traffic present on such links. In addition, changes in transmission bit rate or system configuration changes, such as from a time-division multiplexed system to a subcarrier multiplexed system, would be transparent to the optical amplifier. Of special interest is the UK/Germany 5 system, a submarine link between Britain and Germany, which is slated for completion by 1991. In March 1989, British Telecom International requested bids for implementation of this system, both with electronic repeaters and with optical amplifiers [5]. This fact demonstrates that optical amplifiers are beginning to be considered as technologically feasible system components. As a result, optical amplifiers may soon be present in installed communication systems.

Local area networks and commercial distribution systems employing wavelength division multiplexing indicate possible applications of optical amplifier repeaters which make use of their inherently wide bandwidth. These systems are attractive because the receiver may select any one of the input channels simply by varying the wavelength of a local optical filter or oscillator.

The amplifiers may be used to compensate for splitting losses present in the system, amplifying all of the transmitted channels simultaneously.

Another application of optical amplifiers is that of optical receiver preamplifiers, boosting the optical signal level prior to photodetection by a PIN detector. A great deal of research has been performed in this area over the last five years, and it appears to be a very promising use of optical amplifiers [6-8]. An optical amplifier/PIN diode receiver is very similar to an avalanche photodiode receiver, the type of detector used in most installed fiber optic systems. The gain of the amplifier may be adjusted by varying the amplifier bias current, analogous to changing the reverse bias in the case of an avalanche photodiode. A rigorous noise analysis indicates that the overall noise figure of the system is very close to the noise figure of the optical amplifier, relaxing the bounds on electronic receiver noise and easing the receiver design [9]. Although the noise figure of optical amplifiers is inherently 3 dB or higher as a result of the amplification mechanism, active fiber amplifiers have been constructed with noise figures very close to the theoretical limit of 3 dB. As a result, it becomes possible to construct wideband low noise optical receivers, while at the same time avoiding the speed limitations present in avalanche photodiodes. Figure 1.4 indicates a projection of direct detection receiver sensitivity using presently available avalanche photodiodes (APD, k=0.35), together with the sensitivity expected from an optical amplifier/PIN diode configuration [10]. This plot demonstrates that a 3.6 dB improvement in receiver sensitivity may be achieved at 10 Gbits/s, using a laser preamplifier and PIN diode photodetector as opposed to a conventional, commercially available avalanche photodiode receiver. It should also be noted that if an active fiber amplifier with a noise figure of 3.2 dB is employed, and the total receiver coupling loss is reduced to 0.5 dB, a further 5.3 dB sensitivity improvement may be realized. As a result, an 8.9 dB overall sensitivity enhancement may be achieved as compared to a conventional APD receiver. In addition, this increase in sensitivity becomes more pronounced at higher transmission rates, as the APD begins to reach its fundamental gain-bandwidth product limit.

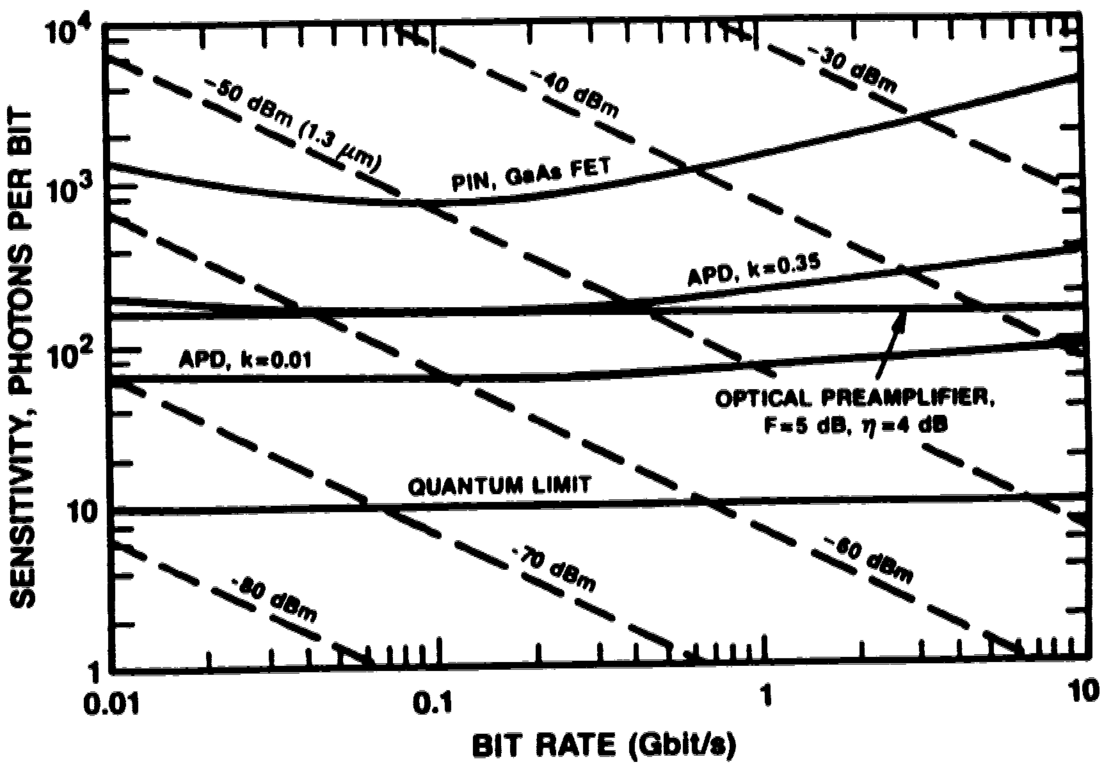

Figure 1.4 Direct Detection Receiver Sensitivity

In addition to the two optical amplifier applications discussed above, namely inline linear repeaters and optical preamplifiers, several other uses are possible, including external laser modulators for intensity modulated [11] and coherent systems [12], all optical signal regenerators [13], optical signal detectors [14], and even applications as optical phase locked loops [15].

The above discussion indicates that optical amplifiers have many applications in communication systems and may be used to increase system transmission capacity dramatically. However, these devices have inherent deficiencies which prohibit their use in installed fiber optic systems. In particular, semiconductor laser amplifiers exhibit a polarization sensitive gain. The value of the gain sensitivity varies depending on the amplifier device structure and operating bias point, but gain variations as high as 5 dB may exist for a commercially available device, as indicated in Appendix A. In addition, laser amplifiers exhibit a gain sensitivity towards both temperature and input wavelength, with the amplitude of the gain fluctuation again dependent on device structure and operating point. It is the purpose of this thesis to introduce a gain control circuit which has been constructed and found to be capable of stabilizing the gain or output power of a semiconductor laser amplifier gain to within 0.1 dB of the desired operating point, in spite of variations in environmental parameters. As a result, the optical amplifier gain or output power may be held constant, within specified bounds, producing a device which may be used as a simple gain block in practical communication systems. It should be noted that although the control system has been tested using a semiconductor laser amplifier, the system may easily be adapted to control the gain or output power of active fiber amplifiers.

The stabilization results presented in this work compare very favorably with the only previously published laser amplifier output power control circuit which was able to reduce environmental sensitivities to approximately 0.2 dB [16]. However, the control circuit introduced in [16] is applicable only to laser amplifiers and not to active fiber amplifiers.

1.3 Thesis Organization

As indicated above, optical amplifiers will likely be important components in future fiber optic systems if some method can be found to control their sensitivity with respect to environmental conditions. This thesis describes the implementation and testing of a system capable of controlling gain or output power of a semiconductor laser amplifier.

Chapter 2 presents the basic theory of semiconductor laser amplifier gain. This chapter includes a discussion of the sensitivity that semiconductor laser amplifiers exhibit towards environmental conditions, and introduces typical values for amplifier gain parameters. This chapter discusses the reasons why optical amplifiers are not employed in present day systems, and provides the motivation behind the gain control circuit which has been implemented.

Chapter 3 introduces the experimental system which has been used to test the optical amplifier and associated gain control system, and explains the overall objectives of the test system. This chapter presents the measured parameters of the optical amplifier under test and indicates its sensitivity with respect to several operating conditions. Chapter 4 introduces the gain control circuit itself, and presents the various system blocks which have been constructed. The desired operating characteristics and specifications for each system component are presented, along with the test results obtained indicating the performance achieved from the circuit. Following this, Chapter 5 presents the measured results of the entire gain control system in both constant gain and constant output power control modes. This chapter also performs a comparison between the results obtained from this experiment and those obtained from other laser amplifier control systems reported in the literature, and introduces the configuration of two proposed optimum laser amplifier control systems.

Chapter 6 presents several applications of the gain control circuit to fiber optic communication systems. This chapter indicates the applicability of the control circuit, and demonstrates the array of configurations in which it may be used to control various optical amplifier properties. This chapter concludes the thesis, and presents the highlights of the gain control circuit and the performance achieved in a fiber optic communication system. A discussion of further research topics is also undertaken, indicating possible directions in which additional work may proceed.

2. THEORY OF SEMICONDUCTOR LASER AMPLIFIERS

The purpose of this chapter is to introduce the fundamental operating characteristics of semiconductor laser amplifiers, beginning with a qualitative description of optical amplification, in order to indicate the basic physical principles involved. This is followed by an analytical investigation of the gain properties of laser amplifiers, which illustrates the physical mechanisms responsible for the environmental sensitivity of laser amplifiers, and provides the motivation for the gain control circuit which has been constructed.

2.1 Principles of Operation

A semiconductor laser amplifier is very similar in structure to an LED and a semiconductor laser. In fact, the same semiconductor diode may act as an LED, an optical amplifier, or a semiconductor laser, depending on the drive current with which it is biased [17].

The basic structure of a buried heterostructure semiconductor diode is shown in Figure 2.1 [17,18]. The diode is made up of several layers of n-doped and p-doped semiconductor material, with the active, or amplifying, region formed of undoped InGaAsP. The active region is the portion of the diode that is responsible for light emission as well as optical amplification when an injected optical signal is present. The device has two partially reflective end facets, which are created by cleaving the semiconductor block along a crystal plane. The residual reflectivity of the end planes is given by [18],

$$R = \left[\frac{\rho-1}{\rho+1}\right]^2 \tag{2.1}$$

where ρ is the refractive index of the material within the active region. Light amplification is achieved by coupling an optical signal into the active region through one of the end facets and coupling the amplified signal out at the other end facet. The semiconductor diode is mounted on a doped semiconductor substrate, and two metallized contacts are added to provide external connections which are used drive a bias current through the device.

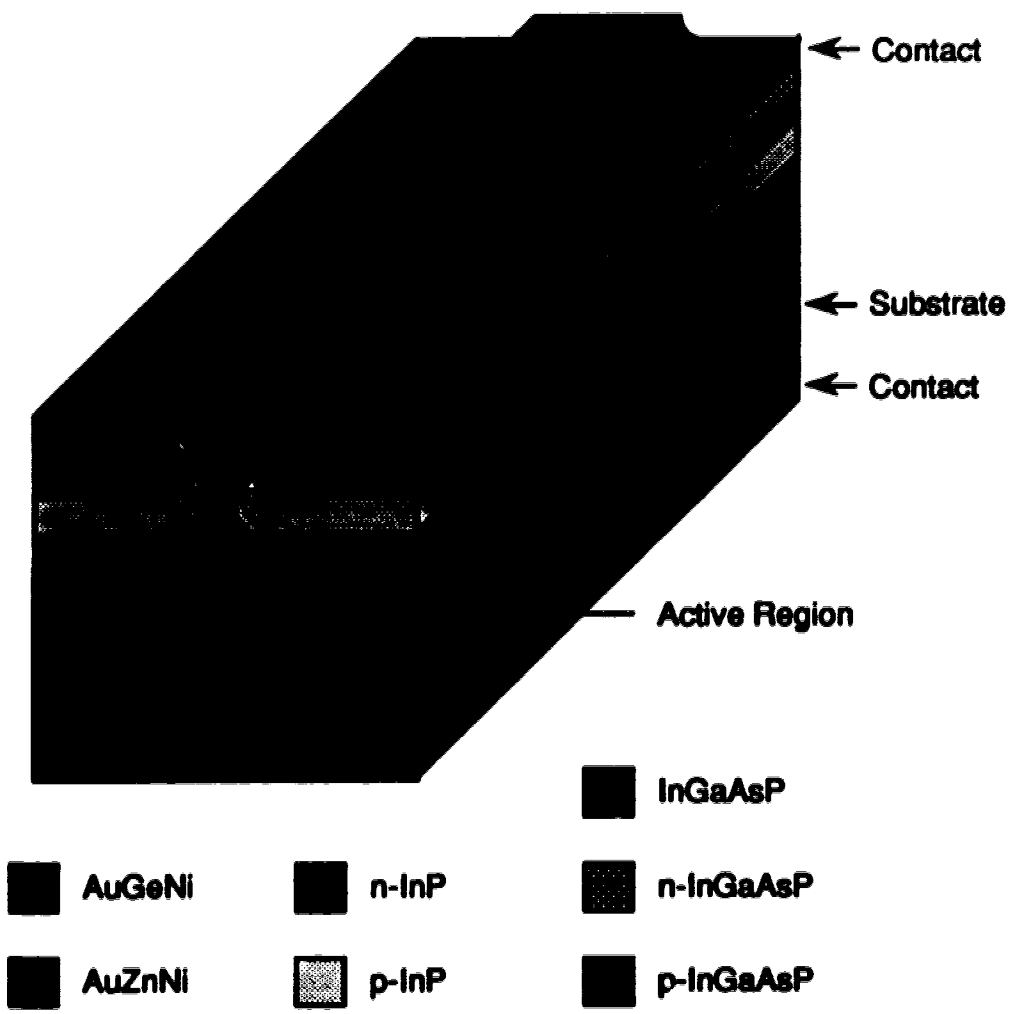

Figure 2.1 Structure of a Buried Heterostructure Semiconductor Diode

Optical amplification may be explained by considering the energy band diagram of the semiconductor material within the active region, as is indicated in Figure 2.2. When a bias current is injected into the active region, electrons absorb sufficient energy to move from the valence band to the conduction band. This operation is called pumping and results in a higher number of free electrons in the conduction band than in the valence band, a phenomenon called population inversion. Complete population inversion exists if all free electrons reside in the conduction band, with none remaining in the valence band.

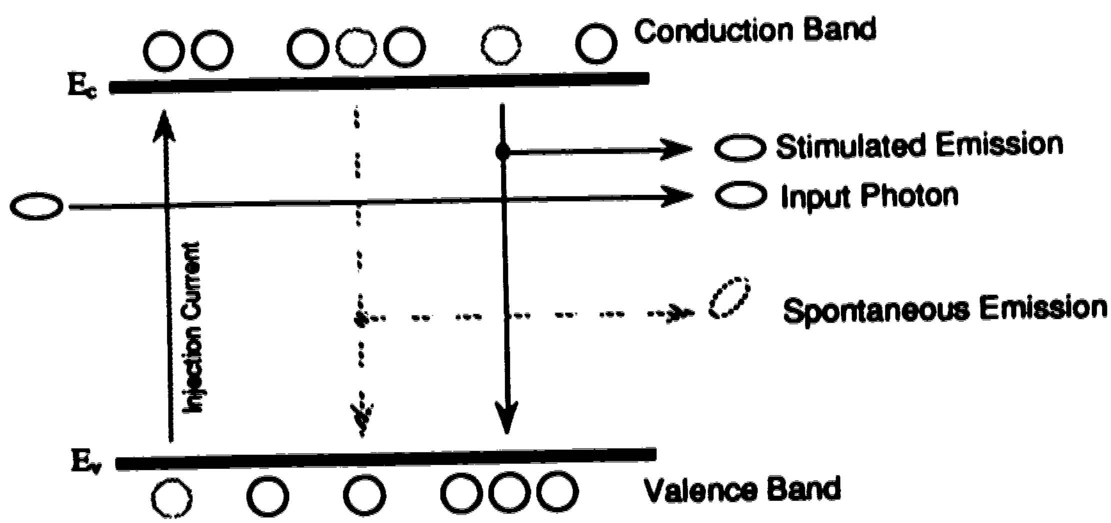

Figure 2.2 Energy Band Diagram of a Semiconductor Laser Amplifier

Over time, some of the electrons in the conduction band spontaneously recombine with holes in the valence band, releasing energy and emitting a photon of light at a wavelength, λ, given by,

$$\lambda = \frac{hc}{E_g} \tag{2.2}$$

where h is Planck's constant, c is the speed of light, and E_g is the energy gap of the material within the active region. The light emitted in this manner is called spontaneous emission and is the source of the main noise components generated by a semiconductor laser amplifier. The electron which recombines may originate from within a band of energy about the level E_c, and falls into a band around E_v. As a result, the energy transferred to the photon, and hence the emission wavelength, varies. As a consequence, the spontaneous emission from an optical amplifier has a wide bandwidth, on the order of 30 to 50 nm.

The second type of light emission in optical amplifiers is called stimulated emission. This process represents the mechanism that is responsible for the optical gain which these amplifiers exhibit. In this case, the interaction of an input photon with the semiconductor lattice results in one electron-hole pair recombination, and in the emission of a photon of light which is identical to the initial photon. As a result, there are now two identical photons where there originally was one, representing a signal gain for the input stream. These two photons may interact further within the active region, resulting in additional stimulated emission and hence increased gain.

If the diode has some form of optical feedback, such as partially reflective end facets or internal refractive index variations, the device may operate as a semiconductor laser. As the bias current is increased from zero the device initially begins to emit light spontaneously over a wide range of wavelengths and behaves as an LED. For bias currents corresponding to internal gains of less than unity, any optical signal coupled into the amplifier is attenuated. As the bias current is increased an enhanced population inversion is created, and the internal gain rises until it is equal to one. This bias point is the threshold of amplification, and any optical signal coupled into the active region will appear at the output neither amplified nor attenuated, assuming ideal coupling and no reflections from the end facets. As the bias current continues to rise, the inverted population increases and the device begins to exhibit optical gain. The point at which the internal gain is able to compensate for all internal losses, such as end facet reflections and photon absorption, is called the threshold of lasing. At this point, the round trip cavity gain is equal to unity and the device becomes a semiconductor laser, emitting light only at those wavelengths which have a round trip phase shift of 2π, corresponding to constructive interference. If the mechanism responsible for the optical feedback is the residual end facet reflectivities, the cavity is called a Fabry-Perot cavity, and the lasing wavelengths are called Fabry-Perot longitudinal modes. Thus, as noted earlier, a single semiconductor diode may behave as an LED, a laser amplifier, or a semiconductor laser depending on the bias current applied to the device.

In the case of an optical amplifier, the end facets are AR coated with a material such as SiO [19] or Si_3N_4 [20] in order to reduce their reflectivity. As a result, the input signal is simply coupled in through the input facet, amplified along the active region, and emitted from the output facet, all with very little reflection from either of the end planes. Devices which have high quality AR coatings, with residual reflectivities on the order of 10^{-4} to 10^{-5}, are called near travelling wave laser amplifiers, and amplify the input optical signal in a single pass through the device. However, devices which have no AR coatings, or only low quality coatings, have substantial reflections from the end planes causing the signal to make multiple passes through the amplifier. Such a device is called a Fabry-Perot laser amplifier and has gain only at wavelengths which correspond to Fabry-Perot longitudinal modes. Figure 2.3 compares the method by which amplification is achieved in the two types of amplifiers.

For both types of amplifier the gain profile has a bandwidth on the order of 30 to 50 nm, due to the range of possible electron-hole pair recombination energies. However, for the Fabry-Perot device the spectrum has a multimode pattern superimposed upon it as a result of the internal resonance effects. The device exhibits gain only at wavelengths which correspond to constructive interference after the signal makes one round trip within the amplifier cavity, giving rise to the gain spectra indicated in Figure 2.4. It is important to note that the depth of the Fabry-Perot resonances depends on the residual facet reflectivities and internal single pass gain, or, equivalently, on the internal round trip cavity gain.

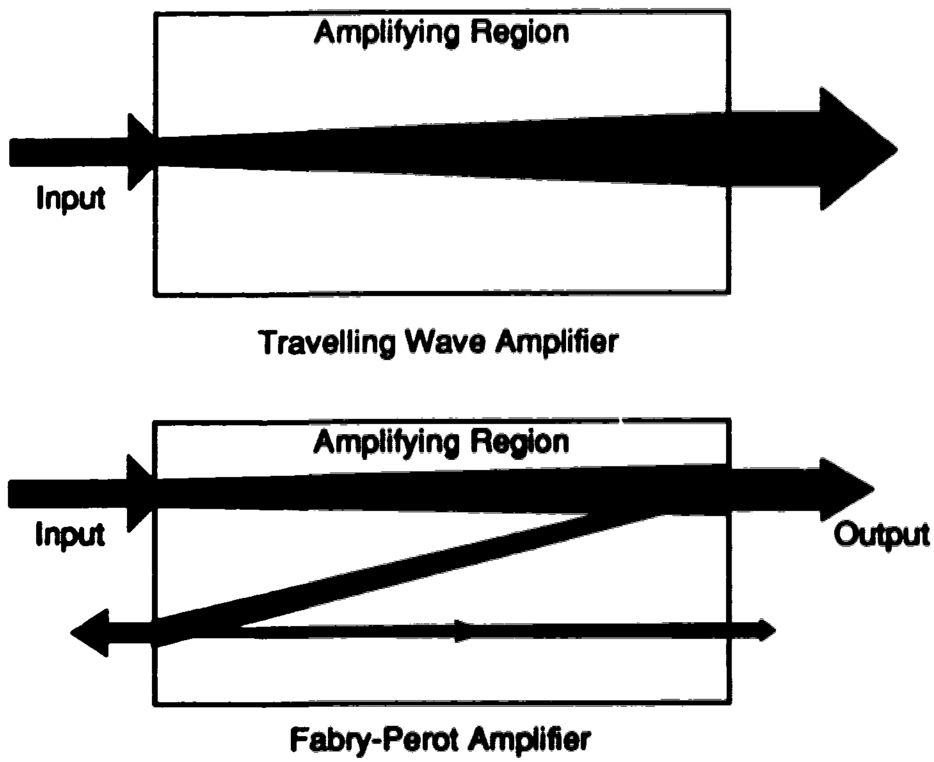

Figure 2.3 Qualitative Comparison Laser Amplifier Gain Mechanisms

One final point which should be discussed is the phenomenon of lasing. A Fabry-Perot amplifier may be driven sufficiently hard to initiate lasing, a result of the optical feedback introduced by the nonzero residual facet reflectivities. The feedback generates a multimode laser output, with the central mode determined by the bandgap of the material and the amplifier bias current. Lasing does not occur, however, for an ideal travelling wave amplifier, as the internal feedback mechanism is not present. The result is a "soft" output power versus current characteristic, with no laser threshold and no knee present, as shown in Figure 2.5 [21]. This figure shows the light output versus current curve for both an uncoated laser and a laser amplifier with antireflection coatings, demonstrating that the familiar laser threshold knee is removed. Practical laser amplifiers lie somewhere in between ideal travelling wave amplifiers and uncoated resonant Fabry-Perot lasers, with a small, but nonzero, residual facet reflectivity. As a result they may exhibit lasing, but only for large drive currents and high internal gain.

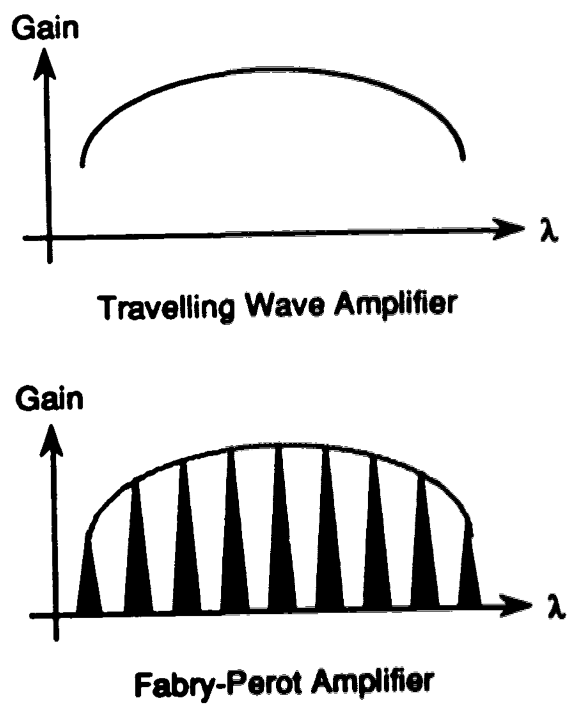

Figure 2.4 Gain spectra of Laser Amplifiers

This discussion has introduced the physical principles governing the operation of semiconductor laser amplifiers. The following section will investigate the gain characteristics of these devices on a quantitative basis, and will discuss some of the apparent deficiencies of laser amplifiers. Appendix A contains the specification sheets for a commercially available laser amplifier, indicating some of the typically specified device parameters and operating characteristics.

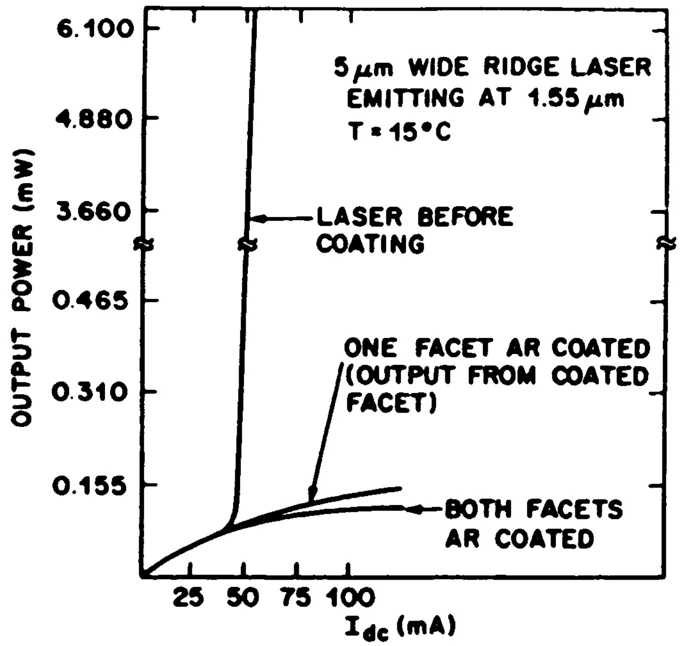

Figure 2.5 LI Characteristic for a Laser Amplifier

2.2 Laser Amplifier Gain Characteristics

In order to introduce the gain characteristics of laser amplifiers, the physical model shown in Figure 2.6 will be used. This model represents the active region as a rectangular volume of length L, width w, and thickness d, constructed of a material of refractive index ρ. The laser amplifier used in this experiment was a Hitachi HLP5400 laser with AR coatings applied by the Heinrich Hertz Institute in Berlin, FRG. This device has L = 250 μm, w = 2.05 μm and d = 0.2 μm, while the refractive index, ρ, is approximately 4 for a 1300 nm

InGaAsP device [22]. The input and output facet reflectivities, R_1 and R_2 respectively, were measured to be 0.08% [23, 24].

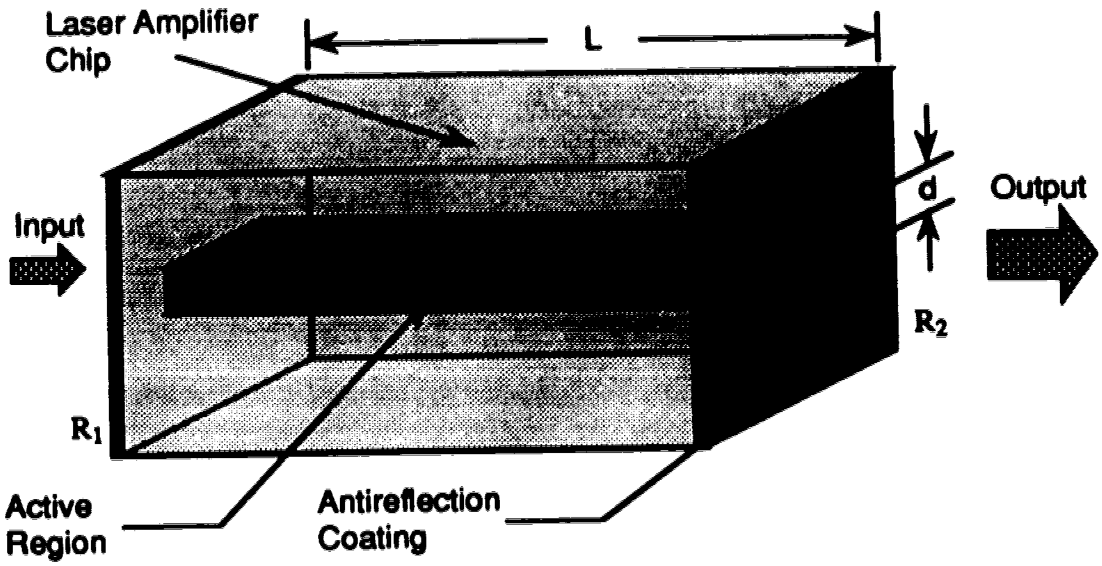

Figure 2.6 Physical model of a Laser Amplifier

2.2.1 Material Gain Coefficient

Considering a signal at wavelength λ travelling along the active region, the gain per unit length imparted to the signal, also called the material gain coefficient, may be expressed as [25]

$$g_O = a(T)[n - n_O(T)] - b[\lambda - \lambda_p]^2 \tag{2.3}$$

where n is the carrier density within the active region and $n_O(T)$ is the transparency carrier density at temperature T. The transparency density represents the carrier density at which the internal gain is one, indicating neither gain nor attenuation for an input signal. a(T) is a temperature dependent gain coefficient which converts excess carrier density, the carrier density less the transparency density, to gain per unit length. The wavelength at which the peak value of gain occurs is represented by λ_p. The gain profile decreases parabolically about this wavelength with a scaling factor of b, where the peak gain wavelength may be expressed as,

$$\lambda_p = \lambda_O + c_\lambda(n - n_{th}). \tag{2.4}$$

In this expression λ_O is the center wavelength of the spontaneous emission spectrum when the laser amplifier is driven with a bias current equal to the original laser threshold current before antireflection coating. The carrier density at this bias current is denoted as n_{th}, and n is again the carrier density within the active region at the chosen operating point. The wavelength shift coefficient, c_λ, indicates the magnitude of the peak gain wavelength shift as a function of the carrier density. This equation demonstrates that the laser amplifier peak gain occurs at the wavelength λ_O when the device is driven at the original laser threshold current. As the current, and hence the carrier density, is increased the peak gain wavelength shifts to shorter wavelengths (c_λ is negative). Specifically, the peak gain wavelength has been known to shift by as much as 50 nm in some cases [25].

Considering again the material gain coefficient, it is observed that the gain profile exhibits a maximum at the peak gain wavelength, which shifts with the operating point. The maximum value of gain is represented by the first term in (2.3) and indicates that the peak value of gain increases with increasing carrier density. Thus, it may be concluded that the gain of the laser amplifier is sensitive to both the bias point of the laser amplifier as well as the input source wavelength.

The material gain coefficient is also function of the temperature of the device. This fact may be demonstrated by considering the transparency density, $n_O(T)$, and the gain coefficient, a(T). The transparency density is temperature dependent, increasing with an increase in temperature, hence decreasing the excess carrier density and reducing the material gain coefficient with temperature. The excess carrier density is converted to gain per unit length by the gain coefficient, a(T), which tends to decrease with temperature, thereby decreasing the material gain coefficient with temperature. As a result, a second order dependence of material gain coefficient on temperature exists.

The plots in Figures 2.7 and 2.8 indicate the variation of the material gain coefficient versus wavelength for different values of device temperature and active region carrier density. These diagrams demonstrate the sensitivity which amplifier gain exhibits towards environmental conditions, in particular the operating point, source wavelength, and device temperature. These graphs have been calculated using the amplifier parameters listed in Tables 2.1 [26] and 2.2, which apply to general 1300 nm InGaAsP devices as well as the specific optical amplifier used in this experiment, respectively. The source code for the program used to calculate the data presented in these figures is contained in Appendix B.

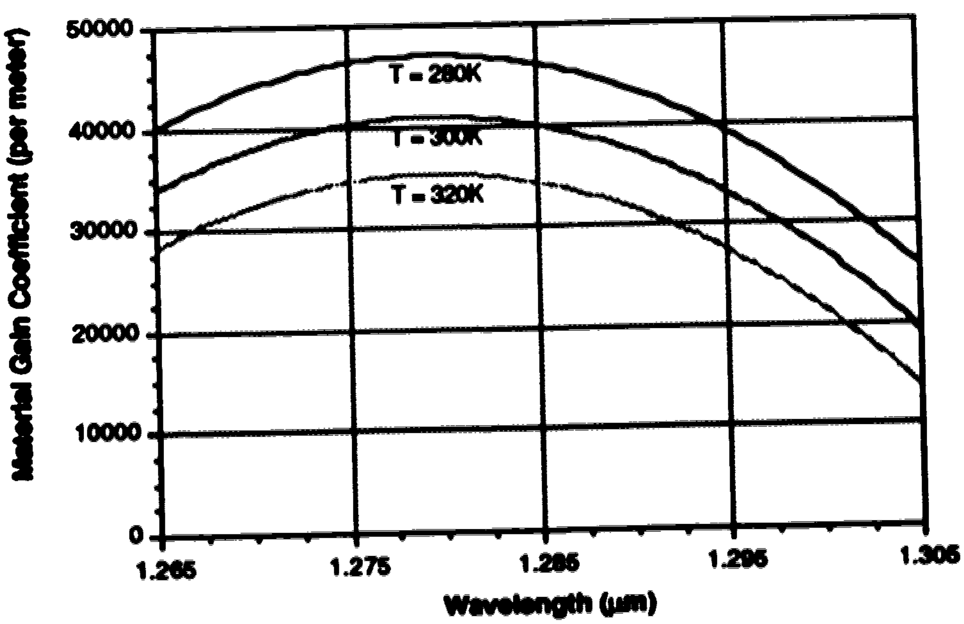

Figure 2.7 Material Gain Coefficient at Various Temperatures ($I = 2.5 I_{th}$)

Table 2.1 Material Gain Parameters for a General InGaAsP Laser Amplifier

Variable	Description	Value
$a(T_o)$	Gain Coefficient at Temperature T_o	$2.2 \cdot 10^{-20}$ m^2
$\frac{da(T)}{dT}$	Temperature Derivative of a	$-8.6 \cdot 10^{-23}$ $\frac{m^2}{K}$
b	Gain Constant	$3.3 \cdot 10^{19}$ m^{-3}
$\frac{dn_o(T)}{dT}$	Temperature Derivative of n_o	$6.1 \cdot 10^{21}$ $\frac{m^{-3}}{K}$

Table 2.2 Material Gain Parameters for a Hitachi HLP5400 Laser Amplifier

Variable	Description	Value
$n_o(T_o)$	Transparency Density at Temperature T_o	$2.18 \cdot 10^{24}$ m^{-3}
λ_o	Peak Gain Wavelength at $n = n_{th}$	$1.3 \cdot 10^{-6}$ m
n_{th}	Threshold Carrier Density	$2.77 \cdot 10^{24}$ m^{-3}
c_λ	Wavelength Shift Coefficient	$-1.61 \cdot 10^{-32}$ m^4

The two sets of curves indicate the sensitivity which the gain coefficient exhibits towards source wavelength. Figure 2.7 also demonstrates the temperature sensitivity that material gain coefficient exhibits, while Figure 2.8 indicates that as the laser amplifier bias point moves from the original threshold current (I_{th}) to 2.5 times this value, the wavelength at which the peak gain occurs moves from 1300 nm down to 1280 nm. Therefore, as the bias current is increased, the gain change observed at a particular wavelength is enhanced or degraded by a shift in the peak gain wavelength. It is important to note that for an actual laser amplifier, as the drive current is increased the gain increases at all wavelengths, and the gain curves do not cross as shown in Figure 2.8. The intersection in this diagram is due to an assumption of constant active region refractive index. In actual devices, as the bias current is increased the carrier density and the material refractive index increase, resulting in an increased gain at all wavelengths. This is indicated in Figure 2.9, which shows the results obtained by the Heinrich Hertz Institute for an AR coated Hitachi HLP5400 laser amplifier [27].

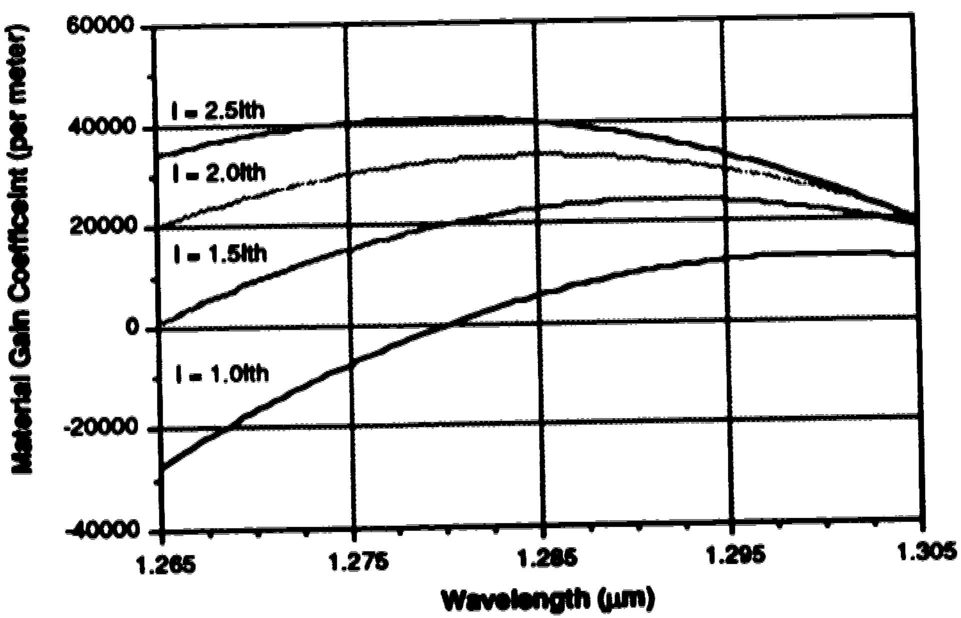

Figure 2.8 Material Gain Coefficient at Various Bias Points (T=300K)

This section has introduced the concept of the material gain coefficient of a semiconductor laser amplifier and has indicated the sensitivity which this gain parameter exhibits towards laser amplifier bias point, input signal wavelength, and device temperature. The following section will consider the overall resonant gain of a laser amplifier and will introduce another factor to which gain is sensitive, namely input signal polarization.

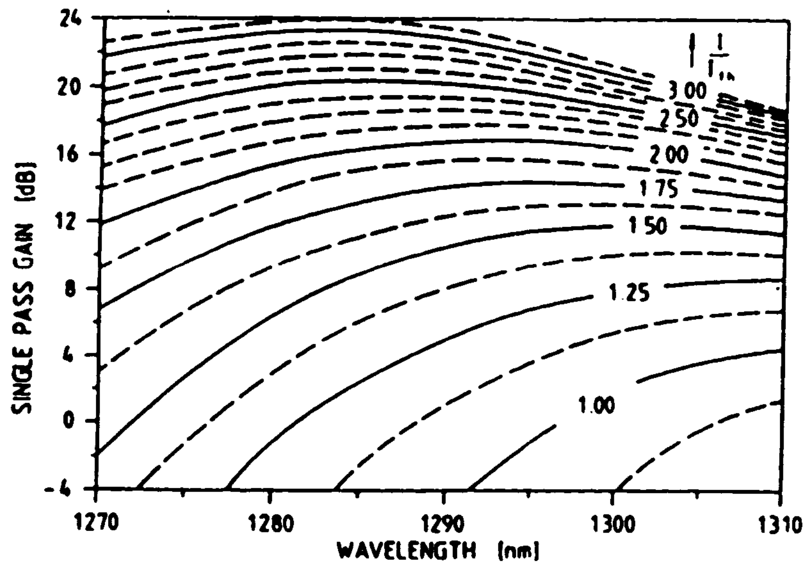

Figure 2.9 Gain Characteristics of a HLP5400 Laser Amplifier

2.2.2 Amplifier Cavity Gain

Given the material gain coefficient, g_O, the single pass gain of a laser amplifier may be expressed as

$$G_s = \exp\left[\left(\frac{\Gamma g_O}{1+\frac{P_{out}}{P_{sat}}} - \alpha\right)L\right] \tag{2.5}$$

where Γ is the optical mode confinement factor indicating the fraction of the signal that is confined to the active region of the amplifier, α is the loss per unit length within the cavity, and L is the amplifier cavity length. The internal loss, α, is caused by such mechanisms as non-radiative spontaneous recombination and photon absorption.

The term $1+P_{out}/P_{sat}$ degrades the confined material gain coefficient and accounts for gain saturation effects. P_{out} is the output optical power of the laser amplifier, and P_{sat} is the output saturation power which may be expressed as [25]

$$P_{sat} = \frac{wdE}{\Gamma\tau a(T)} \ln(2) \tag{2.6}$$

where w is the amplifier cavity width, d the thickness, and τ is the spontaneous carrier lifetime. E is the energy of a photon, which may be expressed as the product of Planck's constant and the emission frequency, and a(T) is the temperature dependent gain coefficient discussed earlier.

The above two expressions indicate that the input optical signal is amplified exponentially as it travels along the active region, with the gain imparted to the signal being degraded as the signal level approaches the saturation intensity. Equivalently, the amplifier may be considered to have an effective material gain coefficient which varies with distance along the amplifier cavity, as a consequence of gain saturation.

It is important to note that the single pass gain exhibits a sensitivity towards bias point, wavelength, and temperature as a result of the dependence that the material gain coefficient exhibits towards these parameters. However, the single pass gain also demonstrates a sensitivity towards the polarization of the input signal, because the confinement factor, Γ, is polarization dependent, as shown in Figure 2.10 [28]. TE and TM modes have unequal confinement factors due to the asymmetrical shape of the active region. The polarization sensitivity of Γ, and hence single pass gain, could possibly be reduced by using a more symmetrical active region; that is, an active region with a width over thickness ratio closer to unity.

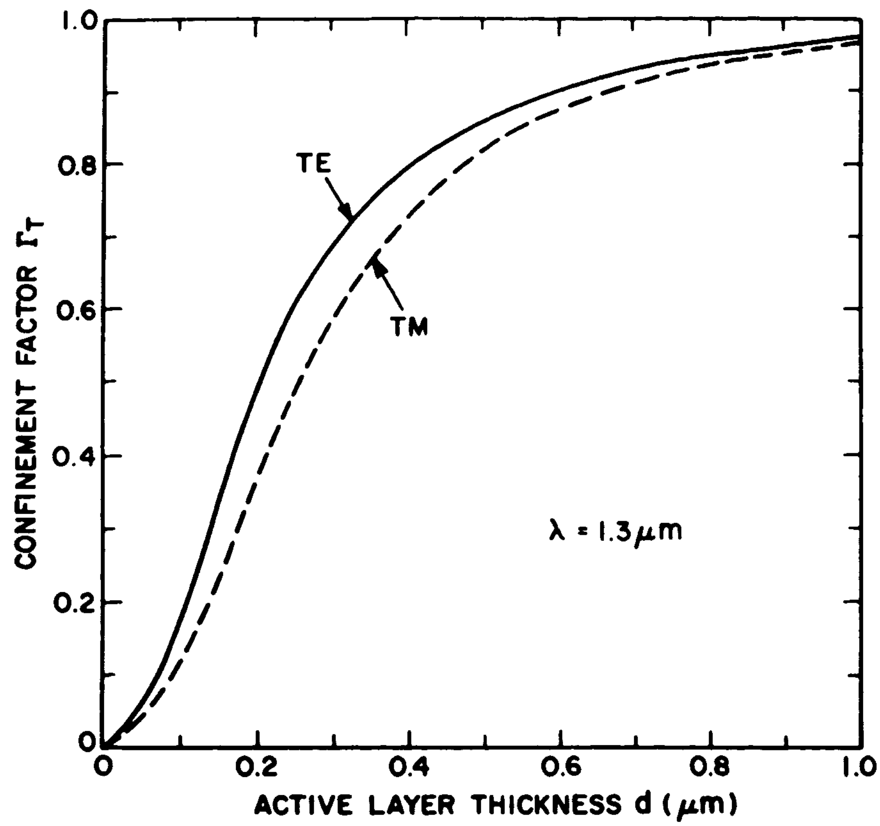

Figure 2.10 Polarization Dependence of Confinement Factor

In the case of an ideal travelling wave amplifier the single pass gain is identical to the resonant amplifier gain, as the device amplifies the input signal in a single pass. However, if the amplifier has nonzero facet reflectivities, some portion of the signal is reflected from the end facets, which results in a resonant type amplifier with a gain given by

$$G = \frac{(1-R_1)(1-R_2)G_s}{(1-G_s\sqrt{R_1R_2})^2 + 4G_s\sqrt{R_1R_2}\sin^2(\theta)} \tag{2.7}$$

The single pass phase shift imparted to the signal is indicated by θ, and may be written as [25]

$$\theta = \frac{2\pi L}{\left(\frac{\lambda}{\rho}\right)} + \frac{g_O L \beta}{2}\left(\frac{P_{out}}{P_{out}+P_{sat}}\right) \quad (2.8)$$

In this expression L is the cavity length, λ is the wavelength of the input signal, and ρ is the refractive index of the material within the active region. The material gain coefficient discussed earlier is denoted by g_O, and β is the linewidth broadening factor. As before, P_{out} is the output optical power and P_{sat} is the output saturation power. It is evident from this expression that the phase shift within the cavity is a constant proportional to the round trip transit time, modified as the device approaches gain saturation due to changes in the active region refractive index.

The expression for amplifier gain indicates that the resonant gain is sensitive to all of the parameters to which the single pass gain exhibits a sensitivity, namely operating point, wavelength, temperature, and polarization. In addition, the residual facet reflectivities, R_1 and R_2, are polarization dependent, as shown in Figure 2.11 [29], introducing a further polarization dependence. This plot indicates that not only does the minimum reflectivity wavelength differ for TE and TM modes, but also demonstrates that the minimum value of reflectivity differs. As a consequence, operation at almost any wavelength results in different facet reflectivities for TE and TM modes. Operation at a compromise wavelength with equal modal reflectivities results in low quality coating reflectivities and, as a result, poor amplifier response. Attempts to combat this difficult polarization problem which have met with reasonable success include the use of such end plane structures as windows [30] and buried facets [31].

Using the amplifier resonant gain model presented above, the gain versus wavelength characteristics shown in Figure 2.12 may be calculated, using the parameter values listed in Table 2.3.

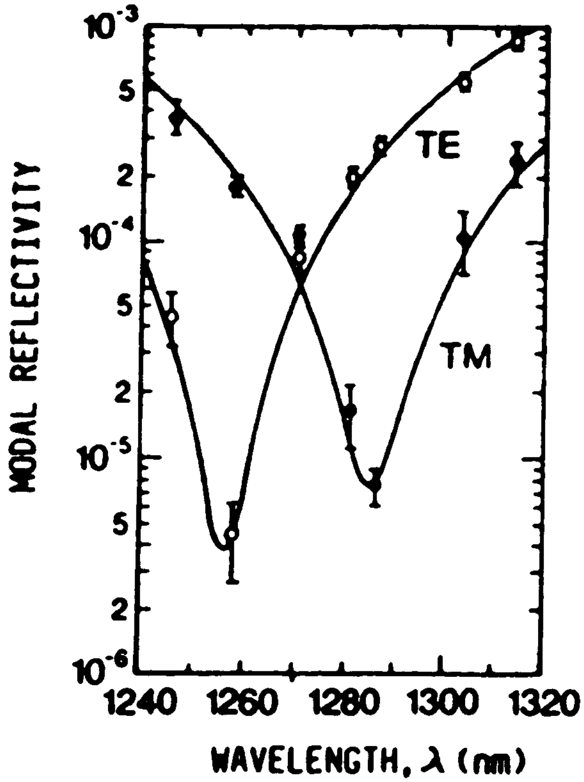

Figure 2.11 Wavelength Dependence of Facet Reflectivity

Table 2.3 Amplifier Gain Parameters for an InGaAsP Laser Amplifier

Variable	Description	Value	Ref.
Γ	Optical Confinement Factor	0.47	[28]
α	Material Loss Coefficient	2000 m^{-1}	[26]
b	Linewidth Broadening Factor	6.6	[26]
τ	Spontaneous Carrier Lifetime	$1.68 \cdot 10^{-9}$ sec	[26]

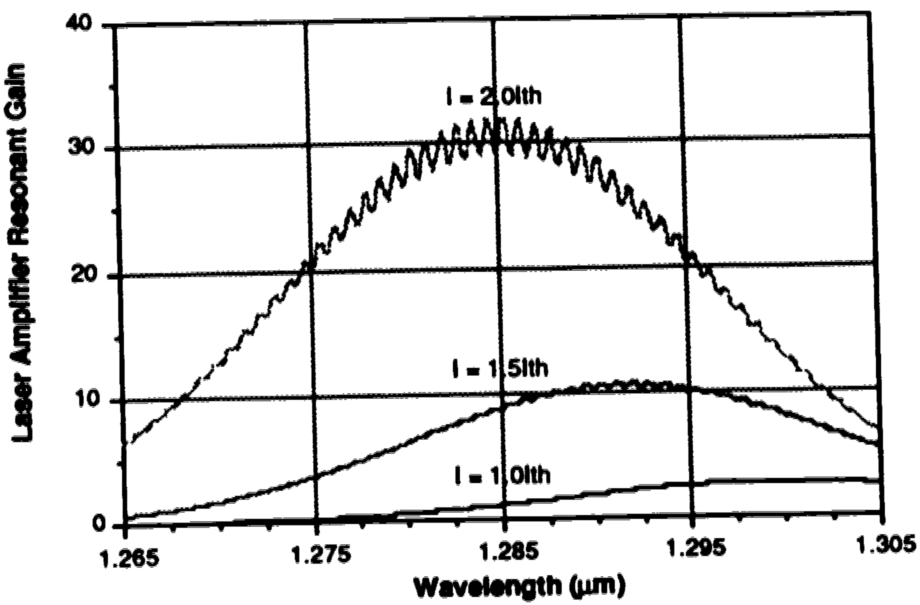

Figure 2.12 Laser Amplifier Gain Profile at Various Drive Currents

This figure demonstrates the resonant nature of optical amplifier gain when there are nonzero residual facet reflectivities, and shows the gain degradation which occurs at wavelengths which do not correspond to Fabry-Perot resonant modes. This figure also demonstrates the shift in peak gain wavelength that is created by increases in drive current. As well, the Fabry-Perot resonant effects are enhanced by increasing the bias current, as expected, because the round trip gain is increasing and the amplifier is approaching the laser threshold. A figure of merit which expresses the ratio of the minimum to maximum values of the Fabry-Perot gain resonances at a particular wavelength is called the non-resonant gain ratio, and is given by [21],

$$G_{nr} = \frac{(1-G_s\sqrt{R_1R_2})^2}{(1+G_s\sqrt{R_1R_2})^2}. \tag{2.9}$$

This expression indicates that not only does the amplifier gain exhibit a variation with bias point, wavelength, temperature and polarization, but the ripple amplitude does as well.

The final gain characteristic to be considered here is the expression for the backward travelling gain. In the case of an amplifier with nonzero residual facet reflectivities, a signal component is returned in the reverse direction. The gain for this component is given by [32]

$$G_B = \frac{(\sqrt{R_1} - \sqrt{R_2}G_s)^2 + 4\sqrt{R_1R_2}G_s\sin^2(\theta)}{(1 - \sqrt{R_1R_2}G_s)^2 + 4\sqrt{R_1R_2}G_s\sin^2(\theta)}, \qquad (2.10)$$

where all parameters are as previously defined. This equation indicates that the backward travelling gain exhibits Fabry-Perot resonant modes within the gain profile. As the residual facet reflectivities approach zero, and the device becomes an ideal travelling wave amplifier, the backward gain approaches zero, as expected for a single pass amplifier with no reflections.

2.3 Environmental Considerations

This chapter has introduced the basic gain characteristics of laser amplifiers and has presented a list of the parameters towards which laser amplifier gain exhibits a sensitivity. Specifically, the gain is dependent on the laser amplifier bias point, input signal wavelength, device temperature, and input signal polarization. In order that the amplifier gain is stable enough to be of use in practical systems, the temperature must be controlled to within a fraction of a degree [33], with equally stringent control required on input signal polarization, wavelength, and amplifier bias current. However, control of these parameters to the required extent is impractical in an installed system. As a result, this project has been undertaken, aimed at implementing an automatic gain control circuit which measures the amplifier gain and controls the device bias point in order to maintain an environmentally stable amplification factor.

In Chapter 3, the fiber optic system which has been used to test the gain control circuit will be introduced. Chapter 4 will follow with a description of the overall control system configuration, as well as an explanation of the building blocks which have been used to implement the laser amplifier gain control system.

3. EXPERIMENTAL FIBER OPTIC SYSTEM

This chapter introduces the experimental fiber optic system which was constructed in order to test the laser amplifier automatic gain control circuit. The entire test system is presented, together with an explanation of the various subcomponents used and their significance in terms of the tests performed on the gain control circuit. In addition, this chapter presents the measured performance specifications of the laser sources and receivers used in the test system, as well as the measured parameters of the laser amplifier used in this experiment. In particular, the gain characteristics of the laser amplifier driven by a constant current source are introduced. This serves to demonstrate the sensitivity that the laser amplifier exhibits towards environmental conditions, indicating the desire for a laser amplifier gain control circuit.

The fiber optic test system that has been built includes several components which have not been used directly in the testing of the gain control circuit. These components have been included in the test system, however, in order to allow future laser amplifier work to be performed. Their function is examined in order to indicate some of the directions along which further research may proceed.

3.1 Fiber Optic Test System

In order to examine the operation of the overall laser amplifier test system, it is necessary to consider the two main subsystems of the link, namely the optical sources and the laser amplifier test bed. In the following sections the configurations of the subsystems will be analyzed, and the function performed by the internal components will be introduced, in terms of the system objectives and the tests performed on the gain control circuit.

3.1.1 Optical Source Subsystem

The layout of the optical source portion of the test system is shown in Figure 3.1. This diagram indicates that two sources are installed, a distributed feedback (DFB) laser and an external cavity laser. The optical sources are used to generate an intensity modulated optical signal, which is in turn used to test the laser amplifier gain control circuit, as well as to facilitate measurements indicating the environmental sensitivity exhibited by the laser amplifier under test.

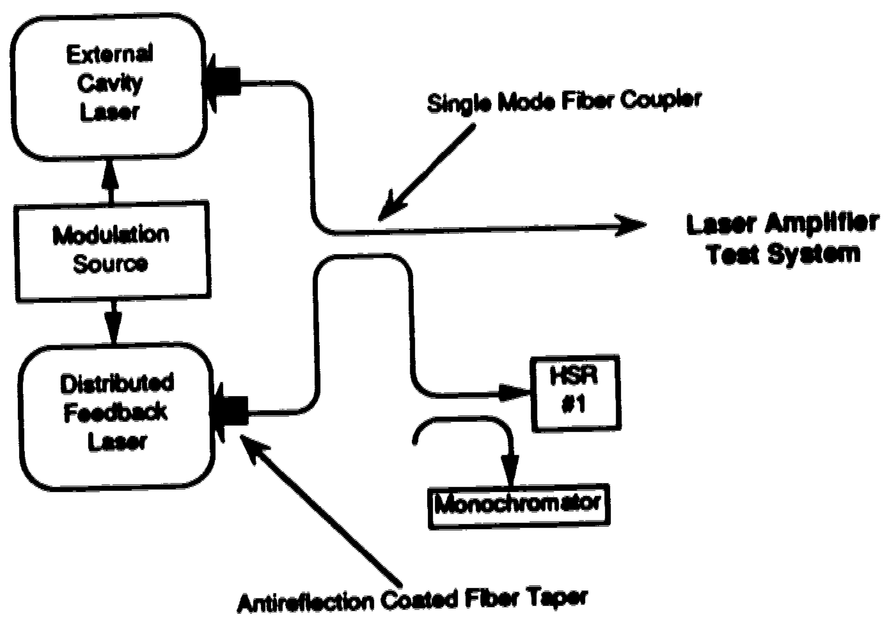

Figure 3.1 Layout of Optical Source Subsystem

The first laser is a Fujitsu FLD130F1SL DFB laser, mounted on a small brass subcarrier, and emitting light at a wavelength of 1293.5 nm. The optical output from this laser is coupled onto single mode fiber using an AR coated single mode fiber taper and a 3-dimensional Optikon manual micropositioner. The peak coupling efficiency which has been achieved using this arrangement is 62%.

The second optical source is an external cavity laser, with the external feedback provided by an Optikon 1200 nm diffraction grating. The optical feedback is injected into the antireflection coated facet of a Fujitsu FLD130D4SJ-A 1300 nm semiconductor laser. The emission wavelength of this laser may be tuned from 1280 to 1310 nm by rotating the diffraction grating with respect to the longitudinal axis of the laser cavity. The threshold current and light versus current characteristic of this laser are dependent on the magnitude of the optical feedback produced by the cavity [34]. The light emitted from this laser is also coupled onto single mode fiber using an AR coated fiber taper and manual micropositioner arrangement, with a maximum coupling efficiency of 65%.

The outputs from the two lasers are combined in a 3 dB single mode fiber coupler. The first coupler output is applied to a second 3 dB coupler in order to divide one half of the optical signal between a scanning monochromator channel and a high speed receiver module. The monochromator is used to determine the optical power spectrum of the lasers, while the high speed receiver is used to detect the combined intensity modulated signal, as well as to measure any interchannel crosstalk products present. The second output from the power combiner is used to drive the laser amplifier test bed, and hence test the laser amplifier control circuitry.

The optical power spectrum of the two lasers, measured using a scanning monochromator, is shown in Figure 3.2, where the external cavity laser has been tuned to operate at a slightly longer wavelength than the DFB laser. This figure indicates the single mode nature of both lasers, and demonstrates that the external cavity laser may be tuned to operate at a wavelength very close to the DFB lasing wavelength. It should be noted that the untuned lasers emit light at wavelengths separated by 22 nm, as compared to the 1 nm spacing shown in this figure.

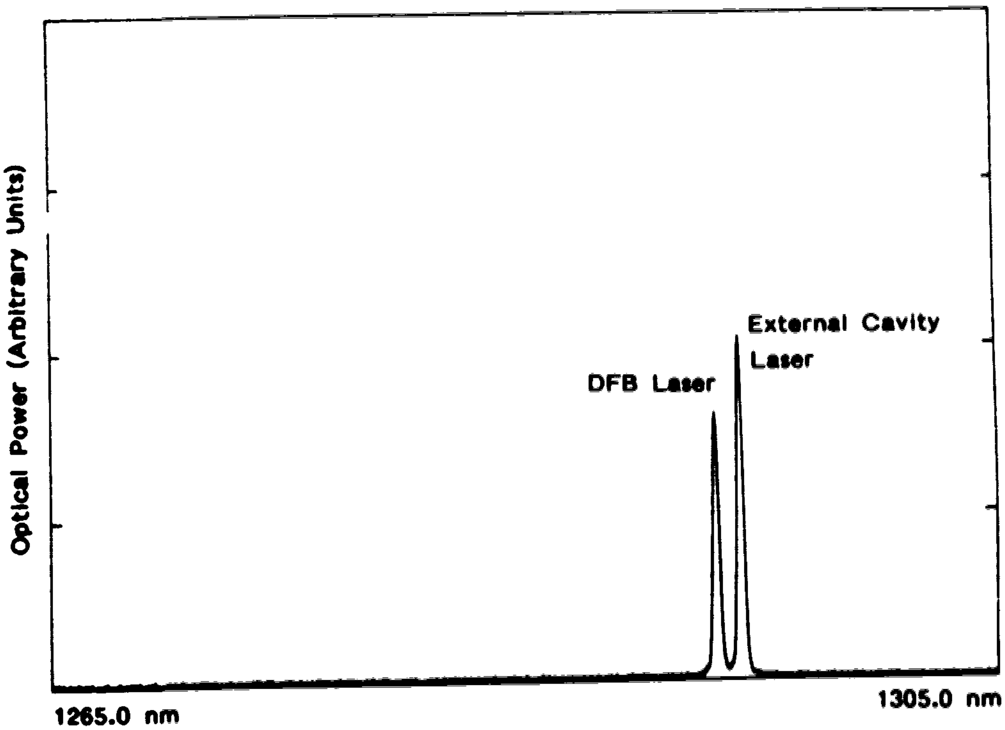

Figure 3.2 Optical Power Spectra of Laser Sources

In the following section the laser driver circuit, which was designed and constructed in order to allow intensity modulation of the two lasers, will be introduced. This will be followed by a description of the high speed receiver modules, and finally by an explanation of laser amplifier interchannel crosstalk which can be measured by the two lasers present in the system.

3.1.1.1 Laser Driver Circuit

The schematic of the circuit that has been used to generate a drive current capable of intensity modulating the two lasers is shown in Figure 3.3. The laser drive current is obtained as a summation of a DC operating point, adjustable using the potentiometer R_1, and an AC component, which is responsible for the amplitude modulation present in the laser output optical signal. The AC component of the drive current is supplied through transistor Q_3.

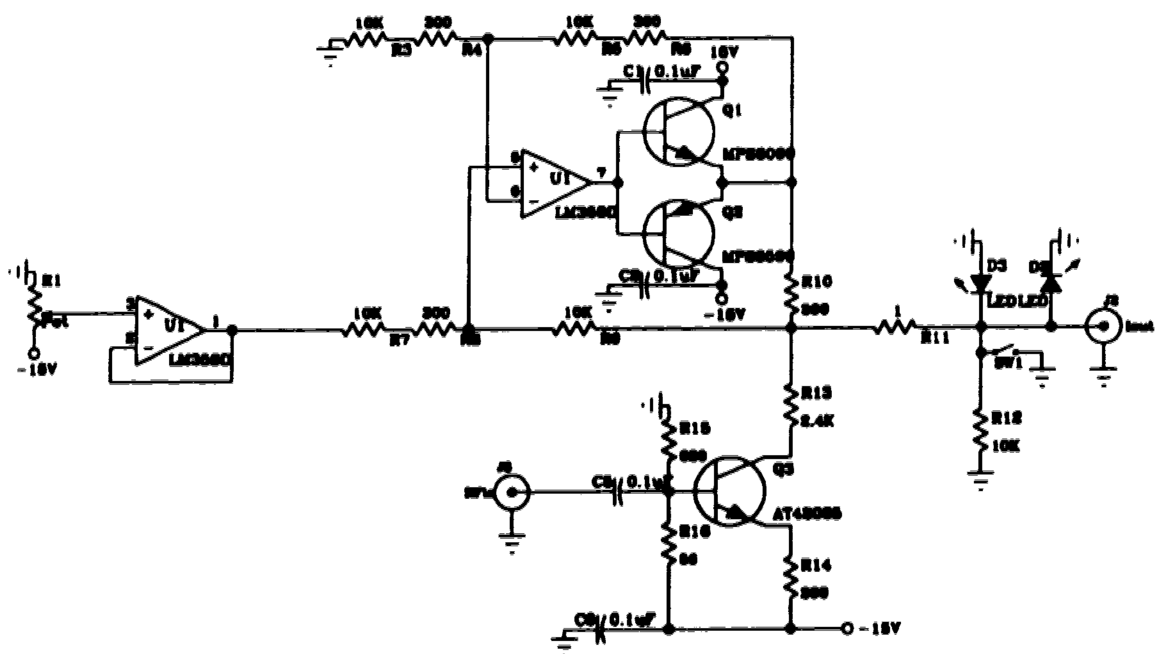

Figure 3.3 Schematic of Laser Driver Circuit

The DC portion of the laser drive current is produced using the Howland voltage to current converter formed by the operational amplifier, U_1, and the resistors R_3 through R_{10}. This voltage controlled current source has a transfer function given by [35],

$$I_{DC} = \frac{(R_3+R_4)}{(R_5+R_6)} \frac{V_{in}}{R_{10}} = \frac{V_{in}}{300\,\Omega} \qquad (3.1)$$

where I_{DC} is the DC output current which is used to bias the laser and V_{in} is the voltage follower output voltage, or equivalently the potentiometer tap voltage. The transistors Q_1 and Q_2 are general purpose devices connected in a push-pull configuration in order to increase the drive capability of the current source. This is necessary because the lasers require bias currents of 30 to 45 mA, whereas the operational amplifier can only supply a short circuit current of approximately 40 mA.

The AC portion of the drive current is supplied by the 50 Ω input impedance common emitter amplifier formed by transistor Q_3 and resistors R_{13} through R_{16}. The voltage at the emitter of Q_3 follows the input voltage, producing the AC component of the drive current which is given by,

$$I_{AC} = \frac{V_{RF}}{R_{14}} = \frac{V_{RF}}{200\,\Omega} \tag{3.2}$$

where V_{RF} is the modulation input voltage. The AC section of the drive circuit is designed to ensure that transistor Q_3 saturates when the input voltage reaches 1 volt peak, generating a maximum AC current of 5 mA.

The final section of the laser driver circuit consists of the protection circuitry present at the output. The 1 Ω resistor, R_{11}, acts as a laser drive current monitor, allowing the laser DC bias current to be measured easily using a DC voltmeter. Resistor R_{12} is present to provide a static discharge path, while the SPST switch is used to allow the laser diode terminals to be shorted together, providing a current bypass around the laser. The two protection LEDs are included in the circuit in order to ensure that the laser cannot be reverse biased by more than the cut-in voltage of an LED, regardless of the drive current direction or the laser connectivity. This voltage is insufficient to cause destructive reverse breakdown of the laser and hence the LEDs protect the laser from destruction caused by a reversed connection. If the LEDs were not present and the laser was connected in the reverse direction, the laser diode reverse voltage would approach the rail, possibly resulting in destructive reverse breakdown of the laser diode.

The measured performance of the laser driver circuit is indicated in the frequency response plot shown in Figure 3.4. The top curve in this diagram corresponds to the laser biased just above threshold, while the bottom curve is measured at 15 mA above threshold. The two curves are almost identical and indicate a modulation bandwidth of approximately 43 MHz, sufficient for DS3 rate transmission. The bandwidth may be increased to approximately 100 MHz by removing the protection circuitry, as a result reducing the capacitive loading present on the output node. The maximum modulation frequency then becomes limited by the capacitance associated with the wiring that is used to connect the driver circuit to the laser diode.

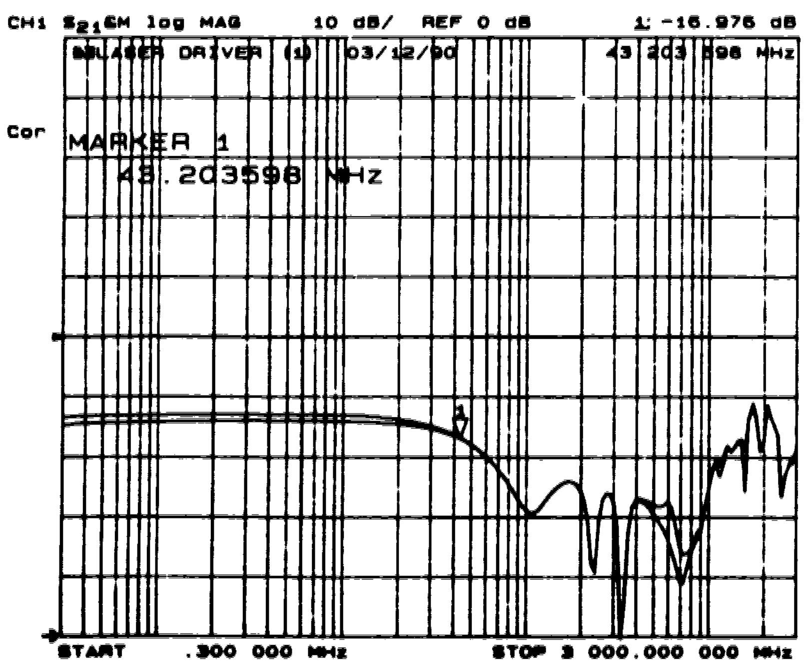

Figure 3.4 Performance of Laser Driver Circuit

This section has introduced the laser driver circuit that was used to intensity modulate the test system laser sources. The following section will present the characteristics of the high speed receiver module which has been used to detect the intensity modulated signals generated by the laser diodes.

3.1.1.2 High Speed Receiver Circuit

The schematic of the high speed receiver circuit is shown in Figure 3.5. Two copies of this circuit were constructed in order to detect the intensity modulated signals present at both the laser amplifier input and output.

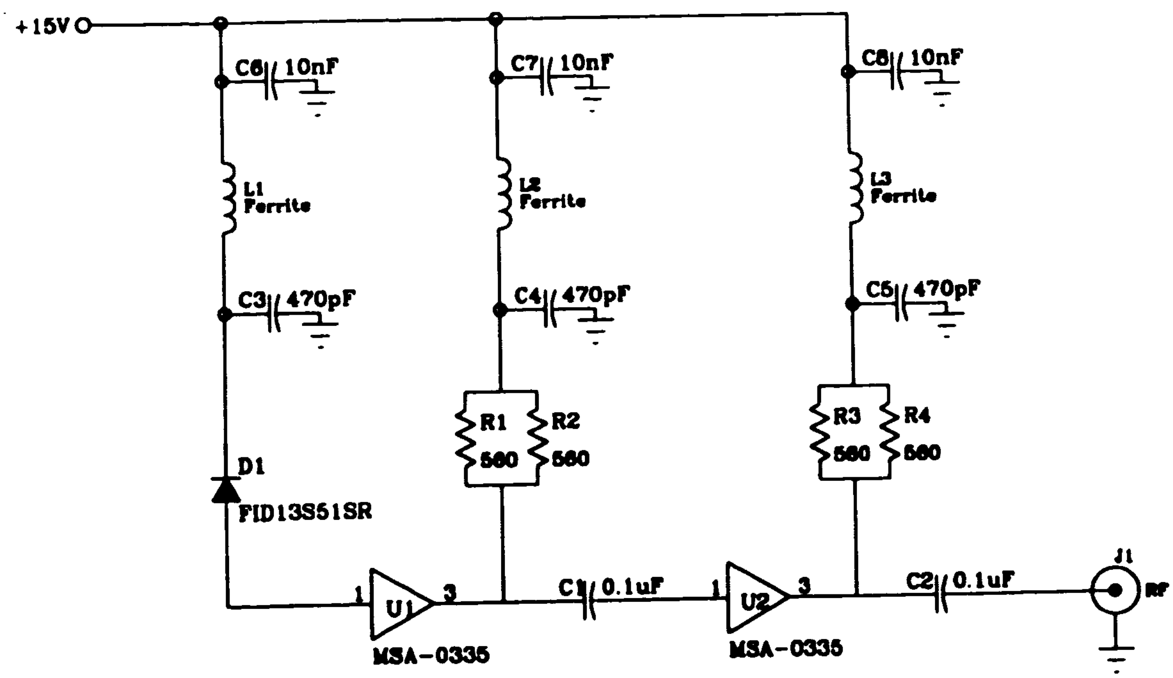

Figure 3.5 High Speed Receiver Schematic

Each of the two circuits was constructed using a Fujitsu FID13S51SR InGaAsP PIN photodiode, mounted on a ceramic substrate. This photodetector has a bandwidth of approximately 1.5 GHz. The photodetector output drives a direct coupled Avantek MSA-0335 wideband amplifier, which has a a midband gain of 12.5 dB, a 3 dB bandwidth of 2.7 GHz, and a 6.0 dB noise figure. The output from this amplifier is passed through a second Avantek gain block, producing an overall gain of 25 dB and a 3 DB bandwidth of approximately 1.7 GHz [36]. Resistors R_1 through R_4 are used to bias the Avantek gain blocks, while the ferrite beads and capacitors C_3 through C_8 are used for power supply decoupling. Given the bandwidth of the photodetector and the amplifiers, the overall receiver bandwidth should be approximately 950 MHz.

The optical receiver modules were constructed using Rogers 5870 duroid circuit boards. The optical detection frequency response which was achieved using one of the two identical receivers is shown in Figure 3.6. This plot indicates that the receiver module has a bandwidth close to the predicted value of 950 MHz. The slight difference is likely caused by stray capacitance introduced in the construction phase. However, these receivers have sufficient bandwidth to measure the signal components properly, as well as any interchannel crosstalk products, present at the laser amplifier input and output.

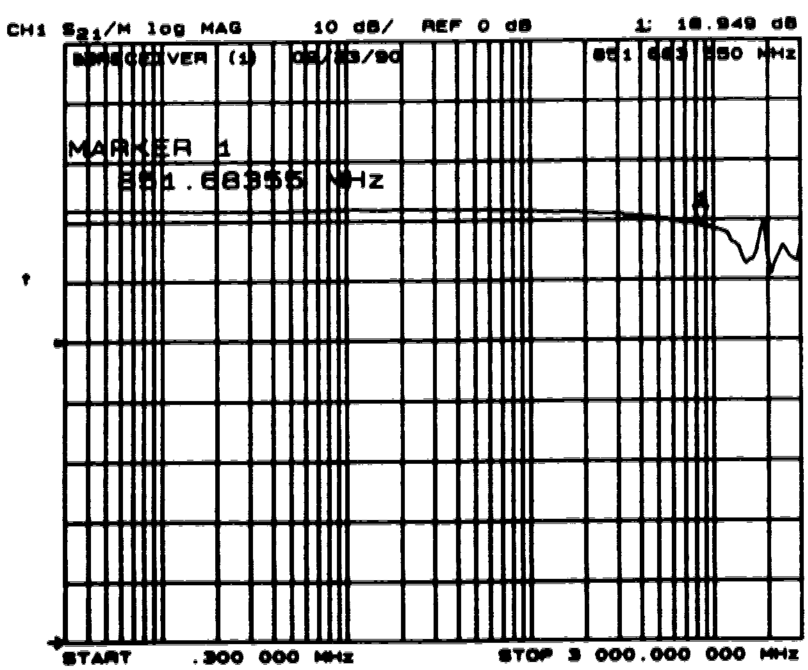

Figure 3.6 High Speed Receiver Frequency Response

This section has introduced the high speed receiver modules constructed in order to characterize the laser amplifier. The following section will explain the concept of laser amplifier interchannel crosstalk, and the reason for installation of two optical sources in the test system.

3.1.1.3 Laser Amplifier Crosstalk

In Chapter 2 the gain characteristics of laser amplifiers were introduced with the assumption that a given drive current injected into the device produces a corresponding carrier density within the active region. The gain of the amplifier can then be determined from this carrier density.

In reality, the carrier density within the active region of a laser amplifier varies as a function of the input optical signal power, according to the rate equation [37],

$$\frac{dn}{dt} = \frac{I_{AC}}{qV} - R(n) - \frac{|E_{out}|^2 - |E_{in}|^2}{E_\lambda V} \tag{3.3}$$

where I_{AC} is the magnitude of the AC portion of the laser amplifier drive current, q is the electronic charge, and V is the volume of the laser amplifier active region. The term E_λ is the energy of a photon of light at the chosen wavelength, λ. The laser amplifier input and output optical signal electric field components are represented by E_{in} and E_{out}, respectively. The total spontaneous carrier recombination is represented by R(n), and may be expressed as [38],

$$R(n) = An + Bn^2 + Cn^3 \tag{3.4}$$

where A, B, and C are recombination coefficients corresponding to nonradiative recombination centers, leakage through heterobarriers, and Auger recombination processes, respectively [29].

Considering the above expression representing the change in carrier density, it is observed that the carrier density varies with the amplitude of the optical signal in the cavity. That is, the carrier density, and therefore the amplifier gain, is modulated if there is an intensity modulated input signal. As a result, if two channels, the first of which is intensity modulated, are simultaneously amplified by a laser amplifier, the second channel will see a time varying gain and interchannel crosstalk induced from the first channel. This type of crosstalk is called saturation induced crosstalk due to the mechanism involved, along with the fact that this type of crosstalk becomes more pronounced as the amplifier approaches gain saturation. There has been an attempt to reduce this type of crosstalk by using a laser amplifier linearization scheme which consists of a fiber delay loop and a laser amplifier driver which has an AC current component [39]. The amplitude of the AC component is determined to ensure that the carrier density within the active region, and thus the gain, remains constant. This type of circuit has achieved reasonable success and shows promise for allowing laser amplifiers to be used in multichannel applications.

The other type of interchannel crosstalk that must be considered is intermodulation distortion. This type of crosstalk may be produced when two or more closely spaced channels are simultaneously amplified by a laser amplifier. In this case, the carrier density within the active region, and therefore the amplifier gain, varies at the beat frequency formed by two of the input channels. As a result, the channels which are being amplified by the laser amplifier see a time varying gain, and intermodulation products are created. The amplitude of the intermodulation components varies as a function of the frequency spacing between the input channels; the crosstalk becomes negligible as the channel spacing approaches the inverse of the spontaneous carrier lifetime [40, 41]. Once again, AT&T has met with reasonable success at reducing these crosstalk products through the use of their laser amplifier linearization circuit [37].

The generation of crosstalk products demonstrates the reason behind the installation of two optical sources. If two channels are simultaneously amplified by a laser amplifier, where one channel is intensity modulated, saturation induced crosstalk products will be introduced by the laser amplifier. As two lasers have been installed, these products may be measured, and attempts made at reducing the crosstalk. A similar argument holds for intermodulation distortion, as the external cavity laser may be tuned to operate at a wavelength very close to that at which the DFB laser operates. As a result, intermodulation products may be generated, and testing of possible crosstalk reduction techniques may proceed.

This section has introduced the optical source portion of the laser amplifier gain control circuit test system, and has shown why two optical sources have been installed. In the following section the other main test subsystem will be introduced, namely the laser amplifier test bed. This subsystem may be used to characterize the environmental sensitivity exhibited by the laser amplifier under test, and the operation of the gain control circuit designed to combat the gain variations may be investigated.

3.1.2 Laser Amplifier Subsystem

The layout of the laser amplifier test bed is shown in Figure 3.7. This section is supplied with an intensity modulated optical input signal from the optical source subsection. The signal is passed through a calibrated manual polarization controller in order to allow rotation of the input signal polarization and hence characterization of the laser amplifier polarization sensitivity. The polarization adjusted signal passes through a 3 dB single mode fiber coupler, and one of the outputs is used by the gain control circuit in order to determine the input optical signal level. The other output is coupled into the laser amplifier through an AR coated fiber taper. At the output of the laser amplifier, the amplified signal is coupled back onto a single mode fiber, again using an AR coated fiber taper. Coupling in to and out of the laser amplifier is achieved using a dual alignment system composed of 3-dimensional manual Optikon micropositioners for coarse alignment, and 3-dimensional piezoelectric micropositioners from Physik Instrumente for fine alignment. The piezoelectric micropositioners are mounted on top of the manual micropositioners.

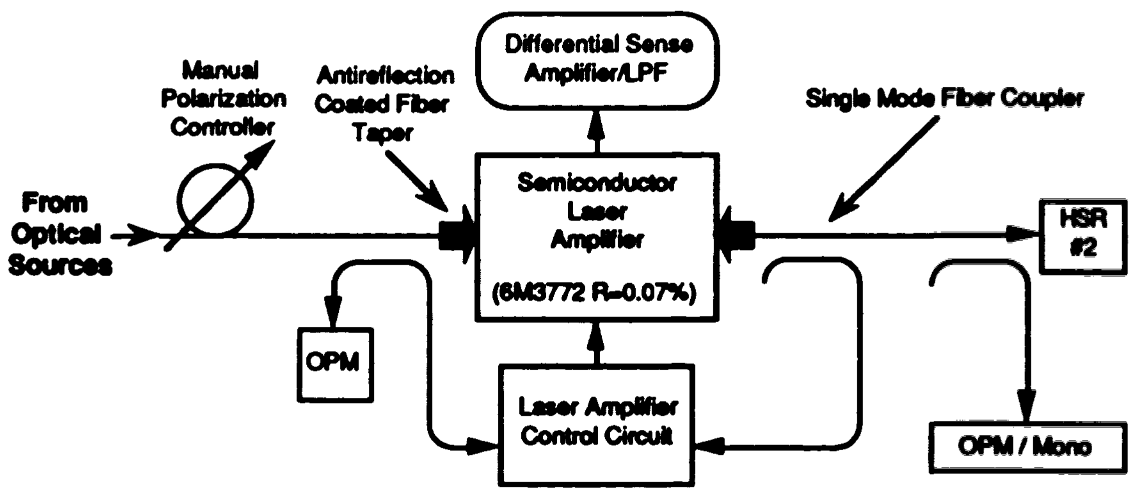

Figure 3.7 Laser Amplifier Subsystem Layout

The laser amplifier output signal is passed through a 5% coupler to extract a small portion of the output signal and allow the gain control circuit to determine the output optical signal level. The remaining 95% of the signal is passed through a 3 dB coupler. One output is focused onto a high speed receiver which may be used to detect the signals present at the laser amplifier output, allowing measurement of interchannel crosstalk components generated by the laser amplifier. The second output is selectively passed to a scanning monochromator channel used to measure the output optical power spectrum, or to an optical power meter in order to determine the absolute output optical power level.

The two optical power meters installed in the system are used to optimize the alignment of the AR coated single mode fiber tapers to the optical amplifier. When no input optical signal is present, the power meters measure the spontaneous emission which has been coupled from the laser amplifier onto the input and output single mode fibers. As a result, by maximizing the fiber coupled spontaneous emission optical power, optimum alignment to the active region of the laser amplifier may be achieved for each fiber independently. When an input signal is applied, alignment by this procedure ensures that the signal travels along the active region of the amplifier and obtains the maximum possible optical gain, and does not simply travel across the active region.

This section has presented the laser amplifier test subsystem. In the following section the measured results which have been obtained using this system for the uncontrolled laser amplifier will be presented, characterizing the environmental sensitivity of the laser amplifier used in this experiment.

3.2 Laser Amplifier Characterization

As indicated in Chapter 2, the laser amplifier used in this experiment is an AR coated Hitachi HLP5400 semiconductor laser, with an active region which is 250 μm long, 2.05 μm wide, and 0.2 μm thick. Prior to AR coating, the semiconductor laser exhibited a threshold current of 28.6 mA, and a lasing wavelength of 1315 nm. After antireflection coating, the laser amplifier was found to have residual facet reflectivities of 0.08%, and no measurable lasing threshold. The measured spontaneous emission optical power spectrum for the laser amplifier is shown in Figure 3.8, where the three curves correspond to drive currents of 28.6 mA (I_{th}), 57.2 mA ($2I_{th}$), and 71.5 mA ($2.5I_{th}$). These plots represent optical power on a linear scale. It should be noted that at a drive current of 71.5 mA the peak gain wavelength is 1280 nm, demonstrating a gain profile shift of 35 nm as a result of AR coating.

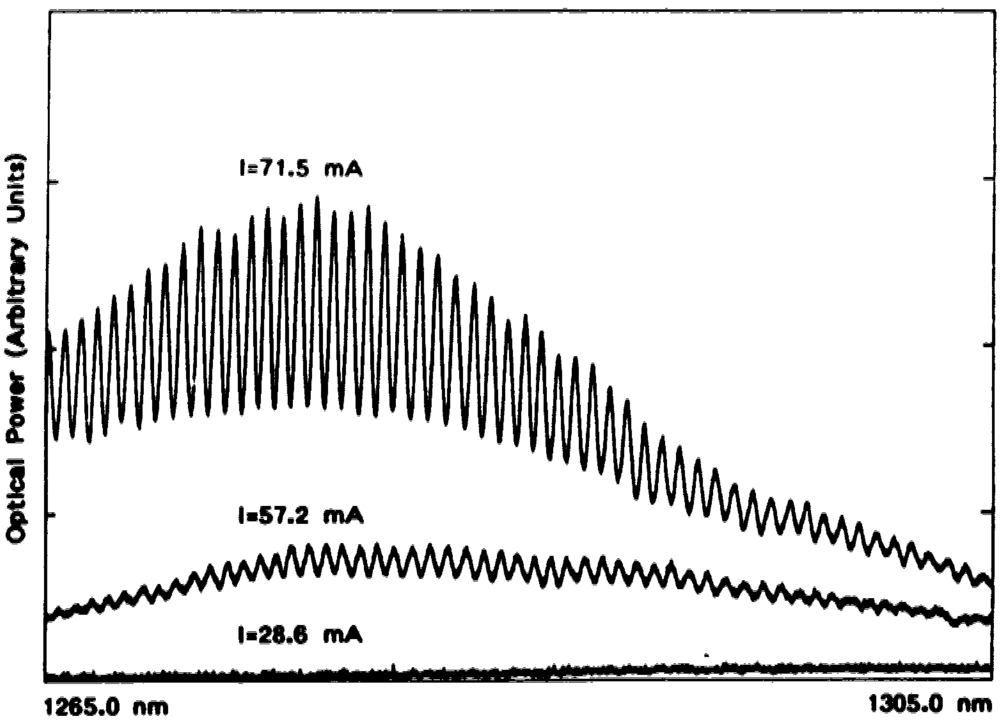

Figure 3.8 Laser Amplifier Spontaneous Emission Optical Power Spectrum

For the laser amplifier used in this experiment, the peak internal gain at a wavelength of 1280 nm and a drive current is 71.5 mA is 23 dB (TE mode), as measured by the Heinrich Hertz Institute following the application of the AR coatings to the laser amplifier [23]. The saturation output power, the optical output power at which the gain is degraded by 3 dB, was measured to be approximately +3 dBm. The DFB laser used to test the gain control circuit emits light at an operating wavelength of 1293.5 nm. As a result, a gain degradation occurs because this wavelength is almost 15 nm longer than the peak gain wavelength. From Figure 3.8 it is observed that the internal gain at this wavelength is approximately 18.8 dB. The measured fiber to fiber gain obtained from the test setup described above is 12.5 dB, indicating a total coupling loss of 6.3 dB. The coupling losses at the input and output facets have been measured to be 3.2 dB and 3.1 dB, respectively. These values compare favorably to the best previously published losses of 3 dB per facet, or a total coupling loss of 6 dB [5].

The following sections introduce measured results that demonstrate the sensitivity which the laser amplifier gain exhibits with respect to changes in amplifier bias point, input signal polarization, amplifier temperature, and input signal wavelength. The tests have been performed using the DFB laser as an intensity modulated optical source. The selected modulation signal was a 10 MHz sine wave generated using an HP8753A Network Analyzer. The fiber to fiber gain was measured by determining the ratio of the laser amplifier input and output signals as detected by the high speed receivers; the ratio was calculated using the network analyzer in an synchronous signal divider mode.

3.2.1 Bias Point Sensitivity

The sensitivity that the laser amplifier gain exhibits towards the operating point provides an indication of how accurately the bias current must be controlled in an installed device. Equivalently, this sensitivity demonstrates how much the bias current can be allowed to vary, while still maintaining the desired gain within set bounds.

The variation of amplifier gain as a function of bias current for the laser amplifier used in this experiment is shown in Figure 3.9. This graph indicates that the unsaturated internal gain of the laser amplifier increases almost exponentially with bias current, as expected from the exponential relationship between single pass gain and carrier density indicated in Chapter 2. The figure also shows that at higher currents the exponential relationship begins to fail as the higher order terms in tho spontaneous recombination model begin to dominate. As a result, the carrier density within the active region is no longer directly proportional to the applied bias current, and the exponential relationship breaks down.

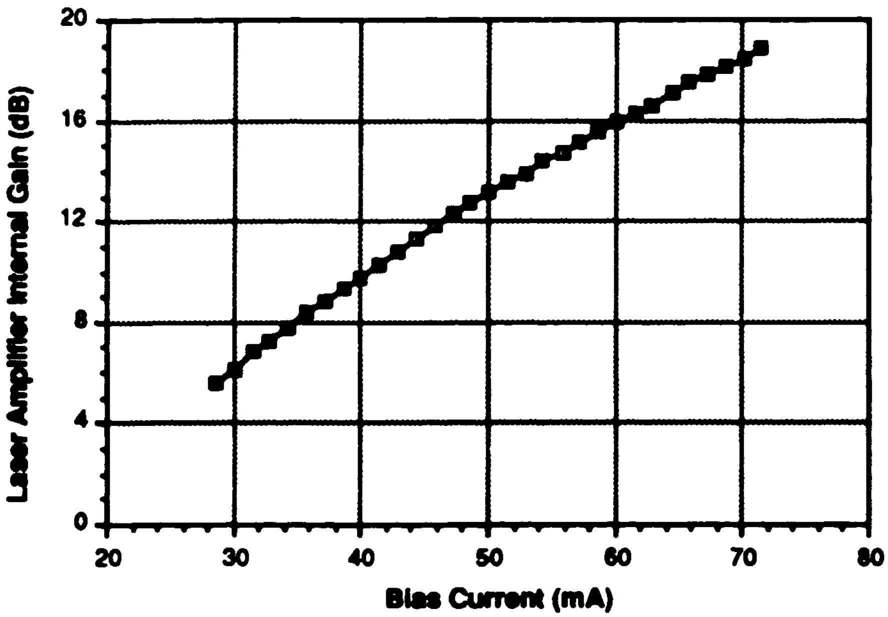

Figure 3.9 Bias Sensitivity of Laser Amplifier

The most important point to be noted about Figure 3.9 is the sensitivity that laser amplifier gain exhibits with respect to the operating bias point. If the gain of the amplifier is to be held constant, fluctuating about the desired setpoint by less than 0.2 dB, the laser amplifier bias current must not change by more that approximately 0.7 mA. A 0.2 dB bound on gain variations represents a reasonable value considering the small error margins allowed in fiber optic systems, and as a consequence imposes a very tight bound on the allowable swing in laser amplifier bias current. However, more importantly, this bound on the absolute value of bias current may be achieved in practice. But, as the amplifier ages, the gain will vary if the bias current is held constant. The resulting gain variations may easily exceed the allowed range for laser amplifier gain. As a result, open loop control of laser amplifier gain becomes very difficult in an installed system, due to variations in internal laser amplifier parameters. Hence, there is a need for a closed loop feedback control system capable of stabilizing laser amplifier gain. Such a result is achieved by the control system implemented in this project.

3.2.2 Polarization Sensitivity

As a consequence of microbends present in the installed fiber link, as well as perturbations and movements of the cable containing the installed optical fiber, the polarization of the light incident on the laser amplifier is constantly changing, albeit at a relatively low speed. As indicated in Chapter 2, the gain of a laser amplifier is sensitive to input signal polarization. For the device used in this experiment, this sensitivity is shown in Figure 3.10.

This plot demonstrates the wide variation in gain which occurs as the input signal polarization is rotated from a gain maximum at 0 degrees, corresponding to a TE polarized input, to a gain minimum at 90 degrees, representing a TM polarized input signal. As stated earlier, the polarization in an installed system will vary in a random fashion, as a result creating random gain fluctuations of up to 5 dB, if the laser amplifier of this experiment is used. To date, several attempts have been made at reducing the polarization sensitivity of laser amplifiers, because control of the input signal polarization is impractical in installed systems. Some of the methods which have been tried include a double pass device employing a Faraday rotator and silvered mirror [42], a balanced structure utilizing a polarizing beam splitter and two optical amplifiers [43], and a thick active region device [44]. Although these attempts have improved polarization sensitivity, they have, in general, introduced other undesirable effects, resulting simply in a transfer from one problem to another.

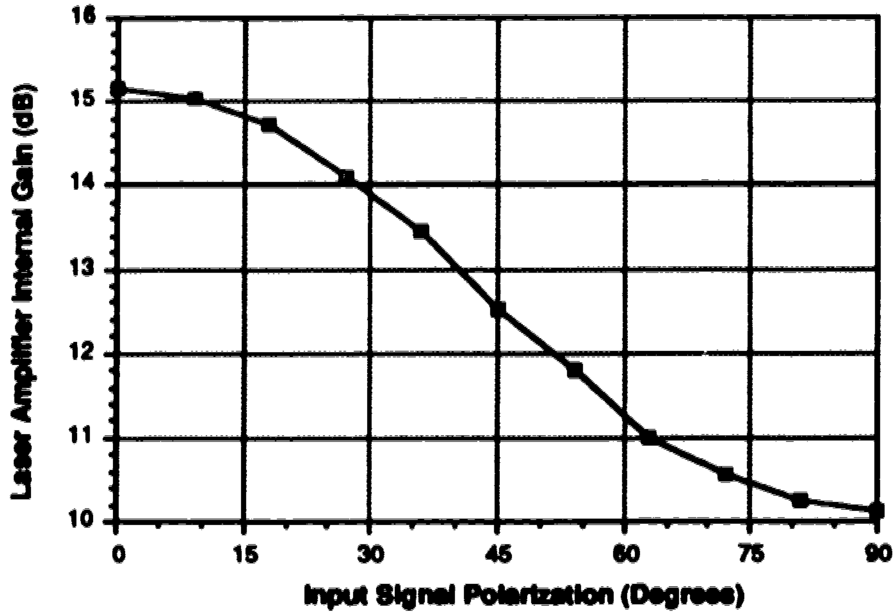

Figure 3.10 Polarization Sensitivity of Laser Amplifier

The above results again indicate the need for a control mechanism, such as the feedback circuit implemented in this project, which modifies the drive current of the laser amplifier in order to maintain polarization insensitivity. The following section will discuss another parameter upon which amplifier gain is dependent, namely the temperature of the device.

3.2.3 Temperature Sensitivity

As examined in Chapter 2, the gain of a laser amplifier exhibits a sensitivity with respect to temperature as a result of the variation of material gain coefficient with device temperature. The variation of gain as a function of temperature for the laser amplifier used in this experiment is indicated in Figure 3.11.

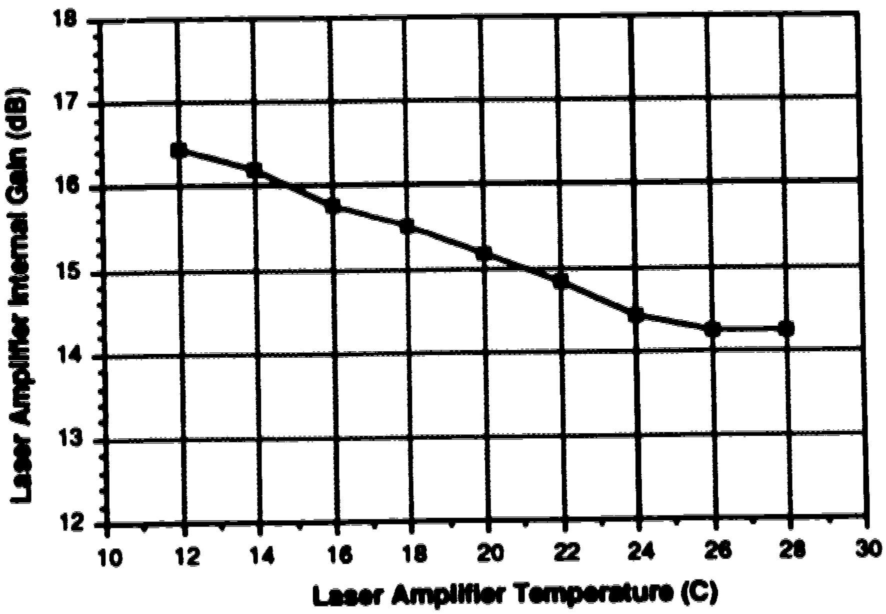

Figure 3.11 Temperature Sensitivity of Laser Amplifier

This graph indicates that the gain of the laser amplifier varies by over 2 dB as the temperature of the device is allowed to vary by 8 °C about a mean value of 20 °C. This temperature change is relatively small compared to the variations in ambient temperature which may be observed in an installed system, indicating a requirement for tight temperature control if the laser amplifier temperature is to be confined to this range. Considering again a 0.2 dB limit on the allowable gain variation in an installed system, the laser amplifier temperature must be controlled more stringently, in particular the temperature may not vary by more than 1 °C about the desired operating point.

The installation of an automatic gain control circuit capable of stabilizing the gain of the amplifier to within 0.2 dB allows the laser amplifier temperature to vary over a wider range. In this way, the specifications of the temperature control circuit may be relaxed, demanding a temperature control circuit which must only ensure that the laser amplifier temperature is maintained within safe operating bounds. This discussion indicates a further motivation behind the implementation of a laser amplifier gain control circuit, namely relaxation of the bounds on laser amplifier operating temperature. The next section will introduce the final gain varying parameter which will be considered here, the wavelength of the input signal.

3.2.4 Wavelength Sensitivity

The wavelength sensitivity exhibited by laser amplifier gain was indicated in Chapter 2. The gain was shown to exhibit a wideband wavelength sensitivity due to decreases in material gain coefficient about the peak gain wavelength. On a finer scale, however, gain variations are created due to the presence of Fabry-Perot resonances induced in the gain spectrum as a result of nonzero residual facet reflectivities. This is the type of fluctuation indicated in Figure 3.12 for the laser amplifier used in this experiment. In this case, the input signal wavelength was varied by changing the temperature of the DFB laser source, allowing slight wavelength tunability.

This plot indicates that the gain of the laser amplifier varies by slightly over 2 dB as the input wavelength traverses one laser amplifier Fabry-Perot resonance. The wavelength difference between gain minima corresponds to one free spectral range of the laser amplifier cavity. The actual magnitude of the gain variation is dependent on the internal laser amplifier single pass gain and residual facet reflectivity at the chosen wavelength. The ratio of gain minima to gain maxima corresponds to the non-resonant gain ratio introduced in Chapter 2. As a consequence, strict control must be placed on the input signal wavelength. Considering again a 0.2 dB allowable gain variation, the input signal wavelength must be controlled to within 0.1 nm, corresponding to an allowed laser source temperature variation of 1 °C. These limits indicate the impractically tight bounds which must be met, reiterating the desire for a control circuit which simply modifies the laser amplifier bias point in order to compensate for the gain degradation.

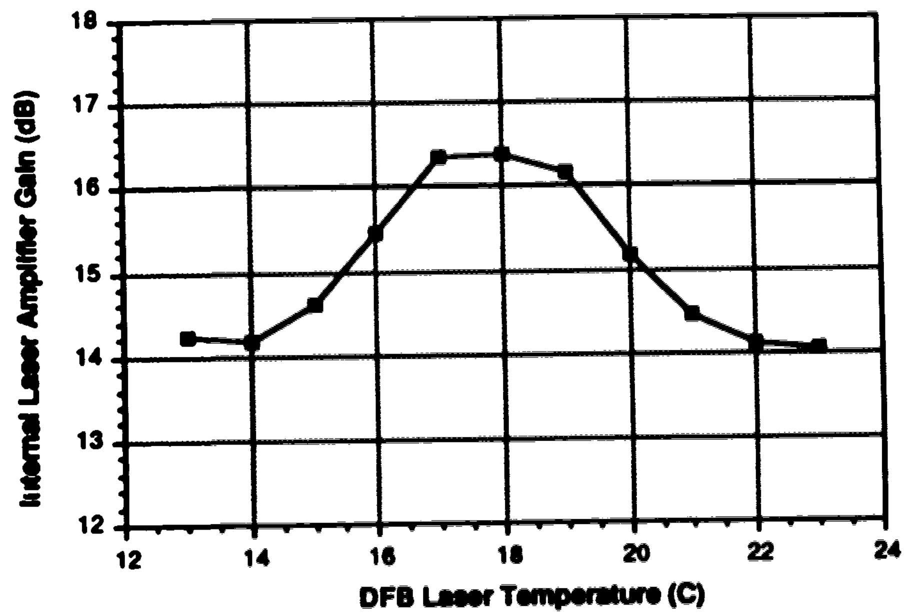

Figure 3.12 Wavelength Sensitivity of Laser Amplifier

3.3 Motivation for a Gain Control Circuit

The above discussion indicates the array of parameters towards which a practical laser amplifier exhibits a gain sensitivity, making these devices presently unusable in installed communication systems. The aim of this project is to construct an automatic control circuit capable of sensing gain or output power changes induced in a laser amplifier, independent of the mechanism responsible for the change, and modifying the amplifier bias current in order to compensate for the variation. In this way, the control circuit can stabilize amplifier gain, in spite of the complicated manner in which the gain varies.

The following chapter will introduce the feedback control circuit configuration chosen to achieve this goal, and will discuss the building blocks used to implement the laser amplifier stabilization circuit. The system is capable of controlling laser amplifier gain or output power to within 0.1 dB, independent of the mechanism responsible for the original perturbation. The gain control circuit is not inherently capable of reducing the other main undesirable property of laser amplifiers, namely the interchannel crosstalk induced by carrier density variations. However, as indicated earlier, this problem has been considered by AT&T, who have designed and built a laser amplifier linearization circuit. Chapter 6 will indicate how the problem of interchannel crosstalk may be reduced using the gain control circuit introduced here, applying both the method of AT&T, along with a new approach proposed as a result of this project.

4. AUTOMATIC GAIN CONTROL CIRCUIT

This chapter presents the automatic gain control circuit that has been constructed to stabilize the gain or output power of a semiconductor laser amplifier. The control circuit is capable of reducing the effect of the environmental sensitivities introduced in Chapter 3 to 0.1 dB, independent of the mechanism responsible for the original gain variation.

The first section of this chapter presents the design specifications of the overall gain control system, and introduces the control system configuration which was selected to achieve these objectives. In addition, the modifications that are required in order to transform the gain control circuit into an output power control circuit are illustrated. The individual control system components are introduced in the second section of this chapter, where the circuit implementation selected along with the performance achieved from each of the individual control system building blocks is indicated. The performance of the control circuit is investigated in Chapter 5, and an indication of the degree to which laser amplifier stabilization has been achieved is presented.

4.1 Automatic Gain Control System

The overall laser amplifier control circuit layout, along with the circuit blocks that have been implemented as subcomponents of the control system, are presented in this section. The function of each of these system building blocks is explained in terms of the overall objectives of the control circuit. In addition, the modifications that are required in order to transform the control system into an automatic output power control circuit are considered, since the control system is capable of being configured in either a constant gain or a constant output power control mode.

4.1.1 AGC System Layout

The main objective of the control circuit is to stabilize the gain or output power of a semiconductor laser amplifier, independent of the mechanism responsible for the original variation. It is desired that the gain control circuit achieve this goal without introducing a bit rate sensitivity. This allows the control system to be used in fiber optic links operating at arbitrary bit rates, and does not degrade the general applicability of the system. The control system is also required to have a wide dynamic range. This ensures that the laser amplifier may be placed anywhere in the fiber span, while at the same time not reducing the effectiveness of the gain control circuit. In this experiment, a 20 dB optical signal range was selected, from -20 dBm to -40 dBm. Finally, the control circuit must be capable of compensating for gain changes which occur due to relatively high speed changes in environmental conditions. Equivalently, the closed loop bandwidth of the control system must be sufficient to ensure that all anticipated high speed environmentally induced gain variations are effectively removed.

The configuration of the automatic gain control system which was selected to meet the above list of objectives is shown in Figure 4.1. The optical portion of the control system consists of two single mode fiber couplers, one at the laser amplifier input and one at the output, which are used for signal extraction. The system also contains an electronic section comprising gain and output power detection circuitry as well as laser amplifier drive circuitry. This section is used to modify the laser amplifier drive current and obtain a constant value of gain or output power.

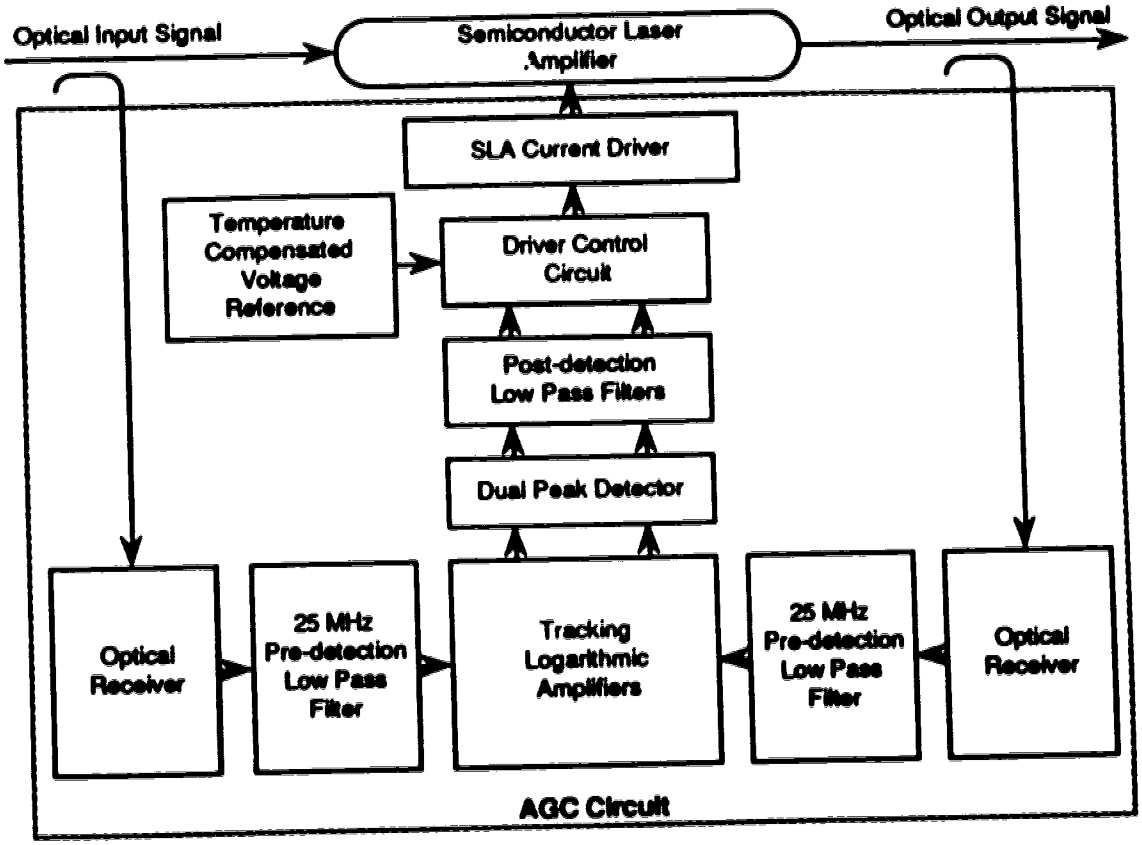

Figure 4.1 Automatic Gain Control System Configuration

The optical portion of the control system consists entirely of the single mode fiber couplers present at the laser amplifier input and output. The input optical coupler was a 3 dB coupler selected due to availability, while the output coupler was chosen to have a 5% signal tap. The output coupling ratio is smaller than the input coupling ratio in order to ensure that the two tapped signals are close to the same magnitude. Although the coupling ratios may be optimized for a given system application, the requirement of similar tapped signal powers results in an extended control circuit operating range, given identical input and output detection circuitry. Considering the coupling ratios used in this experiment, in order to obtain equal signal levels at the input and output taps, the fiber to fiber gain must be approximately 13 dB. This is very close to the measured gain of the test system.

The electronic portion of the control circuit contains two optical receivers which are used to detect the intensity modulated laser amplifier input and output signals. The signals at the optical receiver outputs are simply electrical equivalents of the optical signals, and are of sufficient amplitude to allow processing by the control circuit. The receiver outputs are passed through 25 MHz pre-detection low pass filters in order to bandlimit the electrical signals, as well as to minimize the electrical noise power injected into the control circuitry. Filtering to a bandwidth of 25 MHz precludes signal detection in systems operating at bit rates much higher than 25 Mbits/s. However, the purpose of the control circuit is not to detect the actual transmitted signals, but instead to determine the input and output signal amplitudes in order to calculate the gain or output power of the laser amplifier.

Correct operation of the control circuit is ensured only if some signal content resides in the frequency band below 25 MHz. It is assumed that the signal content within this frequency range accurately reflects the amplitude of the input or output stream. Under this assumption the control circuit exhibits bit rate insensitivity. If no signal content exists within the 25 MHz passband, the control circuit will still operate as desired if a pilot tone is transmitted within this low frequency band. As a consequence, a spectral line is added within a frequency band in which no signal content previously existed.

The outputs from the pre-detection low pass filters are passed through logarithmic amplifiers in order to expand the operating range of the gain control circuit. This is achieved by logarithmically compressing the dynamic range of the signals applied to the amplitude detection circuitry.

Following the logarithmic amplifiers, peak detector circuits are used to extract the peak amplitude of the input and output signals. The attack time constant is chosen to ensure that given an input signal at a frequency as high as 25 MHz, the output will charge to the peak value of the input. The decay rate is adjusted to allow detection of amplitude variations occurring at the input or output of the laser amplifier at speeds up to 40 kHz.

The peak detector outputs are passed through 40 kHz low pass post-detection filters in order to remove any high frequency components present, as well as to reduce the noise power injected into the gain detection circuitry. The post-detection filter outputs are hence bandlimited electrical signals that are logarithmically proportional to the peak input and output optical signal amplitudes. These electrical signals may vary at up to approximately 26 kHz, tracking input signal power shifts or laser amplifier gain variations.

The optical power gain of the laser amplifier is determined by the driver control circuit. This circuit subtracts the two electrical signals representing the input and output optical signal levels. The subtraction operation is equivalent to amplitude division as a result of the logarithmic proportionality that exists between the laser amplifier input and output optical signal levels and the voltage levels applied to the driver control circuit. The measured gain is compared to a voltage representing the desired operating point. The reference voltage is generated by the adjustable temperature compensated voltage reference. The comparison generates an error signal which is passed through an integrator in order to modify the laser amplifier driver control voltage. This voltage is applied to a voltage to current converter, and the output current is driven through the semiconductor laser amplifier. The laser amplifier drive current completes the feedback loop, as the gain is controlled by the laser amplifier drive current, and fed back through the gain detection circuitry.

This discussion has examined the configuration of the laser amplifier gain control circuit and the principles governing its operation. The system presented above was chosen in order to meed the desired goals of the control system, namely bit rate insensitivity, wide dynamic range, high speed control, and most importantly, laser amplifier gain or output power stabilization independent of the mechanism responsible for the original degradation. The results presented in Chapter 5 will indicate the degree to which these goals have been achieved. In particular, they will demonstrate that the gain or output power of the laser amplifier has been stabilized to within 0.1 dB of the desired operating point.

4.1.2 Output Power Control System Layout

The automatic gain control circuit introduced above may be modified to achieve laser amplifier output power stabilization. This mode of control may be attractive in many applications, in particular in systems requiring a constant optical power at specific points within the system, such as the power focused onto a receiver photodetector. The layout of the gain control system, modified to ensure constant output power, is shown in Figure 4.2.

As indicated in the diagram, the output power control system does not require the input portion of the gain control circuit. In particular, the input optical coupler is not required, resulting in an increased signal throughput. As well, the input amplitude detection circuitry is not needed, reducing the implementation cost as compared to the gain control circuit. This system simply determines the output signal amplitude, compares the measured value to the desired operating point, and integrates the resulting error signal in order to obtain the required laser amplifier drive current.

Testing of the output power control circuit has been performed using the gain control configuration. However, the input to the driver control circuit which represents the optical input signal amplitude was tied to ground, thus simulating the constant output power configuration. The system performance results obtained are similar to those which would be achieved by using the actual constant output power configuration, with the advantage that the input single mode fiber coupler does not have to be removed from the test system. However, slightly different operating characteristics may be observed as a consequence of increasing the noise power in the system.

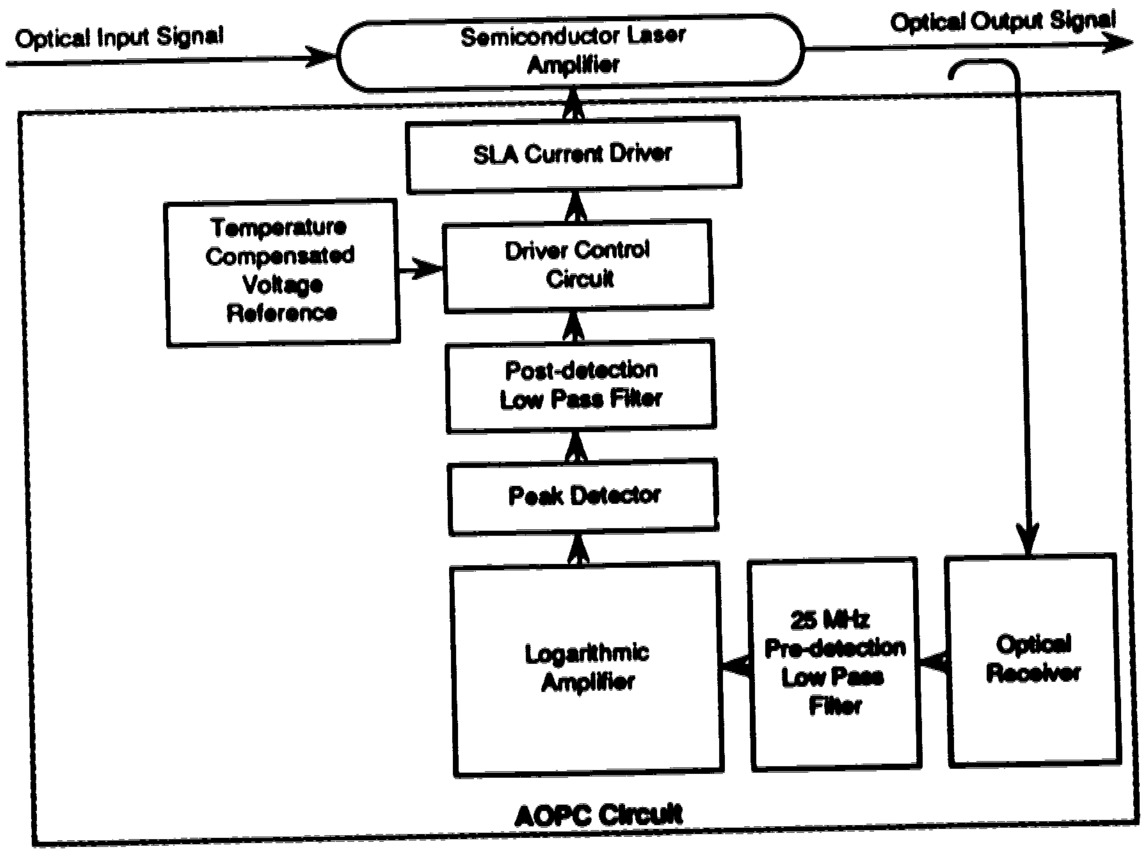

Figure 4.2 Automatic Output Power Control System Configuration

This section has introduced the laser amplifier control system, which may be used in either a gain or an output power control mode. The principles governing its operation have been discussed, and the circuit blocks included in the system have been introduced. The following section presents the design specifications of each of the constituent blocks, and indicates the circuitry chosen to achieve the desired functionality. In addition, the measured performance of each of the control circuit subcomponents is presented.

4.2 AGC System Components

4.2.1 Optical Receiver

The purpose of the optical receiver used in the gain control circuit is to convert the intensity modulated laser amplifier input and output optical signals into their electrical equivalents. The receiver module must have a low noise preamplifier to allow it to detect optical signals over the entire desired operating range extending from 0 dBm down to -40 dBm. In addition, the receiver is required to have an optical bandwidth greater than 25 MHz, in order that the bandwidth of the receiver and pre-detection low pass filter combination remains close to the desired input bandwidth of 25 MHz. The schematic of the optical receiver which was constructed in order to meet these objectives is shown in Figure 4.3. The PIN diode, chosen for availability reasons, is a Fujitsu FID13S51SR wideband InGaAsP photodetector with a 3 dB bandwidth of 1.5 GHz.

A Signetics NE5212 transimpedance amplifier is used as the receiver preamplifier. This device has a transimpedance gain of 7000, a 3 dB bandwidth of approximately 100 MHz, and an rms noise current of 30 nA, measured in a 100 MHz noise bandwidth. Following the transimpedance amplifier is a Signetics NE5205 20 dB gain block with a 3 dB bandwidth of 600 MHz. The specifications of the amplifier block indicate that the optical receiver should meet the desired frequency response criterion, as the 3 dB bandwidth of the optical receiver is well above 25 MHz. As a result, the bandwidth of the optical receiver and pre-detection low pass filter combination will be close to the 25 MHz bandwidth of the filter, as required.

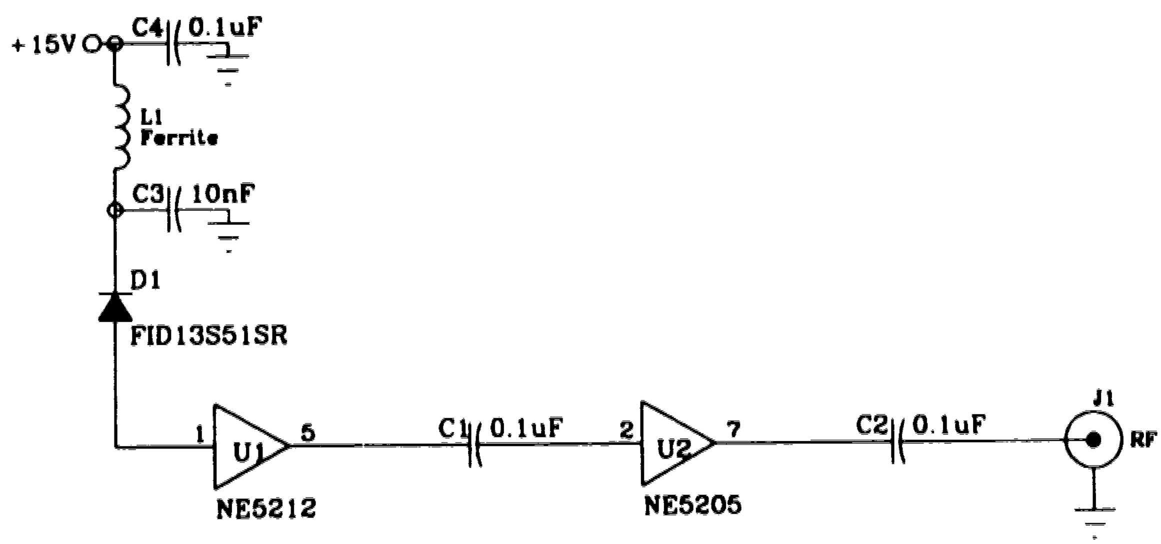

Figure 4.3 Optical Receiver Schematic

The frequency response characteristics of one of the two identical optical receivers are shown in Figure 4.4. This plot indicates that the 3 dB bandwidth of the optical receiver is approximately 120 MHz, sufficient to ensure that the bandwidth of the combined receiver and pre-detection low pass filter will be close to the of 25 Mhz bandwidth of the filter.

The receiver design introduced above comes very close to meeting the specified dynamic range objectives. The lower limit on detectable signal power is determined by the noise power generated by the receiver preamplifier. Assuming that the noise bandwidth of the optical receiver and pre-detection low pass filter pair is 25 MHz, the total rms noise current generated by the transimpedance amplifier is 15 nA. Given a lower bound on signal to noise ratio of 15.6 dB, corresponding to a bit error rate of 10^{-9}, the minimum detectable optical signal power is approximately -40.5 dBm. Therefore, the optical receiver meets the lower bound on the dynamic range, being able to detect a signal at -40 dBm with a signal to noise ratio of greater than 15.6 dB.

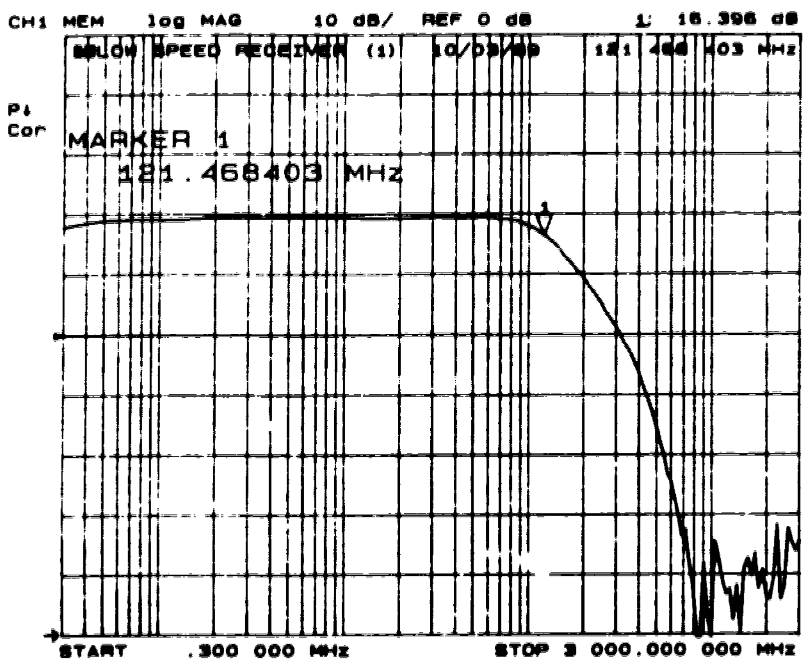

Figure 4.4 Optical Receiver Frequency Response

The upper bound on detectable signal power is determined by saturation of the output device, namely the NE5205 gain block. This device has a saturation output power of +7 dBm, which corresponds to an input signal optical power of -21.2 dBm. As a result, the upper bound on input signal power is close to the desired value of -20 dBm.

This discussion shows that the optical receiver design presented above comes very close to meeting the desired specifications on both input signal dynamic range and frequency response. Specifically, the receiver is capable of detecting intensity modulated optical signals ranging from -21.2 dBm to

-40 dBm, ensuring correct operation of the gain control circuit over a dynamic range of 18.8 dB.

4.2.2 Pre-detection Low Pass Filter

The 25 MHz pre-detection low pass filters are used to bandlimit the input signals, as well as to reduce the noise power incident on the amplitude detection circuitry. Filtering the input and output electrical signals to equal bandwidths allows the gain control circuit to determine the laser amplifier gain or output power regardless of the system bit rate. Although filtering disallows detection of the transmitted signals, gain stabilization is achieved, and the gain control circuit becomes bit rate insensitive. As a consequence, the control system may be used in optical systems operating at arbitrarily high transmission rates.

To achieve the desired frequency response, a 5th order Butterworth low pass filter design was used for the pre-detection filters. A Butterworth filter design was chosen in order to obtain a flat passband, while a 5th order filter was chosen as a tradeoff between sharp rolloff and the difficulty of matching component values in higher order filters. The schematic of the low pass filters is shown in Figure 4.5, where the component values indicated are calculated for a 20 MHz cutoff frequency and a system impedance of 50 Ω. The values were calculated in order to obtain a 20 MHz corner, rather than 25 MHz, as component tolerances were found to be large enough to shift the filter corner from the design value of 20 MHz up to the desired value of 25 MHz.

The pre-detection filters were constructed on fiberglass circuit boards using surface mount components. The 680 nH Coilcraft chip inductors have a self resonant frequency greater than 340 MHz, and a Q factor of 30 at 25 MHz. The frequency response characteristics obtained from one of the two identical filters is shown in Figure 4.6, indicating a 3 dB bandwidth of approximately 25 MHz, as required. The passband contains only a very small ripple, as expected from a Butterworth filter.

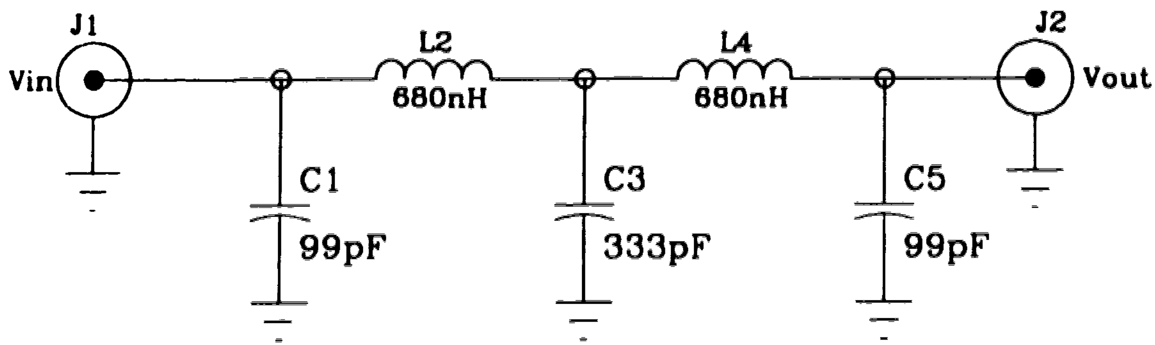

Figure 4.5 Pre-detection Low Pass Filter Schematic

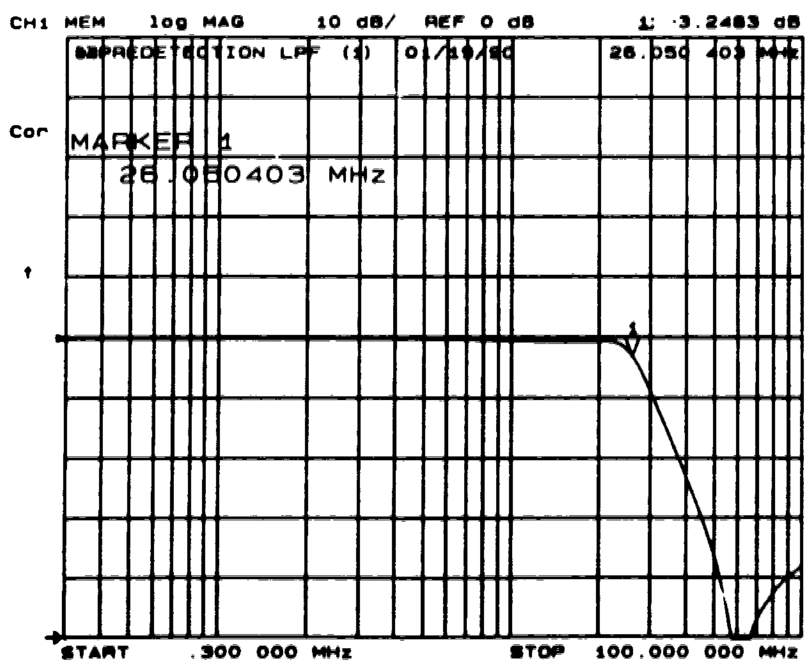

Figure 4.6 Pre-detection Low Pass Filter Frequency Response

As indicated above, the difference between the measured 3 dB bandwidth of the filters, and the design value of 20 MHz may be attributed to tolerances present in the inductor and capacitor component values. An error in the value of the components within the circuit induces a shift in the resonant frequencies of the tuned circuits, pushing the 3 dB bandwidth from the expected value of 20 MHz out to 25 MHz.

4.2.3 Logarithmic Amplifier

Logarithmic amplifiers are used to compress the dynamic range of the detected optical signals. In order that the gain control circuit have a wide dynamic range, the optical receiver considered above was designed to detect optical signals extending over an optical signal range of 20 dB, corresponding to a 40 dB electrical dynamic range. However, to allow signal amplitude detection this range must be compressed, because it is very difficult to construct a peak detector circuit which operates over such a wide signal range. For this reason, logarithmic amplifiers were constructed to compress the 40 dB electrical signal range, as a result generating an output which varies over a range of approximately 10 dB. This represents a dynamic range over which a peak detector circuit functions correctly. The logarithmic amplifiers constructed in this project have a 60 dB dynamic range, as opposed to a 40 dB range, so that they extend past the edges of the dynamic range provided by the optical receiver circuit. Therefore, the logarithmic amplifiers do not reduce the overall dynamic range of the gain control circuit below that which is obtained from the optical receiver.

The logarithmic amplifiers constructed in this project are dual polarity circuits. They produce an output voltage which is approximately the logarithm of the input voltage at each point along the waveform, independent of the polarity of the input signal. Actually, the amplifiers used do not generate true logarithms, but instead produce a pseudo-logarithmic output which is generated as a summation of hyperbolic tangents. The hyperbolic tangent functions are generated by the voltage to current relationship of a bipolar transistor differential pair [45].

The schematic of the logarithmic amplifier design is shown in Figure 4.7. The logarithmic amplifier contains an input emitter follower stage which is used for matching purposes. This stage is followed by four parallel pseudo-logarithmic stages, each of which operates over a designated portion of the total input dynamic range. These stages generate an output current which is approximately the logarithm of the input voltage, over a limited dynamic range. Specifically, each stage in the design generates a pseudo-logarithmic output over a 15 dB dynamic range, with the four stage circuit producing a logarithmic transfer function over a 60 dB dynamic range.

The logarithmic ranges of the four stages are staggered with respect to each other by amplifying or attenuating the signal applied to each stage. The currents generated by the four stages are summed together in the shared load resistor, thus generating the logarithm of the input voltage over the entire operating range of 60 dB. The four parallel stages are identical in order to ensure that each path has an equal propagation delay from input to output. As a result, the signals traversing the various paths are summed in phase at the output node, allowing logarithmic reconstruction of the signal at the output node.

The gain or attenuation applied to the input signal in each path is achieved using an emitter follower stage in combination with a linear feedback video amplifier gain block [46]. The two cascaded amplifiers have been used in order to produce signal gains of 24.5 dB, 9.5 dB, -5.5 dB, and -20.5 dB in front of the differential pairs present in the four parallel branches, respectively. The schematic of tha video amplifier that has been selected for this application is shown in Figure 4.8, where RCA CA3046 matched transistors have been used in this circuit in order to avoid mismatch problems in the differential pair, as well as to provide temperature tracking.

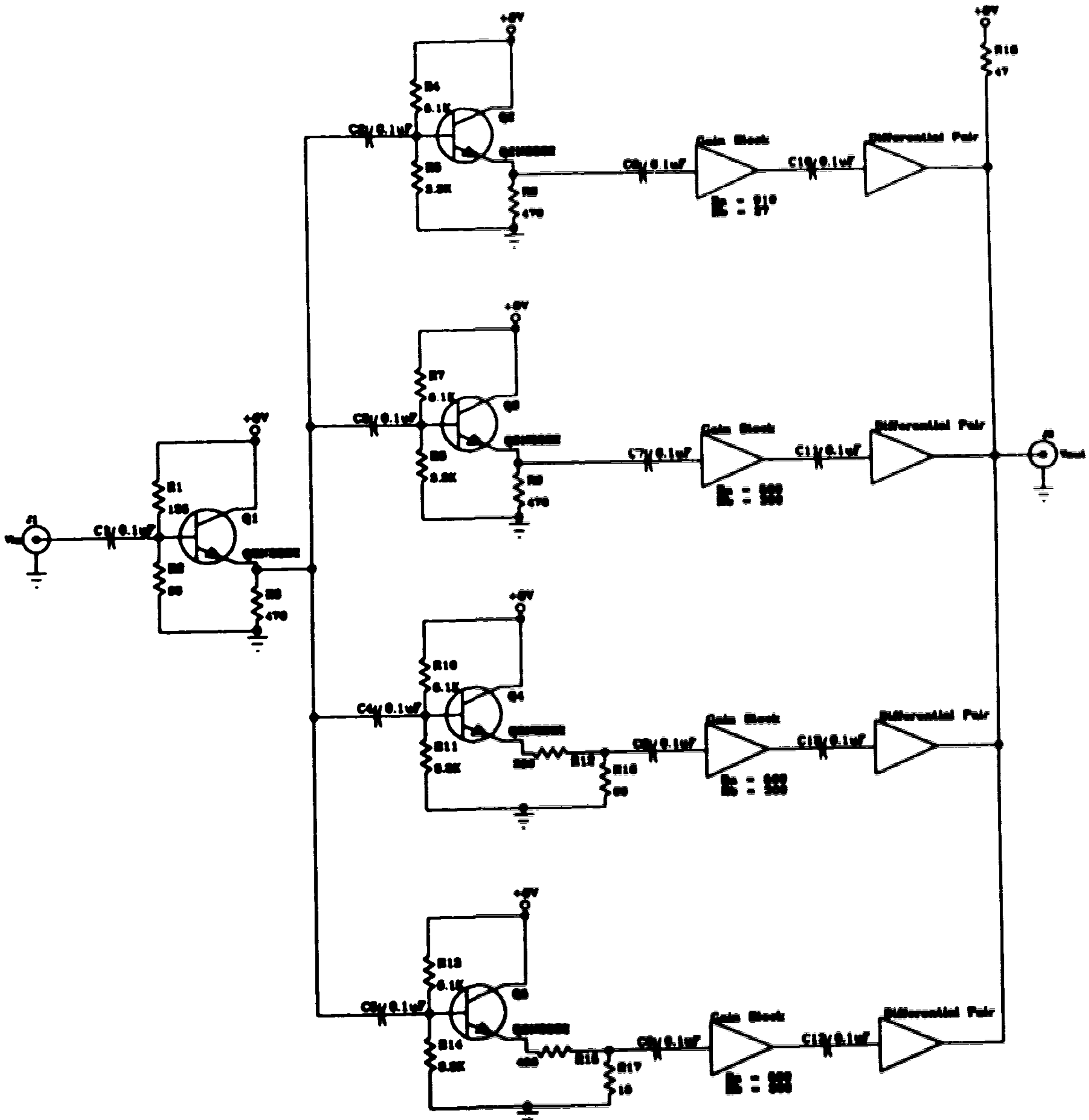

Figure 4.7 Logarithmic Amplifier Schematic

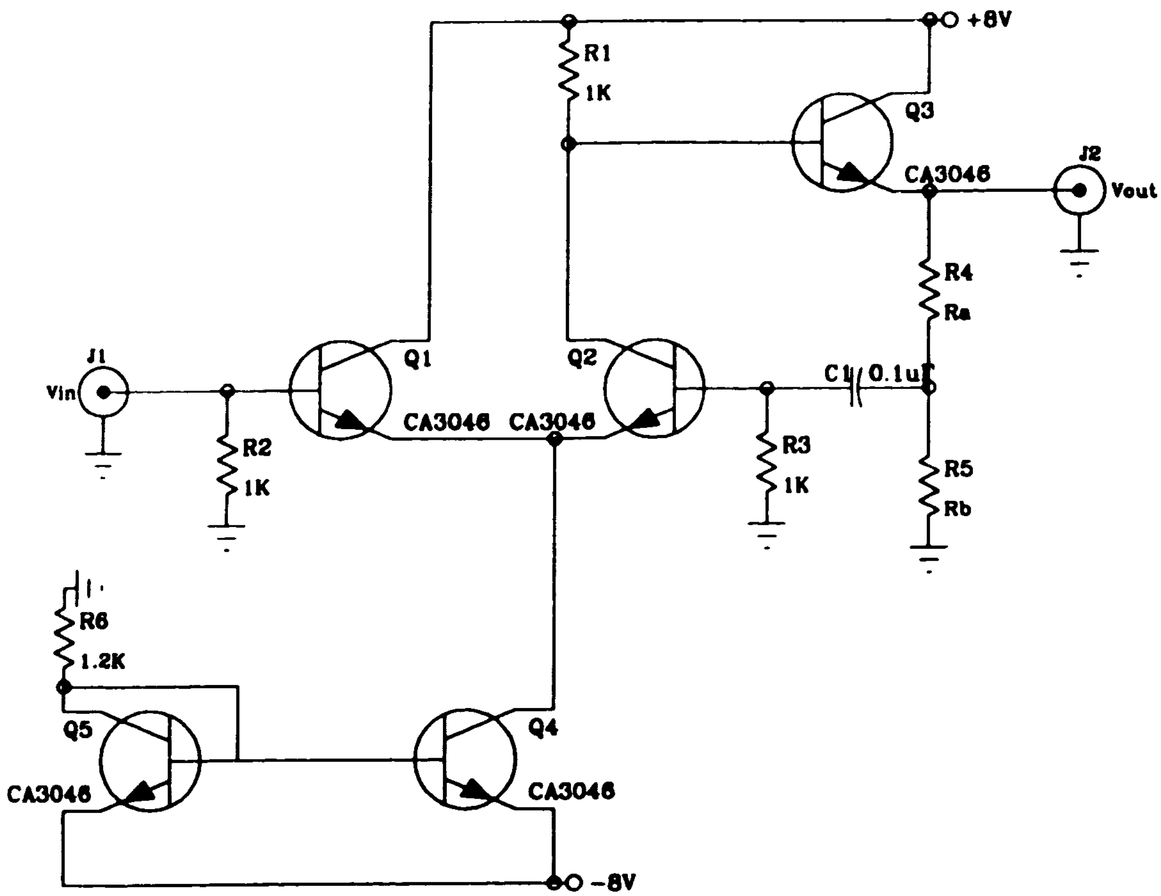

Figure 4.8 Linear Feedback Video Amplifier Schematic

The linear feedback video amplifier is based upon a bipolar differential pair, formed by transistors Q_1 and Q_2, biased by a current mirror consisting of transistors Q_4 and Q_5. Feedback around the differential pair is provided by the emitter follower transistor, Q_3, and the resistive divider formed by R_4 and R_5. Given a large open loop gain, the gain of the differential pair, this circuit is similar to a non-inverting opera..onal amplifier circuit. In this case, the gain element is the differential pair, and feedback is achieved using the resistive divider connected to the inverting input. The gain of the closed loop circuit may be expressed as

$$G_{CL} = 1+\frac{R_a}{R_b}, \tag{4.1}$$

analogous to the result for a non-inverting operational amplifier circuit.

This expression holds if the open loop gain is greater that the closed loop gain by more than 20 dB, where the open loop gain is,

$$G_{OL} = g_m R_c = \frac{I_c}{V_T} R_1 \, . \tag{4.2}$$

In this expression g_m is the transconductance of the transistors within the differential pair, I_c is the bias current driven through the transistors, and V_T is the volt equivalent of temperature.

Differential pair amplifiers are used to generate the hyperbolic tangent components that are summed in the load resistor to generate the logarithmic transfer function. The schematic of the cells used to perform this function is shown in Figure 4.9, where RCA CA3046 matched transistors have again been used in order to avoid differential pair mismatch effects which would result in an output offset voltage.

The differential pair, formed by transistors Q_1 and Q_2, is biased by the current mirror formed by transistors Q_4 and Q_5. The output current from this circuit is given by [45],

$$I_{out} = I_c \cdot \tanh\left(\frac{V_{in} A_V}{2V_T}\right) \tag{4.3}$$

where I_c represents the bias current of the transistors within the differential pair, V_{in} is the logarithmic amplifier input signal amplitude, and A_V is the gain in front of the selected differential pair. The hyperbolic tangent voltage to current transfer function approximates a logarithm over a limited range, and operation of the logarithmic amplifier is in fact based upon this characteristic. The output currents from the four parallel stages are combined in the 47 Ω load resistor, where each differential pair has a different value of A_V. As a result, the logarithmic ranges of the parallel paths are combined and the overall circuit acts as a wide dynamic range pseudo-logarithmic amplifier.

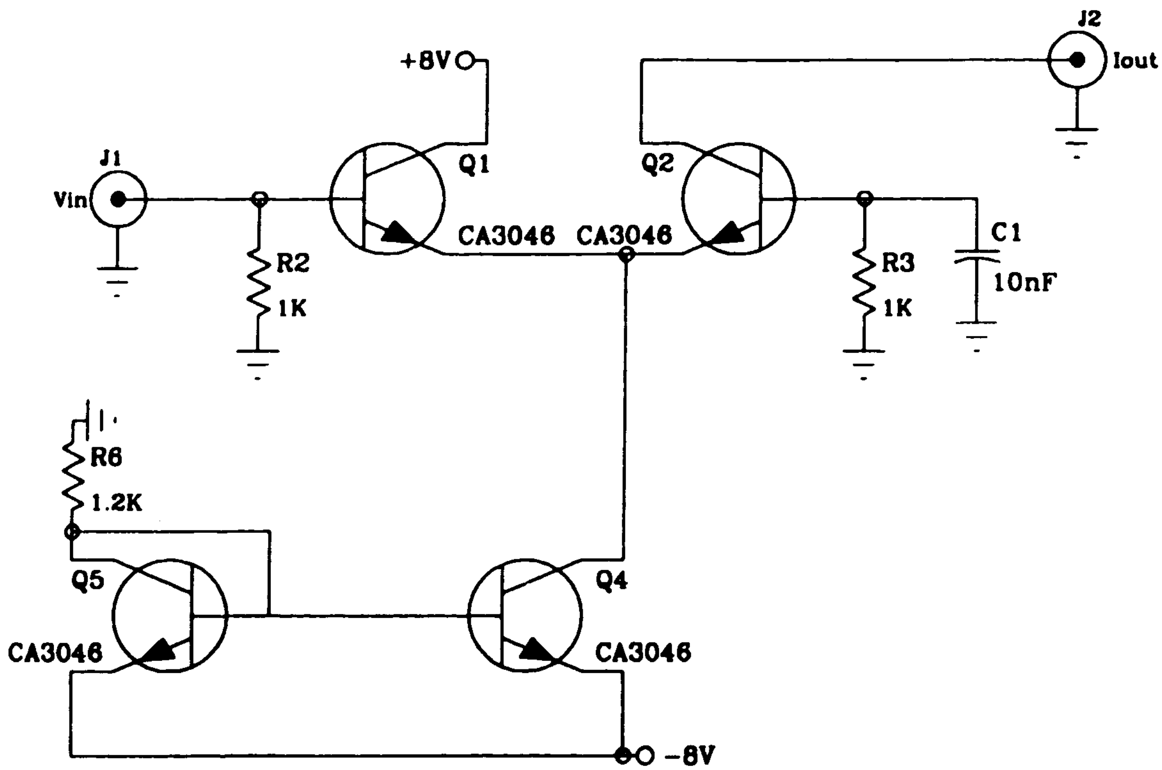

Figure 4.9 Differential Pair Pseudo-Logarithmic Cell Schematic

The components present at the logarithmic amplifier output are shown in Figure 4.10. The four lower curves indicate the outputs of the individual stages, calculated using equation (4.3), with a 47 Ω load resistor. The four curves are offset with respect to each other due the signal gain present in front of each differential pair. The upper curve represents the summation of the four stage outputs, indicating that the summation generates an approximation to a logarithmic transfer function over a wide dynamic range. As noted earlier, the individual sections provide a logarithmic response over a limited dynamic range.

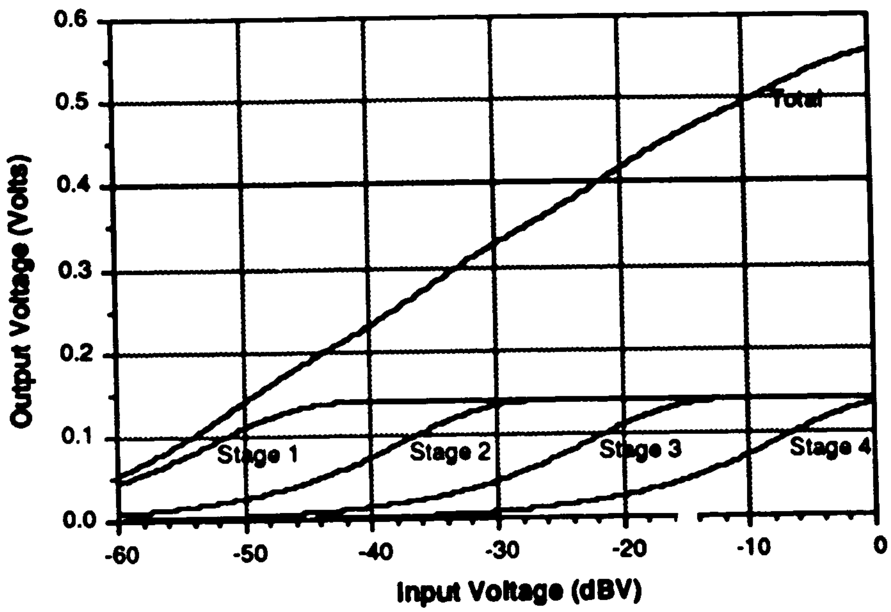

Figure 4.10 Theoretical Logarithmic Amplifier Output Components

Figure 4.10 indicates that the pseudo-logarithmic transfer function has a slight ripple, corresponding to a ±0.6 dB logarithmic accuracy. This ripple may be reduced by using a higher number of parallel stages, with each stage covering a smaller dynamic range. For example, a six stage logarithmic amplifier, with each stage covering a 10 dB dynamic range, would also have a 60 dB total dynamic range but with a logarithmic accuracy better than ±0.25 dB [46]. The figure also indicates that the transfer function begins to deviate from a logarithm as the input voltage approaches the limits of the selected operating range.

The transfer characteristic of one of the two identical logarithmic amplifiers which was constructed is shown in Figure 4.11. This figure includes the theoretical results presented above for comparison, and demonstrates that the measured characteristic closely tracks the theoretical characteristic, with the only distinction being a slight difference in slope. Equation (4.3) indicates that the slope of the transfer characteristic is given by the product of the differential pair bias current and the impedance of the load resistor. The curves shown below indicate that the measured slope is 10.3 mV/dB, whereas the theoretically calculated slope is 9.4 mV/dB. These values indicate an error of less than 10%, well within component tolerances. More important than the actual logarithmic accuracy, however, is the fact that the two logarithmic amplifiers track each other very closely. As a result, very small differential offsets are produced as the signal levels shift for a constant value of gain.

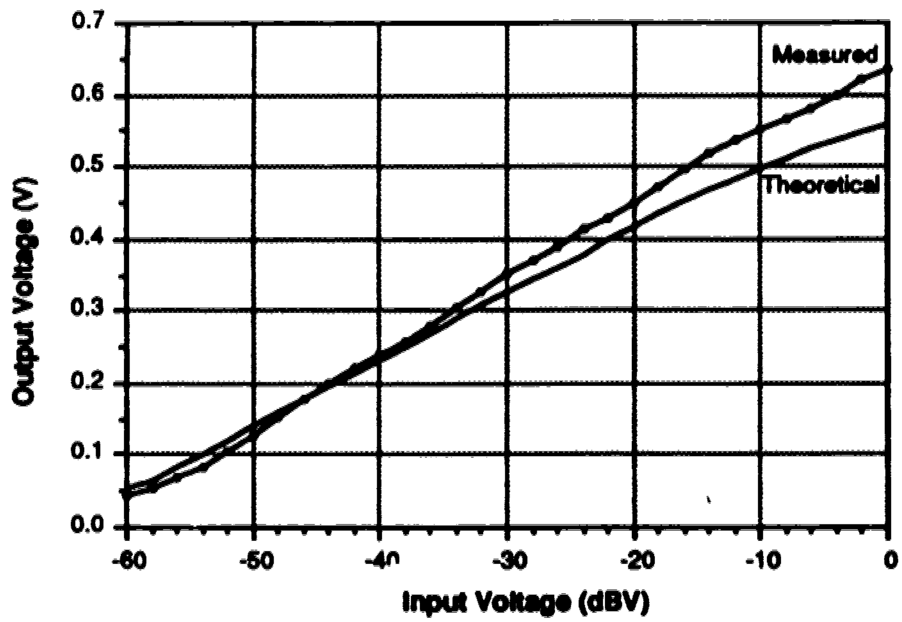

Figure 4.11 Transfer Function of Logarithmic Amplifier

An investigation of the frequency response characteristics of the logarithmic amplifier reveals a dependence on the magnitude of the input signal. In particular, as the input signal amplitude varies over the full operating range of the optical receiver, the bandwidth of the logarithmic amplifier shifts from 150 MHz down to 26 MHz. This shift may be understood by considering the stage which is generating the peak portion of the output signal. At high input signal levels, where the bandwidth is largest, the stage with the lowest gain generates the peak component of the output, while the other stages are simply delivering full output current to tl. 'oad. This stage, as a result of being the lowest gain stage, has the highest bandwidth. When the input signal level is low, the stage with the highest gain, and hence the lowest bandwidth, is delivering the peak component of the output signal, while the other stages supply no current to the load. Therefore, an inverse relationship exists between signal amplitude and bandwidth, as a consequence of having several stages each with a different stage gain and bandwidth.

The logarithmic amplifier is the control system block with the lowest bandwidth, and hence determines the overall limit on control system input bandwidth. If a larger portion of the input signal spectrum is to be used, the bandwidth of the logarithmic amplifier must be increased. The bandwidth of the other components within the high speed portion of the gain control circuit, namely the optical receiver and pre-detection low pass filter, may easily be extended to bandwidths above 25 MHz. Teledyne Microelectronics manufactures a logarithmic amplifier which operates from 5 kHz to 100 MHz, with a 70 dB dynamic range and a ±1.0 dB logarithmic accuracy. This device operates over a military temperature range from -55 °C to +125 °C. A device of this nature could be installed in the gain control circuit in order to allow an input passband of up to 100 MHz. This would permit the gain control circuit to use a larger portion of the input spectrum and, as a consequence of the rigid specifications of this logarithmic amplifier, would allow installation of the gain control system in harsh operating environments.

4.2.4 Peak Detector

The two peak detector circuits in the gain control system determine the peak value of the input and output electrical signals, generating lower speed electrical signals which are logarithmically proportional to the laser amplifier input and output optical signal levels. The signals applied to the peak detectors vary over a dynamic range of approximately 10 dB, as a result of the logarithmic signal compression that is used. The peak detectors must have a small attack time constant in order to charge to the peak value of the input signal, given that it may vary at up to 25 MHz. In addition, the decay time constant must be adjusted such that the peak detector is able to track optical level variations caused by input power shifts or laser amplifier gain variations.

The schematic of the peak detector circuit used in the gain control system is shown in Figure 4.12. This circuit has been designed with an attack time constant of approximately 2 ns, and a decay time constant of 6.6 μs.

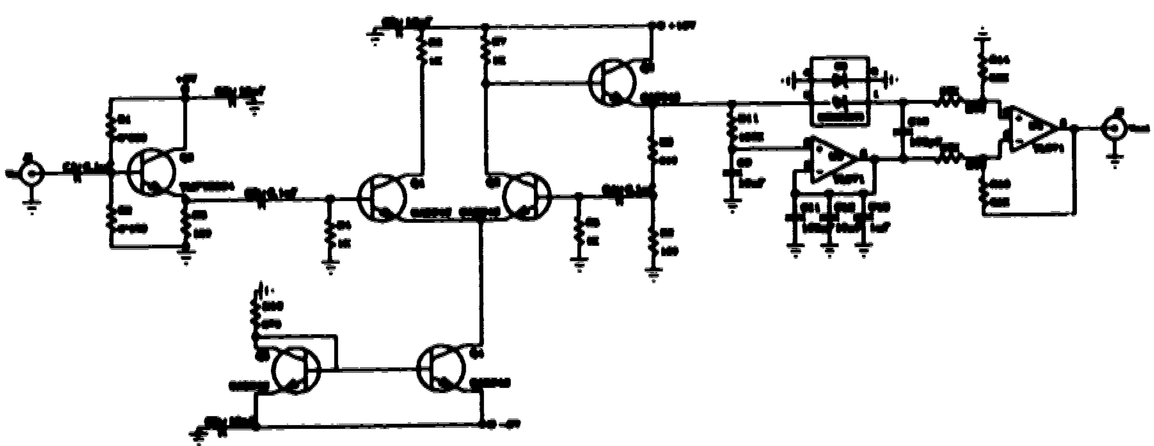

Figure 4.12 Peak Detector Circuit Schematic

The input stage of the peak detector circuit is an emitter follower amplifier, which is used to buffer the input and provide a matched load of 50 Ω to the logarithmic amplifier circuit. Following this is a linear feedback video amplifier, operating at a voltage gain of 10. The purpose of this stage is to amplify the output of the logarithmic amplifier to a level suitable for detection by the passive peak detector circuit.

The video amplifier drives the peak detector section of the circuit. The rectification and peak detection operations are performed by the combination of the HSMS-2825 high speed Schottky diode and the peak charging capacitor, C_{10}. The RC low pass filter formed by R_{11} and C_9 is used to remove the DC portion of the video amplifier output. The filter is used as opposed to a series blocking capacitor, as insertion of a blocking capacitor creates a clamping circuit instead of a peak detection circuit. The result is a peak detector circuit that produces an output which is the peak value of the AC portion of the video amplifier output.

The output driver stage of the peak detector circuit is a differentially connected operational amplifier, which is used as a buffer to prevent loading on the peak detector circuit. As a result, the time constants of the peak detector circuit are not affected by the load impedance seen by the circuit. In addition, use of the differential amplifier results in an output signal which is the peak value of the AC portion of the input signal. The DC offset present at the output of the linear feedback video amplifier has been removed by applying the offset to the negative terminal of the differential amplifier.

The attack time constant of the peak detector circuit is determined by the value of the charging capacitance, C_{10}, and the impedance of the source which charges the capacitor. Given a series resistance of approximately 10 Ω for the diode, and assuming a value of 100 for the current gain (h_{FE}) of transistor Q_3, the charging capacitor is charged by a source with an impedance of approximately 20 Ω. As a result, the attack time constant is about 2 ns. This value is sufficiently small to ensure that the peak detector circuit completely charges to the peak value of an input signal varying at up to 25 MHz. The decay time constant is determined by the value of the charging capacitor, C_{10}, and the resistors through which it discharges, namely R_{12} and R_{14}. As a result, the decay time constant is about 6.6 μs, allowing the peak detector to track optical signal level variations which occur at speeds up to approximately 40 kHz, as desired.

Correct operation of the peak detector circuit is demonstrated in Figure 4.13. This figure shows the output generated by the peak detector, given a 25 MHz input carrier, amplitude modulated at 40 kHz. The minimum and maximum values of the input waveform correspond to the extreme values which may be produced by the logarithmic amplifier, given the 20 dB optical operating range of the optical receivers. Therefore, the peak detector circuit operates over the full dynamic range of the gain control circuit.

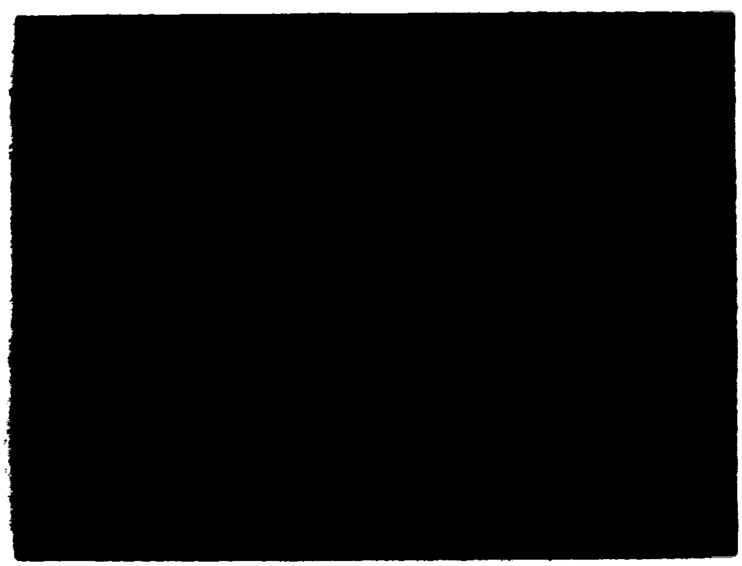

Figure 4.13 Peak Detector Circuit Output

4.2.5 Post-Detection Low Pass Filter

The post-detection low pass filters are used to remove unwanted frequency components, namely those above 40 kHz, from the peak detector outputs, as well as to reduce the noise power which is applied to the gain detection circuitry. The schematic of the post-detection low pass filters used in the gain control system is given in Figure 4.14. This filter is a second order Butterworth active low pass filter. The cutoff frequency is the inverse of the RC time constant of the filter; in this case the 3 dB corner frequency is 40 kHz. Resistors R_3 and R_4 are chosen to satisfy the second order Butterworth transfer function, as a consequence creating a DC voltage gain of approximately 1.6 (4.1 dB). The filters do not contain any circuitry used to null the offsets of the operational amplifiers, because any offsets present within the gain control system may be effectively removed by modifying the reference operating point of the control circuit.

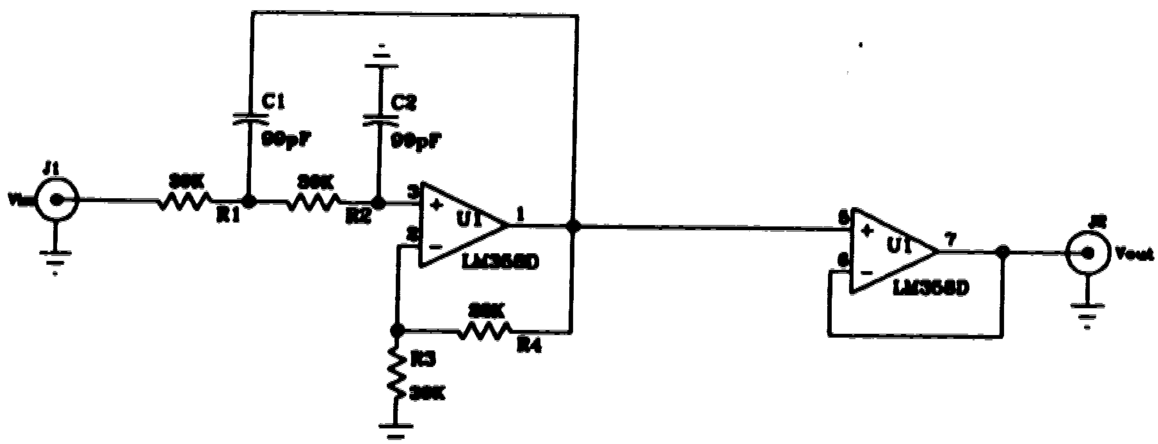

Figure 4.14 Post-Detection Low Pass Filter Schematic

The frequency response of one of the post-detection low pass filters is shown in Figure 4.15. This plot shows both the amplitude and phase response of the circuit, indicating a 3 dB bandwidth of 36 kHz, or equivalently a 90° phase shift present from input to output at 36 kHz. This plot indicates that the low pass filter meets the expected frequency response criterion, and the overall 180° phase shift near the corner frequency of 36 kHz is as expected for a second order filter.

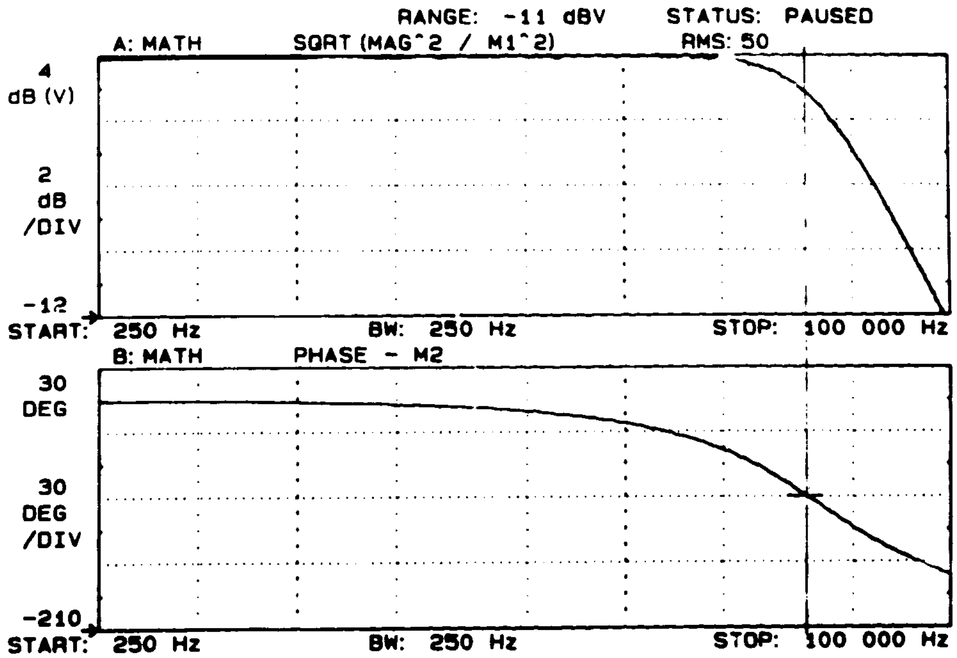

Figure 4.15 Post-Detection Low Pass Filter Frequency Response

4.2.6 Driver Control Circuit

The purpose of the driver control circuit is to determine the gain or output power of the laser amplifier and to compare the measured value to the desired operating point. An error signal is generated as a result, and integrated in order to modify the bias current through the laser amplifier, and hence control the amplifier gain. As a result of the integrator in the feedback loop, the steady state error of the control loop approaches zero.

The driver control circuit is required to operate at 40 kHz as the inputs are driven by the 40 kHz post-detection low pass filters. As a result of the low speed of operation, operational amplifier circuits may be used to determine the laser amplifier gain and bias current control signals. The schematic of the driver control circuit design is shown in Figure 4.16.

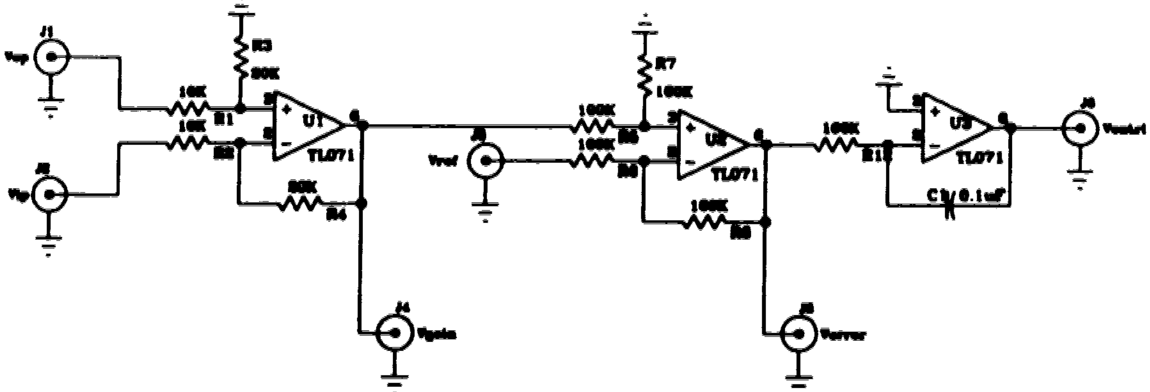

Figure 4.16 Driver Control Circuit Schematic

The input section of this circuit subtracts the two signals representing the output and input optical signal powers, respectively. This is equivalent to amplitude division because of the logarithmic proportionality that exists between the electrical signal levels and the optical power levels present at the laser amplifier input and output. This stage has a voltage gain of two in order to increase the slope of the measured gain voltage as much as possible, reducing the sensitivity of the gain control circuit with respect to the reference operating point.

The second stage of this circuit subtracts the measured gain from the desired operating point, which is supplied by the the temperature compensated voltage reference. The output of this stage is the negative of the error signal, which is in turn passed through the final inverting integrator stage. The integrator has a time constant of 10 ms, and a transfer function given by [36],

$$H_{Integ}(s) = \frac{150 \cdot 10^3}{\left(\frac{s}{1.06 \cdot 10^{-4}} + 1\right)\left(\frac{s}{3.75 \cdot 10^6} - 1\right)} \tag{4.4}$$

indicating that the integrator contains a pole at $1.06 \cdot 10^{-4}$ Hz. From a rigorous analysis of the control system this pole is found to be the dominant closed loop pole and acts to stabilize the feedback control system.

The output of the driver control circuit is a voltage proportional to the bias current which must be driven through the laser amplifier to achieve a laser amplifier gain or output power equal to the desired value. It is important to note that the required current is not derived as an absolute value given the desired amplifier gain or output power, but instead is calculated by the integrator in order to maintain the selected value. In this way, the control circuit is able to compensate for all possible environmentally induced gain or output power variations, and is able to stabilize the laser amplifier independent of the mechanism responsible for the variation.

4.2.7 Temperature Compensated Voltage Reference

The temperature compensated voltage reference provides a stable reference source that is used to set the desired laser amplifier gain or output power. During the initial phase of testing it was found that a power supply and resistive divider circuit could not be used as the reference source, because the desired operating point varied by up to 0.25 dB. This deviation was tracked by the gain control circuit, creating fluctuations in laser amplifier gain of up to 0.25 dB. As a result, it was not possible to measure the relatively small gain variations which were induced by environmental changes and removed by the gain control circuit.

The schematic of the voltage reference used to obtain an environmentally stable gain or output power reference setpoint is shown in Figure 4.17. This circuit is constructed using a TL431 adjustable precision shunt regulator which develops a reference voltage of 2.5 Volts across R_3. This voltage has a temperature coefficient of less than 30 ppm/°C, and produces a very stable source which may be used as the reference setpoint for the gain control circuit. In addition, the sensitivity of the gain control circuit with respect to the reference voltage has been reduced by maximizing the slope of the measured gain voltage versus laser amplifier gain characteristic, as indicated in the previous section.

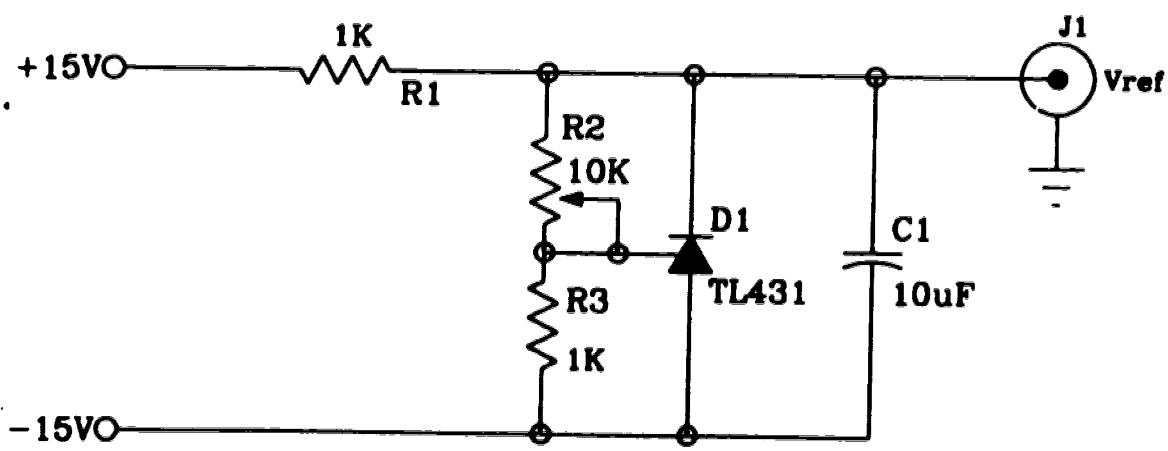

Figure 4.17 Temperature Compensated Voltage Reference Schematic

Operation of the voltage reference circuit relies upon generation of a constant voltage across R_3 by the shunt regulator, independent of the temperature or bias current driven through the regulator. The voltage across the resistor is held constant at 2.5 Volts, and the voltage across the potentiometer is,

$$V_{R_2} = 2.5 \cdot \frac{R_2}{R_3} \tag{4.5}$$

where R_2 is the resistance of the potentiometer. The voltage across the potentiometer may hence range from 0 to 25 V, as the potentiometer resistance is tuned from 0 to 10 kΩ, respectively. In this way, the reference output voltage may be tuned from -12.5 V through to 12.5 V, at each point having a temperature coefficient of only 30 ppm/°C.

The current flowing through resistor R_1 is a function of the output voltage. However, this stage sees a high impedance load, so the full current through R_1 flows through the shunt regulator. As a result, the range of regulator drive currents is from 2.5 mA to 27.5 mA, a range over which the shunt regulator voltage remains constant at 2.5 V, ensuring proper operation of the temperature compensated voltage reference circuit.

4.2.8 Laser Amplifier Current Driver

The laser amplifier current driver is required to produce an output current which is directly proportional to the control voltage generated by the driver control circuit. The circuit design used to perform this operation is similar to the circuit which was introduced earlier to produce the DC portion of the laser source drive current. The schematic of the laser amplifier current driver is shown in Figure 4.18.

The input stage of this circuit limits the range of the signal applied to the voltage to current converter, limiting the laser amplifier drive current to a safe range. When the input voltage exceeds +10 V, the Zener diode conducts in the reverse direction, clamping the output voltage at -10V. If the input control voltage becomes negative, a condition which may result in reverse biasing the laser amplifier, the zener diode conducts in the forward direction and limits the output voltage to approximately +0.7V.

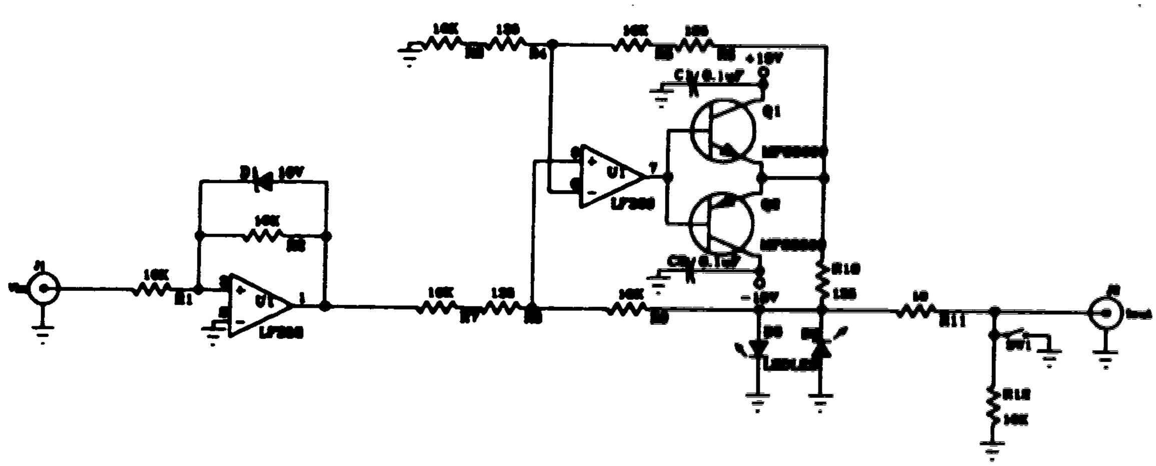

Figure 4.18 Laser Amplifier Current Driver Schematic

The output from the input clipping stage is applied to an enhanced drive Howland voltage to current converter which has a push pull output configuration. The voltage applied to this circuit is restricted to operate between approximately 0 V and -10 V, creating a limited current sink which pulls the desired drive current through the laser amplifier.

The output circuitry is used for protection of the laser amplifier. The two LEDs act to ensure that the laser amplifier is never reverse biased by more than the cut-in voltage of an LED. The switch is present to allow the laser amplifier terminals to be shorted together, providing a current bypass around the laser amplifier. The 10 kΩ resistor is used for static discharge, while the 10 Ω resistor acts as a current monitor, allowing the laser amplifier drive current to be monitored through use of a DC voltmeter.

The entire drive circuit is based upon conventional operational amplifier technology, allowing the drive current to change at speeds high enough to compensate for all expected gain or output power variations induced by environmental factors.

4.3 AGC System Testing

This chapter has introduced the basic structure of the laser amplifier gain control circuit, and has presented the principles governing the operation of the system. In addition, the building blocks of the gain control system have been examined, and the design specifications and performance of each of the blocks has been investigated.

The following chapter will consider the performance of the entire control system, in terms of the gain and output power stabilization which has been achieved using this system. As well, a comparison will be made between the gain control circuit implemented in this project and previous laser amplifier control circuit attempts which have been made a research institutes in the United States and Europe. The result of this comparison will be the introduction of two optimum gain control circuits which compensate for gain or output power variations as well as laser amplifier interchannel crosstalk.

5. AGC CIRCUIT PERFORMANCE

This chapter presents experimental results indicating the performance of the control circuit introduced in Chapter 4, and demonstrates the extent to which laser amplifier gain and output power stabilization have been achieved. The calibration curves for the gain control circuit, indicating the ability of the control system to measure the gain or output power of the laser amplifier, are first presented. This is followed by a discussion of the degree to which gain and output power stabilization which have been obtained, for the laser amplifier introduced in Chapter 3. In addition, the response time of the control system is investigated, demonstrating the ability of the system to track high speed laser amplifier gain and output power fluctuations.

In the final section of this chapter, the results obtained from the control circuit implemented in this project are compared with previously published laser amplifier control schemes, and two alternative optimum amplifier control system configurations are proposed. The optimal systems are designed to achieve gain or output power control, as well as to reduce laser amplifier interchannel crosstalk.

5.1 System Calibration

This section presents the results obtained from the gain control circuit calibration, indicating the internal control voltage generated within the control system for a given value of laser amplifier gain or output power. The transfer curves generated demonstrate the ability of the control system to measure the laser amplifier gain or output power. In addition, these curves may be used to determine the reference voltage which must be applied to the control circuit in order to achieve the desired value of gain or optical output power.

5.1.1 Laser Amplifier Gain

The transfer characteristic representing the internal control system voltage that is generated by the driver control circuit, as a function of the gain of the laser amplifier, was measured using the electrical system shown in Figure 5.1. The calibration was performed using an electrical system rather that the experimental fiber optic system introduced in Chapter 3, in order to avoid measurement errors induced by drifts in laser amplifier alignment. Drifts in fiber alignment occur within the time span required to perform the calibration test. These drifts would degrade the accuracy and repeatability of the calibration results if the fiber optic test system were used to perform the control circuit calibration.

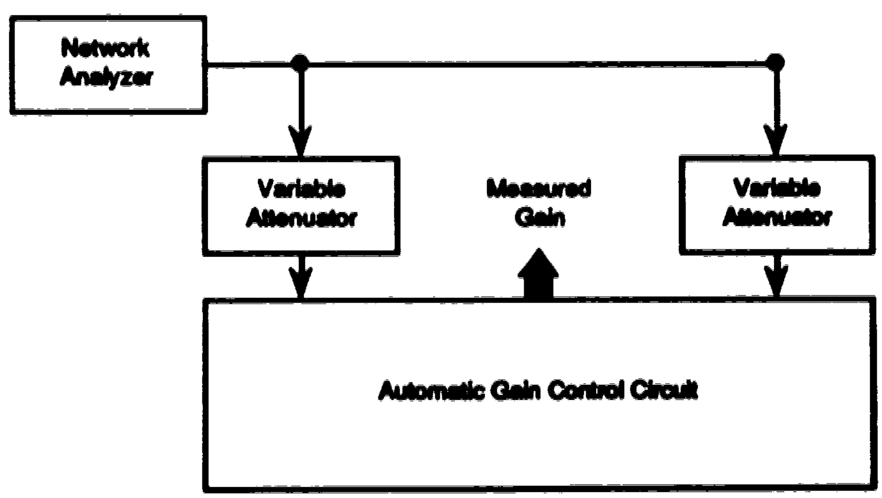

Figure 5.1 Gain Calibration Test System

The gain calibration system consists of an HP8753A Network Analyzer which is used as a 10 MHz sinusoidal source, and two Wavetek variable attenuators which have a resolution of 1 dB and a total attenuation range of

80 dB. The outputs from the variable attenuators are applied directly to the 25 MHz pre-detection low pass filters present in the gain control circuit, bypassing the optical receiver modules.

The network analyzer generates an electrical output signal which is equal in amplitude to the electrical signal which would be produced by the optical receivers if a -20 dBm optical input signal were applied. The electrical signal generated lies within the 25 MHz passband of the gain control circuit in order that the control system is able to detect the input and output amplitudes. The variable attenuators are used to model changes in laser amplifier gain. Modifying the attenuation present in the input and output paths makes it possible to vary the effective laser amplifier gain, and hence test the ability of the gain control circuit to detect laser amplifier gain variations. Correct operation of the control system may be verified by monitoring the internal control voltage that is produced, ensuring that it tracks laser amplifier gain variations.

The transfer characteristic of the gain control circuit, in terms of the internal control voltage produced by the driver control circuit, as a function of the effective laser amplifier gain, is shown in Figure 5.2. This plot shows that the internal voltage generated by the driver control circuit is logarithmically proportional to the gain of the laser amplifier, as expected due to the presence of the logarithmic amplifiers within the control circuit. The transfer characteristic contains a slight ripple created by the ripple present in the transfer function of the pseudo-logarithmic amplifiers. However, this ripple does not affect the operation of the gain control circuit because the control system simply adjusts the laser amplifier bias point in order to achieve the desired value of gain, as determined by the reference voltage. The ripple present in the characteristic does not affect this operation, as the curve increases monotonically. Instead, the ripple in the control voltage characteristic simply modifies the reference voltage which is required to obtain a selected fiber to fiber gain, and does not reduce the accuracy of the control circuit.

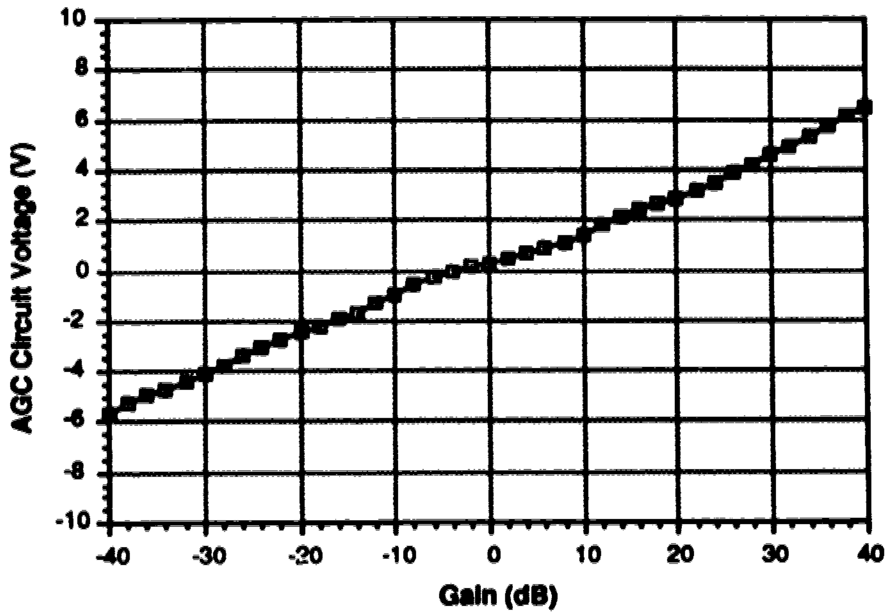

Figure 5.2 AGC Circuit Gain Calibration Plot

The calibration plot shown in Figure 5.2 demonstrates the ability of the control system to detect the gain of a laser amplifier over a wide dynamic range. Specifically, the system is capable of detecting amplifier gain over a 40 dB electrical range, or equivalently a 20 dB optical range, meeting the original design objectives. In addition, the transfer characteristic specifies the reference voltage which must be applied to the control circuit in order to achieve a selected value of gain. It should be noted that the wide dynamic range demonstrated in the diagram exists only if the higher of the input and output signal levels corresponds to an optical power of -20 dBm. If the input and output levels are equal the control system is capable of detecting gain over a 20 dB optical range, or equivalently a 40 dB electrical range. As the input and output signal levels begin to differ from each other this range diminishes until a dynamic range of 0 dB exists when the input and output levels differ by 20 dB.

5.1.2 Laser Amplifier Output Power

The transfer characteristic which demonstrates the relationship between the internal control voltage generated by the driver control circuit, and the optical output power emitted by the iaser amplifier, was measured using the test system shown in Figure 5.3. The control system calibration was again performed using an electrical system rather that the experimental fiber optic system in order to avoid introducing errors in the results as a consequence of drifts in the laser amplifier alignment.

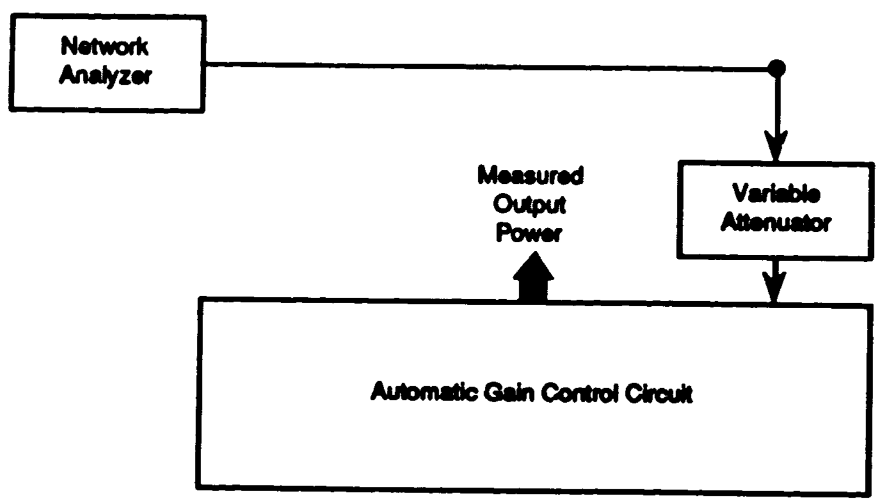

Figure 5.3 Output Power Calibration Test System

This configuration is similar to the test system which was used to measure the gain transfer characteristic, with the exception that the input variable attenuator has been removed. Instead, the input to the driver control circuit which represents the input optical signal level has been tied to ground, thereby emulating the output power configuration of the control circuit. The network analyzer has again been used to generate a sinusoidal signal lying within the passband of the control circuit. The magnitude of this signal is equal to the amplitude of the electrical output signal which would be generated by the output optical receiver, given an optical signal amplitude of -20 dBm. In this test system the variable attenuator is used to model changes in laser amplifier output power, changes which are detected by the control circuit.

The transfer characteristic of the control circuit, in terms of the internal voltage generated by the driver control control circuit for a specified output power, is indicated in Figure 5.4. This curve demonstrates the ability of the control system to detect changes in laser amplifier output power, again extending over an electrical signal range of 40 dB. As a result, the control system is capable of sensing laser amplifier output power variations over an optical signal range extending from -20 dBm to -40 dBm, allowing the control system to achieve optical amplifier stabilization over this dynamic range.

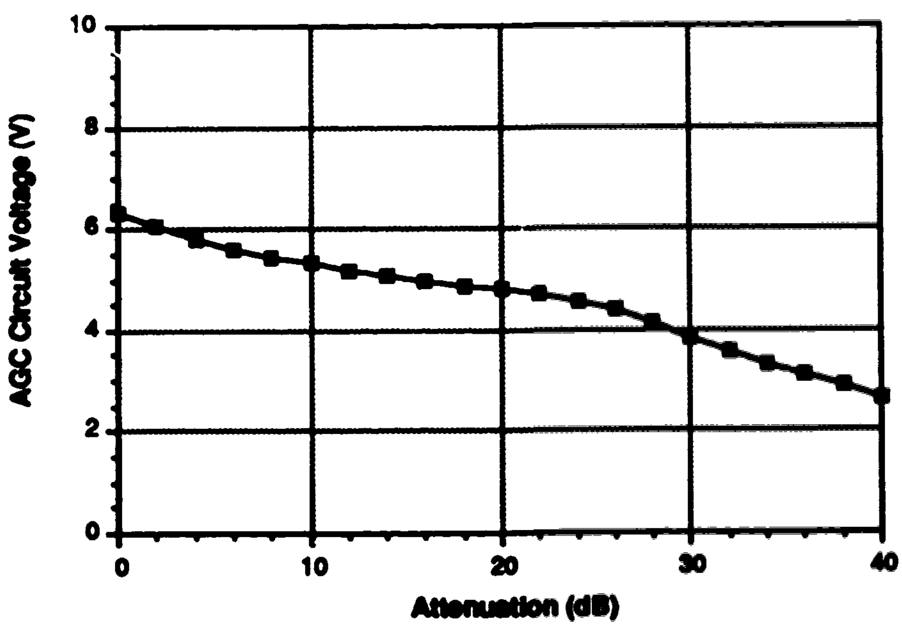

Figure 5.4 AGC Circuit Output Power Calibration Plot

Figure 5.4 also demonstrates that a logarithmic proportionality exists between the laser amplifier output power and the internal control voltage generated by the driver control circuit. This is identical to the result obtained for control circuit gain measurement, and, as earlier, the ripple in the characteristic does not affect the operation of the control circuit. The ripple present in the transfer characteristic simply modifies the reference voltage which must be generated for a desired output power, and does not affect the accuracy of the circuit.

5.2 System Performance

This section presents the measured results that demonstrate the performance which has been obtained from the gain control system, in terms of the level of gain and output power stabilization that has been achieved. In addition, the response speed of the control circuit is investigated, indicating the ability of the system to compensate for high speed variations in laser amplifier gain or output power. The results which are presented have been measured using the fiber optic test system introduced in Chapter 3, where the DFB laser source has been used to generate an intensity modulated input optical signal.

The modulation signal which has been used to intensity modulate the DFB laser is a 10 MHz sinusoid generated using an HP8753A Network Analyzer. The signal frequency was selected to lie within the passband of the control circuit, thereby allowing the system to detect the input and output optical signal levels and attempt to perform gain or output power stabilization. The network analyzer was chosen as a signal source in order to allow synchronous detection of the laser amplifier gain or output power. This is achieved by using the network analyzer to synchronously determine the amplitudes of the detected electrical signals generated by the input and output optical receivers. In this way, the network analyzer is effectively able to determine the amplitude of the laser amplifier input and output optical signals, which in turn allows the network analyzer to calculate the gain or output power of the laser amplifier. As a result, precise gain and output power measurements are possible, with an accuracy of better than 0.1 dB. It is for this reason that the network analyzer was selected as the modulation source, as opposed to a digital test set which would not allow synchronous gain or output power detection.

The control system test results which are presented below have been measured using a 10 MHz sinusoidal modulation source. However, the same tests have also been performed using both a DS3 rate (44.736 Mbits/s) 2^{15}-1 PRBS, as well as a 90 Mbits/s 2^7-1 PRBS digital data stream as the source laser modulation signal. No noticeable degradation in gain or output power stabilization was observed in either case, demonstrating the bit rate insensitivity of the gain control circuit. Therefore, the control circuit fulfills one of the original design specifications, and does not limit operation of the laser amplifier, combined with the gain control system, to optical links transmitting at a specified bit rate. However, as indicated above, the results presented below were obtained using a 10 MHz sinusoidal optical modulation signal which was generated using the HP network analyzer, thus allowing synchronous gain and output power detection for accurate measurements.

One attribute of the bit rate insensitivity of the control circuit should be noted. There exists a lower limit on the transmission bit rate below which the low frequency content present in the transmitted data signal may be interpreted as gain or output power variations, and removed by the control system. This effect could result in the generation of error floors in digital transmission systems, when long strings of zeros or ones are present in the data stream. This problem may be overcome, however, by reducing the passband of the gain control circuit, allowing the control system to only remove gain variations which occur below a user specified cutoff frequency. This frequency may be chosen to ensure that the gain control circuit does not remove any information from the transmitted signal.

The original design specifications of the gain control circuit stated that the system must operate over a wide optical signal dynamic range. Specifically, the control system is required to function correctly given optical signal amplitudes ranging from -20 dBm down to -40 dBm. The gain stabilization results presented below have been obtained from tests performed on the control circuit with an input optical signal power of -30 dBm. This power level lies in the center of the desired operating range. However, correct operation of the control circuit has been confirmed for input optical powers of -20 dBm and -32 dBm, indicating that the control system does operate over a wide dynamic range, as required. In fact, these upper and lower constraints on input signal power were determined by source laser to fiber coupling, and not by the gain control circuit. The calibration results presented introduced earlier suggest that gain or output power stabilization should be achievable over the full dynamic range specified, in particular from -20 dBm to -40 dBm.

This discussion indicates that the gain control circuit fulfills two of the original design specifications, namely bit rate insensitivity and laser amplifier stabilization over a wide optical dynamic range. The remaining design criteria, high speed control and gain or output power stabilization independent of the mechanism responsible for the original degradation, will be addressed by the results presented in the following sections. The results indicate that the control circuit satisfies all of the original design specifications.

5.2.1 Laser Amplifier Stabilization

This section introduces the steady state results which have been obtained for the control system when it is used to stabilize the fiber to fiber gain or the output signal power of the semiconductor laser amplifier introduced in Chapter 3. In particular, the reduction in laser amplifier sensitivity with respect to input signal polarization, amplifier temperature, and signal wavelength are considered. The gain stabilization results presented below have been obtained at an input signal power of -30 dBm, and a desired internal gain of 15.2 dB, corresponding to an amplifier drive current of 57.2 mA, twice the original threshold current. As noted above, similar gain sensitivity measurements have been made at other input signal power levels, demonstrating the wide dynamic operating range of the control circuit. The output power stabilization measurements presented below have been obtained for an input signal power of -20 dBm, and a laser amplifier output power of -11.1 dBm, again corresponding to an internal gain of 15.2 dB.

5.2.1.1 Polarization Sensitivity

The reduction in polarization sensitivity achieved using the control circuit is shown in Figure 5.5, where the gain sensitivity exhibited by the uncontrolled amplifier considered in Chapter 3 has been included for comparison. The two curves demonstrate the gain variation which results from a 90° rotation in the input signal polarization, from a TE polarized input at 0° to a TM polarized input at 90°. The gain sensitivity exhibited with respect to input signal polarization is seen to be reduced from slightly over 5 dB for the uncontrolled laser amplifier, to less than 0.1 dB when the gain control circuit is employed. This result indicates a dramatic improvement in polarization sensitivity, and allows the laser amplifier to be used in system applications which have a randomly varying input polarization. The gain fluctuations are limited by the control circuit to less than 0.1 dB, well within the bounds required for operation in an installed fiber optic communication system.

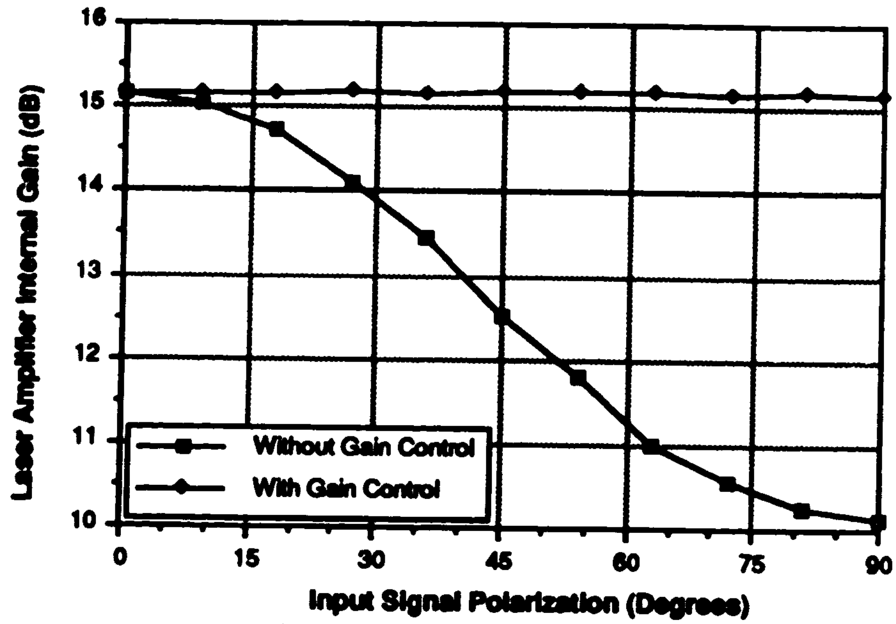

Figure 5.5 Polarization Sensitivity Exhibited by Laser Amplifier Gain

The reduction in polarization sensitivity which is achieved using the control system in the gain control mode also demonstrates the ability of the control circuit to stabilize the output power of a laser amplifier. The results in Figure 5.5 have been measured at a constant input optical signal power. Thus, as a consequence of a stable value of gain, the controlled laser amplifier has a stabilized output power. The input portion of the control system simply detects a constant input signal level, effectively causing the control circuit to operate in an output power control mode. The only difference is that a nonzero DC value is applied to the input side of the driver control circuit, where in the output power control mode, this input is tied to ground. However, the circuit operates in the same manner in either case, indicating that the control system is capable of stabilizing either the gain or the output signal power of the laser amplifier, independent of the input signal polarization.

The above discussion indicates a second application of the control system. The control circuit may be used to stabilize the output power of a laser amplifier at a preselected level, or alternatively it may be configured to produce a constant laser amplifier output power, referenced with respect to an arbitrary signal level within the system. For example, the control circuit may be used to ensure that the output signal level is held constant at -30 dBm, or alternatively the output power may be stabilized 20 dB above the signal level present in a second fiber within the transmission system. The transmission rates of the two fibers do not even have to be the same.

The variation of laser amplifier drive current as a function of the input signal polarization is shown in Figure 5.6, where the uncontrolled laser amplifier gain curve has again been included for comparison. The two curves indicate that the bias current driven through the laser amplifier by the gain control circuit is approximately inversely proportional to the uncontrolled amplifier gain variation. However, the two curves are not truly inverses because increases in amplifier bias current increase the amplitude of the laser amplifier Fabry-Perot resonances, and shift the resonant peaks to shorter wavelengths. These second order effects vary the gain of the laser amplifier at a particular wavelength, preventing gain stabilization from being performed by simply determining the magnitude of the original gain variation and adjusting the bias current to compensate for the deviation. Instead, some form of feedback control, such as in the circuit implemented in this project, is required.

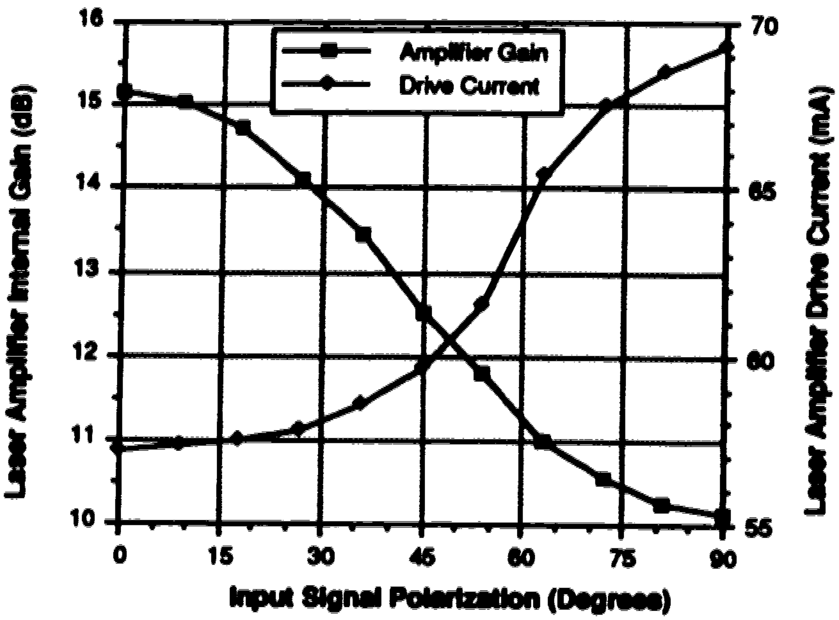

Figure 5.6 Polarization Dependence of Laser Amplifier Drive Current

5.2.1.2 Temperature Sensitivity

The reduction in the temperature sensitivity of the laser amplifier introduced in Chapter 3, as a result of the use of the control circuitry, is indicated in Figure 5.7. The temperature of the laser amplifier chip was varied by changing the amplitude of the drive current applied to the Peltier cooler upon which the laser amplifier was mounted. The actual device temperature was determined by measuring the resistance of a temperature calibrated thermistor which was placed beside the laser amplifier chip. The figure indicates that the gain of the laser amplifier is stabilized to within 0.1 dB of the desired operating point, while the amplifier temperature varies over a range of 16 °C. Without the gain control circuit, the amplifier gain fluctuates by approximately 2 dB over the same device temperature range. Therefore, use of the gain control circuit relaxes the constraints placed on the operating temperature range of the laser amplifier. Temperature control of the laser amplifier is required only to ensure that the chip temperature remains within safe operating bounds. As earlier, the laser amplifier input power was held constant during the generation of these curves. As a consequence, the results indicate that the control system is also capable of achieving laser amplifier output power stabilization in addition to gain control.

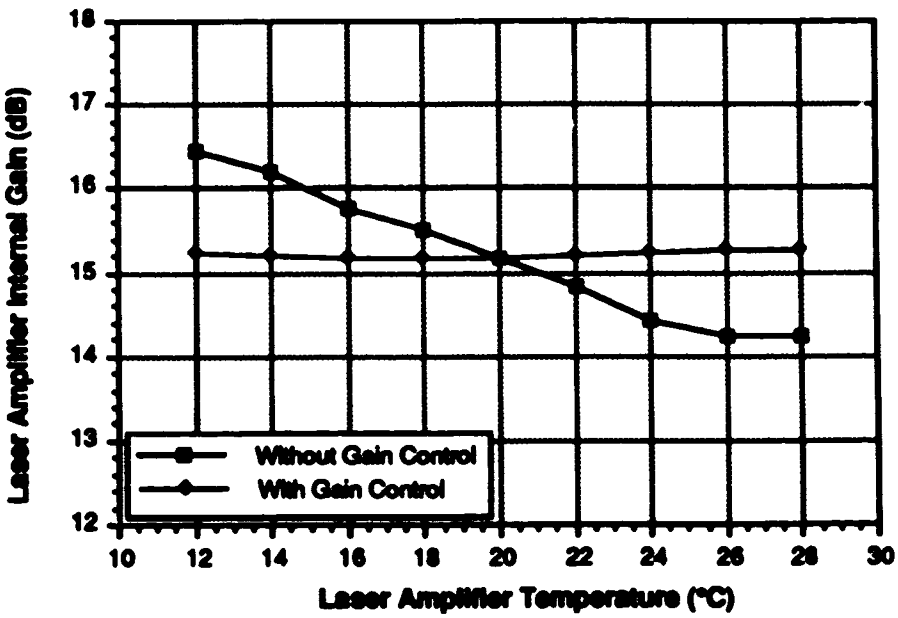

Figure 5.7 Temperature Sensitivity Exhibited by Laser Amplifier Gain

The variation of laser amplifier bias current as a function of the temperature of the laser amplifier is shown in Figure 5.8, where the original gain fluctuation has been included for comparison. The curves indicate that the variation in laser amplifier bias current again approximates the inverse of the original gain fluctuation. However, as in the case of polarization sensitivity, increasing the bias current of the laser amplifier modifies the magnitude of the laser amplifier Fabry-Perot resonances, and shifts these resonances to shorter wavelengths. These second order effects again require that closed loop feedback control is employed in order to achieve gain stabilization, and disallow the use of open loop stabilization methods.

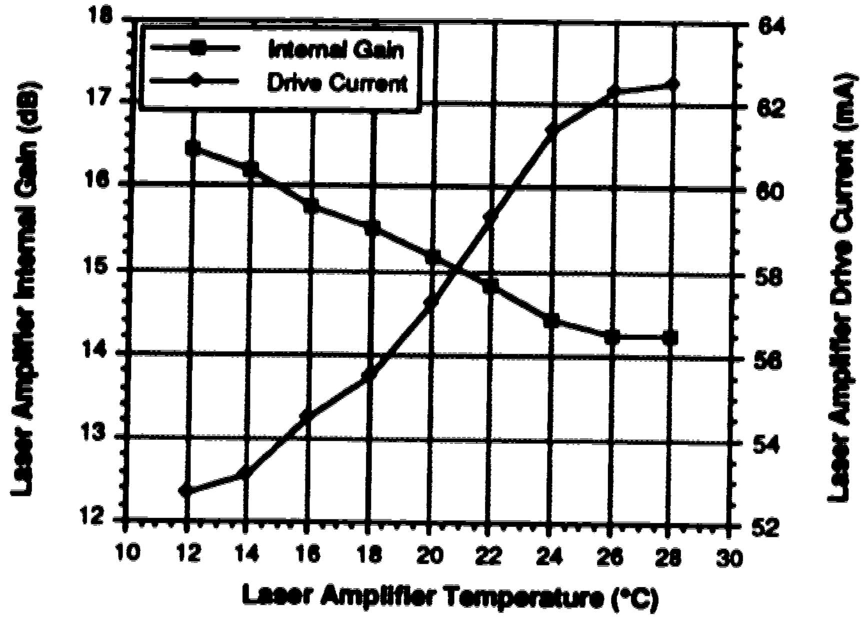

Figure 5.8 Temperature Dependence of Laser Amplifier Drive Current

5.2.1.3 Wavelength Sensitivity

The gain stabilization that is achieved as the input signal wavelength is varied is shown in Figure 5.9. The temperature of the DFB laser was varied by changing the amplitude of the drive current applied to the Peltier cooler upon which the source laser was mounted. The laser temperature was determined by measuring the resistance of a temperature calibrated thermistor which was placed beside the laser. This diagram indicates that as the temperature of the DFB source laser varies, thereby tuning the source wavelength through one Fabry-Perot resonance of the optical amplifier, the gain of the uncontrolled laser amplifier varies by slightly over 2 dB. With the gain control circuit in place, the gain fluctuation is reduced to less than 0.1 dB, indicating a dramatic decrease in the sensitivity that the laser amplifier gain exhibits towards the input wavelength. As a result, the limits placed on the emission wavelength of the source may be loosened, because the gain fluctuation has been reduced to less than 0.1 dB. This has been achieved while the source wavelength has been tuned through approximately 1.06 nm, one free spectral range of the laser amplifier. Loosening the bound on source wavelength subsequently relaxes the limits placed on the allowable source laser temperature. As a consequence, design of the source laser temperature control circuit is simplified. Again, as earlier, the figure also indicates the ability of the control circuit to stabilize the laser amplifier output power constant, independent of the input signal wavelength. This is demonstrated as the results have been measured at a constant input signal power.

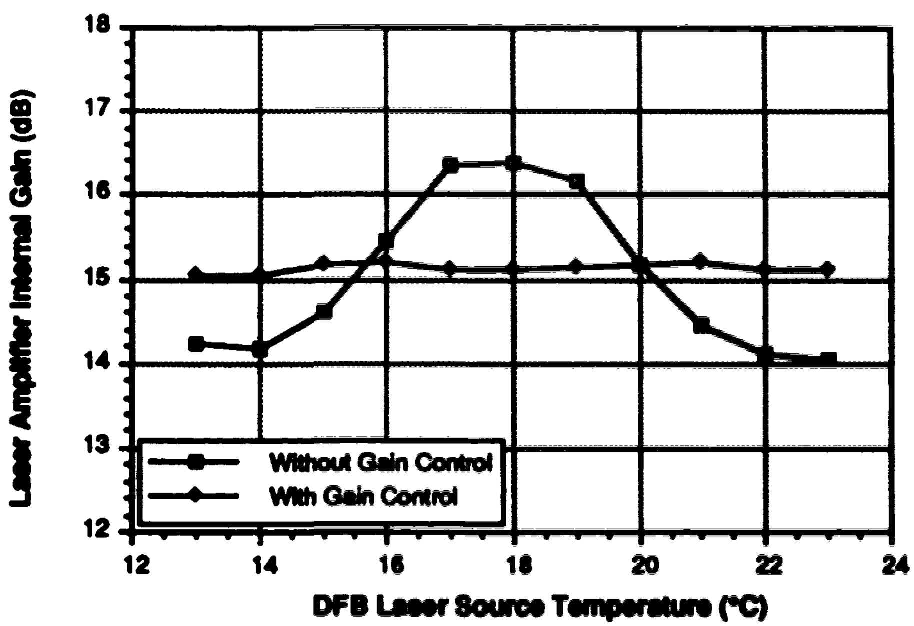

Figure 5.9 Wavelength Sensitivity Exhibited by Laser Amplifier Gain

The variation of laser amplifier bias current as a function of the laser source temperature is shown in Figure 5.10, where the gain of the uncontrolled amplifier has again been included for comparison. These curves demonstrate that a simple relationship between the laser amplifier bias current and the original gain variation does not exist. This is a result of the shift in the Fabry-

Perot resonances which is created due to changes in laser amplifier bias current. As the bias current is increased from 57.2 mA to 71.5 mA the Fabry-Perot resonances shift by approximately 0.5 nm, as indicated in the laser amplifier spontaneous emission spectrum shown in Figure 3.8. As a consequence, as the bias current sweeps over this range, the wavelengths corresponding to resonant gain minima shift to lie at gain maxima. Therefore, due to shifts in the resonant gain spectrum, the bias current and original gain variation do not exhibit any simple relationship. This factor again necessitates the use of a feedback control system, as used in this project, in order to achieve gain or output power stabilization.

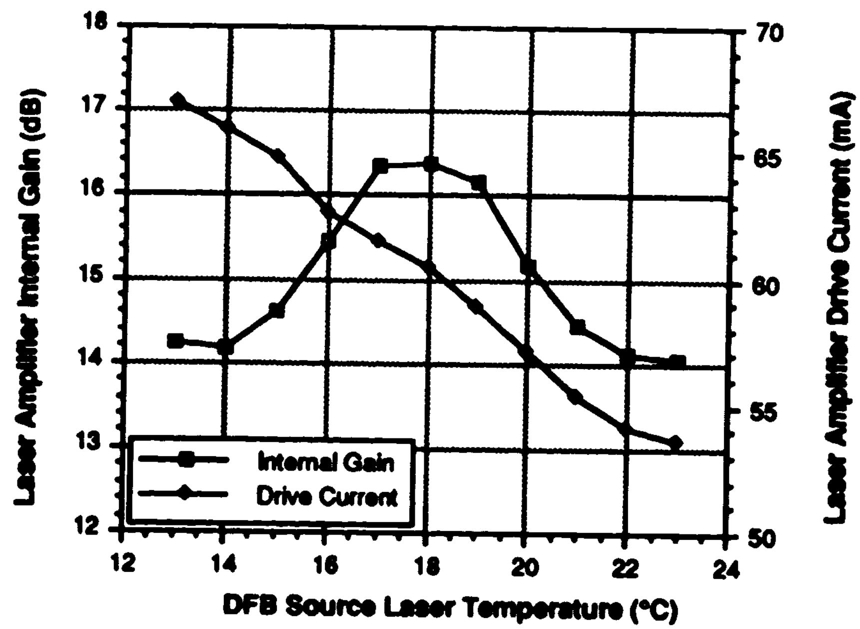

Figure 5.10 Wavelength Dependence of Laser Amplifier Drive Current

5.2.1.4 Input Power Sensitivity

The output power stabilization which is achieved as the input signal power varies is shown in Figure 5.11. This plot indicates the variation in output signal power which occurs as the source laser modulation signal amplitude is swept over a 7 dB range by varying the amplitude of the 10 MHz sinusoid generated by the network analyzer. The uncontrolled amplifier maintains a constant value of gain, producing a linear relationship between the applied signal power and the laser amplifier output power. However, with the control circuit in place, the output power is stabilized to within 0.1 dB.

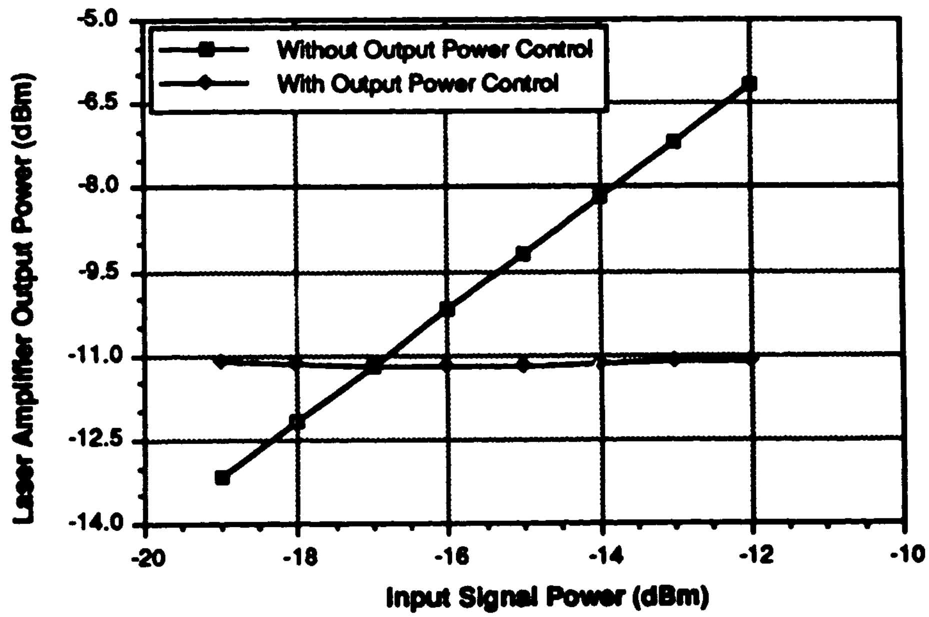

Figure 5.11 Input Power Sensitivity of Output Power

The plot demonstrates the ability of the control circuit to stabilize the output power of the laser amplifier, and indicates the applicability the output power control system may have to optical preamplifiers. Using the control system, the power incident on a receiver photodetector may be held constant, independent of variations in input signal power. This mode of operation represents an alternative to a gain controlled APD optical receiver. The gain of the laser amplifier may be regulated in order to stabilize the electrical signal power at the output of the photodetector, analogous to gain controlled APD receivers. However, the laser amplifier receiver avoids the gain bandwidth product limitations present in avalanche photodiodes, producing higher speed receiver modules.

The variation of laser amplifier bias current as a function of the applied signal power is shown in Figure 5.12, where the uncontrolled laser amplifier output signal power has been included for comparison. The curves indicate that the bias current and output power curves are not inverse functions, as a result of shifts in the Fabry-Perot resonance spectrum. In addition, the exponential relationship between laser amplifier gain and applied bias current begins to break down at high bias currents, as a consequence of the nonlinear recombination model introduced earlier. Therefore, the two curves in Figure 5.12 deviate from true inverses by a larger proportion at high bias currents, indicating the need for a closed loop feedback control system as opposed to a simple open loop system.

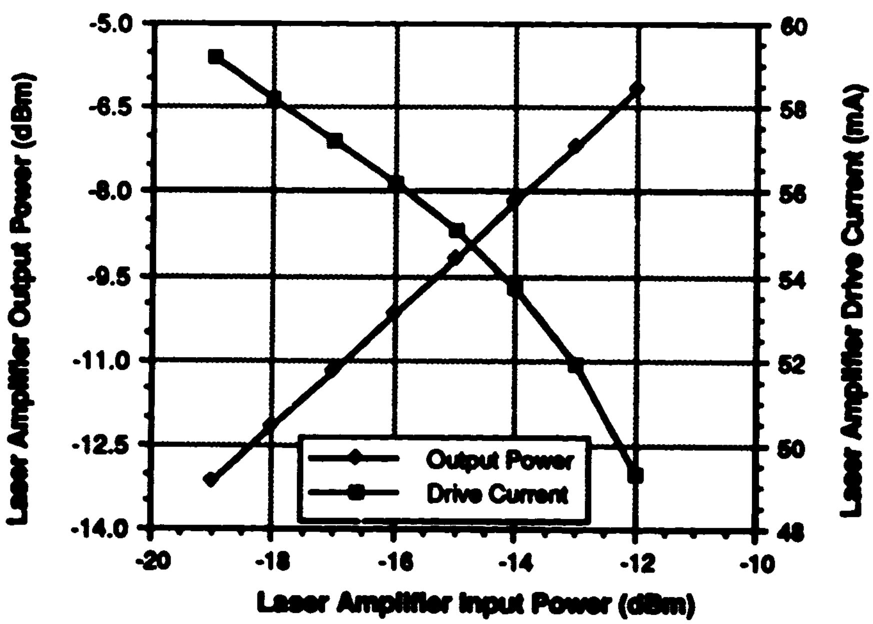

Figure 5.12 Input Power Dependence of Laser Amplifier Drive Current

5.2.1.5 Overall Laser Amplifier Stabilization

This section has demonstrated the reduction in laser amplifier gain and output power sensitivity which may be achieved through the use of a closed loop feedback control circuit. As noted above, some form of feedback control is required in order to obtain accurate stabilization as a result of second order effects which exist between laser amplifier drive current and the optical gain of the device. The control system introduced in Chapter 4 is capable of stabilizing the gain or output power of a semiconductor laser amplifier to within 0.1 dB of the desired value, independent of the mechanism responsible for the original variation. As a result, the control system fulfills the third design specification introduced earlier, namely accurate control of laser amplifier gain or output power. The final design criteria, in particular the ability of the control system to compensate for high speed variations in gain or output power, is considered in the next section.

One observation must be noted in regards to the accurate stabilization provided by the gain control system. If either the input or output gain control circuit signal paths have a time varying gain as a result of fluctuations in internal system parameters, the stabilization provided by the control circuit may be degraded. As a consequence, the gain or output power of the laser amplifier may be allowed to fluctuate by more than the above specified bound of 0.1 dB. For example, if the input or output optical couplers have a polarization or wavelength sensitive coupling ratio, stabilization of the extracted laser amplifier gain or output pcwer may not result in a stable value of laser amplifier gain or transmitted signal power. In addition, if the gain of the electronic portion of the control circuit varies as the temperature of the system changes, or if the sensitivity of the optical receivers varies with changes in input signal wavelength, the open loop gain of the control circuit may vary. As a result, the laser amplifier gain or output power may again be allowed to fluctuate by more than 0.1 dB. In addition, the variations in control circuit gain may act to reduce the gain margin of the feedback control system. In the extreme case, the variations in gain may be sufficient to induce instabilities into the system.

Several methods may be used to reduce the fluctuations in laser amplifier gain or output power which are created by variations in control circuit gain. Polarization and wavelength insensitive optical couplers must be used in order to achieve control circuit stabilization against changes in optical coupling ratios. In the electronic portion of the system, temperature compensation circuitry is required to stabilize the gain of the control circuit. As a result, the laser amplifier stabilization provided by the control circuit is optimized. The overall level of control may then be as low as 0.1 dB, if the internal control circuit gain variations are reduced to this level.

5.2.3 Control System Response Speed

The results presented above indicate the accuracy with which the gain or output power of a laser amplifier may be stabilized through use of the feedback control system introduced in Chapter 4. However, this level of accuracy is achieved only if the control system is allowed to reach steady state conditions, given an initial fluctuation in laser amplifier gain or output power. The ability of the control system to reduce high speed gain or output power variations may be investigated by considering the response speed of the control system.

The response of the control system has been tested by configuring the control system to operate in an output power control mode, and by applying a amplitude modulated carrier to the laser amplifier input. Specifically, a 10 MHz carrier has been amplitude modulated by a 1 kHz square wave and used to intensity modulate the DFB source laser. The electrical modulation signal applied to the laser is shown in Figure 5.13.

The intensity modulated optical signal emitted from the DFB laser is applied to the input of the laser amplifier. The control system is configured in an output power control mode, so that it attempts to remove the 1 kHz amplitude modulation present on the 10 MHz carrier. The output of the laser amplifier then simply becomes a constant amplitude 10 MHz carrier, with the 1 kHz amplitude modulation removed.

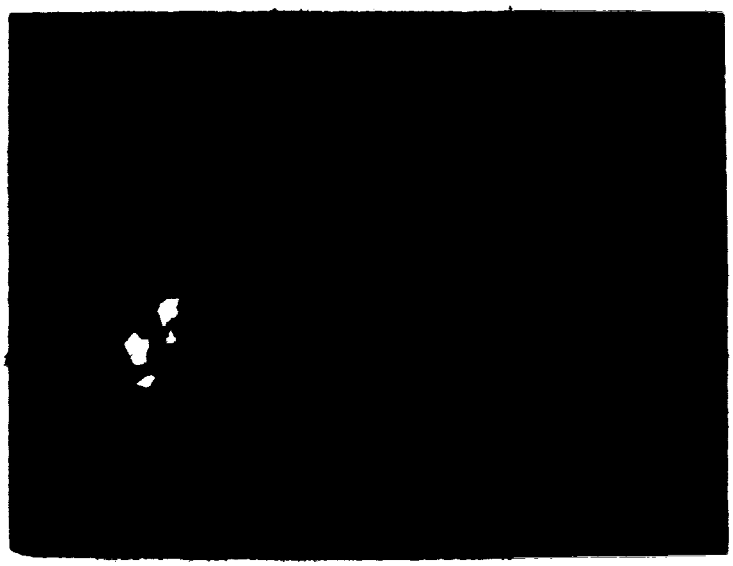

Figure 5.13 Control Circuit Response Time Test Input Signal

The response speed of the control circuit, and hence its ability to track high speed gain and output power variations, may be investigated by examining the AC portion of the laser amplifier drive current and the time required for this component to reach steady state conditions. The drive current is varied by the control system in order to a maintain constant output optical power, and is shown in Figure 5.14. This figure indicates the shape of the AC portion of the laser amplifier drive current for four different values of integrator resistor. Specifically, the resistance values are 2210 Ω, 3920 Ω, 10.0 kΩ, and 20.0 kΩ, for the outer through inner curves, respectively.

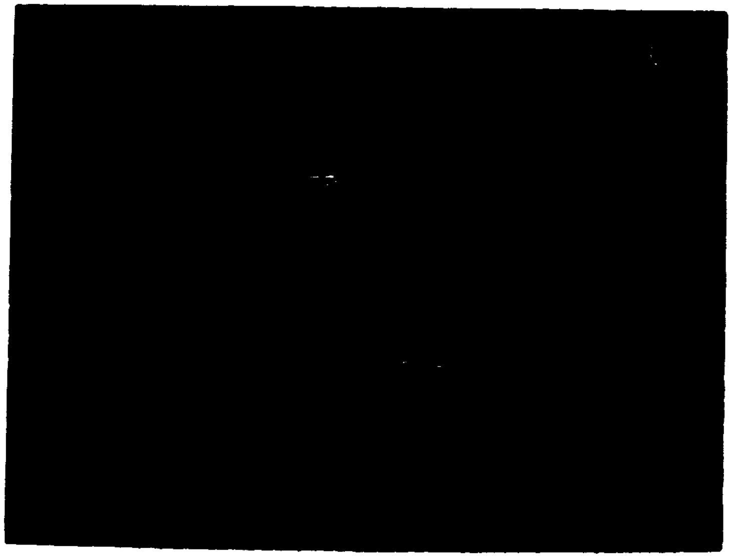

Figure 5.14 Laser Amplifier Drive Current Required to Maintain Constant Output Power

This diagram demonstrates that as the value of the integrator resistor is reduced, decreasing the time constant of the integrator, the response of the gain control circuit improves. In particular, as the integrator resistor is reduced, the control system reaches steady state conditions more quickly for a given input power variation. This indicates an enhanced ability to track high speed gain or output power fluctuations. This improvement in response speed is due to an increase in the open loop gain of the control circuit, which is in turn created by reductions in the integrator time constant. As a result, the closed loop bandwidth of the control system is increased.

The figure demonstrates that for an integrator resistor smaller than approximately 2 kΩ, the control system becomes unstable and breaks into oscillation. This instability may be removed by performing a closed loop analysis of the gain control circuit and inserting compensation circuitry which stabilizes the loop, ensuring stable operation at higher open loop gain. In this way the control loop will be able to track higher speed gain or output power variations. The plot also indicates that if the integrator resistor is less than approximately 4 kΩ, the control system very quickly reaches steady state conditions and is capable of significantly reducing gain or output power fluctuations which occur at up to 5 kHz. Using an integrator resistor of 2210 Ω it was found that the control circuit may compensate for gain and output power fluctuations occurring at up to approximately 6 kHz.

This discussion indicates that the control system is not only capable of reducing gain and output power fluctuations to less that 0.1 dB, but is able to achieve these results at speeds up to 6 kHz. Therefore, the control system meets the final design criterion, namely the ability to compensate for all anticipated high speed gain and output power fluctuations. Specifically, temperature induced variations will generally occur at speeds much less than 6 kHz, and the control system may easily reduce gain and output power fluctuations created by temperature variations. In addition, a significant portion of the random polarization changes occurring within a fiber optic system will be at speeds lower than 6 kHz, indicating that the control system will be capable of reducing gain and output power fluctuations induced by random polarization rotations as well.

5.3 Control Circuit Comparison

The control system constructed in this project meets all the original design specifications, namely bit rate insensitivity, operation over a wide dynamic range, high speed gain control, and accurate control of gain and output power, independent of the mechanism responsible for the original fluctuation. In particular, the system reduces variations in laser amplifier gain or output power which occur at up to 6 kHz to less than 0.1 dB. This level of control is achieved over a 20 dB optical signal power range, and operation of the control circuit proceeds independent of the transmission bit rate.

This section presents previously published attempts at laser amplifier control and compares the results obtained from these independent experiments to those achieved in this project. As a consequence two possible configurations of an optimum control system are proposed, indicating further research topics which may be pursued as a result of this work.

5.3.1 BTRL Output Power Control System

British Telecom Research Laboratories (BTRL) introduced the output power control system shown in Figure 5.15 at the 14^{th} European Conference on Optical Communications in September, 1988 [16]. Operation of this system is based upon variations in the laser amplifier junction potential.

The optical signal injected into the laser amplifier in this system is amplitude modulated at 10 kHz. As noted in Chapter 3, if an intensity modulated signal is injected into a laser amplifier, variations in the carrier density within the active region result. Therefore, in this case the carrier density is modulated at 10 kHz. It has been shown that variations in the active region carrier density produce fluctuations in the laser amplifier junction potential, because the junction voltage is a direct function of the carrier density within the active region [47]. It has also been shown that changes in the laser amplifier output signal optical power may be monitored by measuring changes in the product of the laser amplifier junction potential and the drive current applied to the amplifier [16]. The BTRL output power control system achieves output power stabilization by adjusting the laser amplifier bias current in order to ensure that this product remains constant.

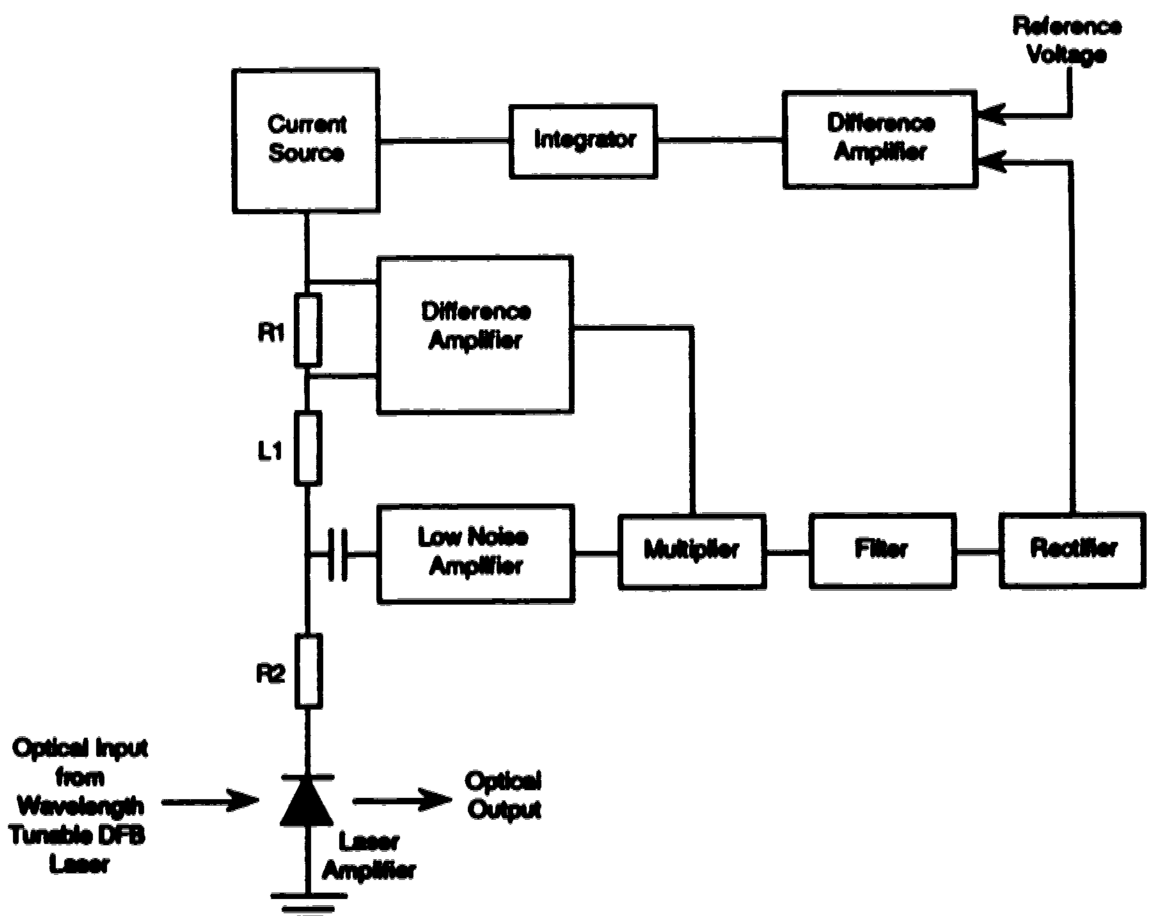

Figure 5.15 BTRL Gain Control Circuit

The results presented for this system indicate that variations in the output power of the laser amplifier are reduced from 2 dB for an uncontrolled laser amplifier to approximately 0.2 dB when the control system is employed. This performance is slightly poorer than the results obtained from the system implemented in this project. Both systems are bit rate insensitive and capable of high speed control. Overall, the two systems have similar properties, with the control system of this project having a slightly tighter bound on the laser amplifier output power. The main difference between the two systems is the ability of the system introduced in this work to perform laser amplifier gain control, along with the ease with which laser amplifier linearization, or equivalently interchannel crosstalk reduction, may be achieved. In particular, the system implemented in this project allows amplifier linearization to be performed very simply, with only slight modifications required in order to reduce interchannel crosstalk. The BTRL system, however, requires significant changes in order to achieve amplifier linearization. This fact will be demonstrated when the configurations of possible optimum control systems are proposed.

5.3.2 AT&T Laser Amplifier Linearization

A laser amplifier linearization scheme, introduced by AT&T, is shown in Figure 5.16 [37]. This system detects the combined intensity modulated laser amplifier input signal, and increases the laser amplifier drive current in phase with the amplifier input optical signal. In this way, the carrier density within the active region may be held constant. This ensures that the gain does not vary with the input signal modulation, and interchannel crosstalk is reduced as a consequence. Results have been presented which indicate that both saturation induced crosstalk and intermodulation distortion are reduced through use of this system [37, 39].

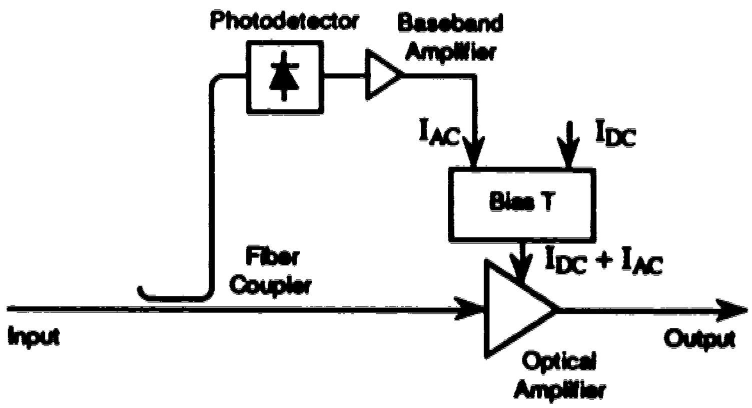

Figure 5.16 AT&T Laser Amplifier Linearization Scheme

A linearization scheme such as this one may be used in conjunction with the gain control system implemented in this project by installing a wideband input optical receiver into the system. This receiver must be capable of detecting the modulation present on the input optical stream. A parallel path within the control circuit would be created in order to generate the AC component of the laser amplifier drive current. This component ensures a constant active region carrier density and therefore constant laser amplifier gain. As a result, interchannel crosstalk could be reduced, while environmentally induced gain or output power variations could still be effectively eliminated.

5.3.3 Optimum Control System

This section proposes two possible implementations of an optimum control system aimed at achieving both gain or output power stabilization, as well as interchannel crosstalk reduction. Both of the proposed systems pave the way for installation of optical amplifiers into fiber optic systems.

The first configuration was briefly introduced above. The optimum system is constructed with a wideband optical receiver present in the input path of the control system constructed in this project. The receiver must be capable of detecting the intensity modulated laser amplifier input signal, and hence the form of the active region carrier density fluctuations. Carrier density variations within a laser amplifier may only occur at up to approximately 2 GHz, due to the finite lifetime of the carriers within the active region [37]. Therefore, the input optical receiver is only required to detect intensity modulated signals up to this frequency, which is easily achievable using present technology. One portion of the receiver output is passed through the input 25 MHz pre-detection low pass filter in order to drive the gain or output power stabilization circuitry. This feedback control path generates the lower speed portion of the laser amplifier drive current. As second component of the receiver output is passed through a feedforward wideband amplifier and produces the higher speed portion of the laser amplifier drive current, which is used to achieve amplifier linearization, as in the AT&T control system. As a result, the overall control system is capable of performing both of the desired functions.

This approach indicates the ease with which the linearization circuitry may be integrated into the control system implemented in this project. The two control mechanisms operate in parallel, generating both low and high speed amplifier drive current components, which are responsible for gain or output power stabilization and amplifier linearization, respectively. Integration of the linearization scheme into the BTRL gain control system, however, is not as simple, because the entire linearization circuitry must be installed independent of the output power control circuitry. The two operations are not as compatible when the BTRL control system is used.

The second optimum control circuit configuration is identical to the control system implemented in this project, with the laser amplifier current driver replaced by a wideband, low impedance voltage controlled voltage source. The voltage applied to the laser amplifier is varied by the control system in order to obtain the desired value of gain or output power. Use of a voltage source ensures that the laser amplifier junction potential remains constant, allowing the drive current to vary as required to maintain a constant potential. However, given a constant junction potential, the carrier density within the active region must be constant, thereby resulting in reduced interchannel crosstalk. Therefore, this system also performs both of the desired operations.

This method of control requires little modification to the control system already implemented in this project, and represents a new linearization approach which becomes feasible due to the introduction of the closed loop control system presented in this work. Testing of this optimum system represents one of the main areas of further research which may proceed as a consequence of the results presented here. In particular, an investigation into the feasibility of a laser amplifier voltage source driver, as well as the design difficulty involved are two areas which require further study. Although this method may present difficulties in implementation, in particular with the low impedance voltage source, this linearization scheme may provide greater end returns. This optimum control system is completely incompatible with the BTRL output power control system introduced earlier. The BTRL control circuit relies on the ability to detect changes in the laser amplifier junction potential. However, introduction of a laser amplifier voltage driver aimed at reducing interchannel crosstalk results in a constant junction potential which does not contain a time varying component. As a result, the BTRL control scheme cannot be applied with this method of laser amplifier linearization.

6. SUMMARY

This chapter discusses some of the possible applications of the control circuit to fiber optic systems. Specifically, the applications considered include bit rate insensitive stabilization of fiber optic repeaters, receiver preamplifier output power control, active fiber amplifier control, and fiber optic system performance monitoring. This chapter also summarizes the performance that has been obtained from the control system, and indicates some of the directions along which further research may proceed.

6.1 AGC Circuit Applications

This section is devoted to presenting some of the possible fiber optic system applications of optical amplifiers which become possible through the use of the control system introduced in this work. The applications presented here indicate only a sampling of the possible control functions that the gain control circuit may be used to perform.

6.1.1 Bit Rate Insensitive Fiber Optic Repeater

The control system may be employed in a gain control mode in order to stabilize the gain of a semiconductor laser amplifier, allowing the amplifier to be installed as a constant gain block within a fiber optic communication system. Alternatively, the control system may be configured to maintain a constant optical output power, using the laser amplifier as a gain block which ensures that the optical signal level at specified points within the fiber optic system remains at the desired level. As the laser amplifier and the associated control system are both bit rate insensitive components, the combined system exhibits bit rate insensitivity and may be installed as a stable repeater in a communication link operating at an arbitrary transmission rate. System upgrades to higher and higher transmission speeds are transparent to the laser amplifier and control circuit pair. As a result, the amount of system equipment which must be replaced when the transmission rate is increased is minimized. This is particularly advantageous in submarine links where replacement of amplifier modules is a very costly venture. Presently used regenerative repeaters are not bit rate insensitive and do not offer this degree of flexibility. This attribute represents one of the main advantages of a controlled laser amplifier over present day regenerative repeaters.

The wide dynamic operating range of the laser amplifier control system permits a controlled laser amplifier repeater to be placed at almost any point within a fiber optic link, while maintaining a stable gain or output power. This allows the repeater block to be placed at the required point within the system in order to achieve optimum response in terms of signal to noise ratio and bit error rate. If required, the control system logarithmic amplifiers and receiver preamplifiers may be modified to extend the dynamic operating range even further, or alternatively to shift the bounds on the allowable optical power levels required for correct operation. In this way, it is possible to achieve optimum response in any optical system.

A controlled laser amplifier repeater block provides one other advantage when compared to presently used regenerative repeaters, namely the ability to directly amplify the input optical signal in all types of fiber optic systems, both incoherent and coherent. In particular, a laser amplifier repeater operates correctly whether it is used in intensity modulated systems, subcarrier multiplexed systems, or frequency or wavelength division multiplexed systems. This ability reflects the general nature of optical amplifiers, and demonstrates the applicability of optical amplifiers to future fiber optic systems. The wide bandwidth and bit rate insensitivity of a laser amplifier allow it to amplify several input channels simultaneously, an operation which is not achievable using regenerative repeaters. However, this ability will be required in future fiber optic systems. The control system simply stabilizes the gain or output power of the amplifier by detecting the intensity modulated portion of the combined input stream. For systems which do not contain an intensity modulated component within the passband of the control system, a pilot tone inserted at the input of the fiber optic system may be used to ensure controlled operation of the laser amplifier repeater in all fiber optic system types.

6.1.2 Optical Receiver Preamplifier

The laser amplifier control system may be configured in the output power control mode in order to stabilize the signal power focused onto the photodetector in an optical preamplifier/PIN diode receiver. This type of system becomes more attractive at high bit rates where APD receivers become increasingly difficult to build due to the fundamental gain bandwidth product limit of APDs. In contrast to APD receivers, an optical preamplifier and PIN diode photodetector separates the gain and photodetection portions of the receiver. The gain is achieved using the laser amplifier, while a wideband PIN diode may be used to detect the input intensity modulated signal, resulting in an overall increase in detection bandwidth. The control system is employed to stabilize the electrical signal amplitude present at the output of the PIN diode, in turn simplifying the design of the signal detection and processing circuitry. The configuration of a system of this type is shown in Figure 6.1. This system is analogous to a gain controlled APD receiver where feedback control is used to stabilize the signal level at the output of the APD. In the APD receiver the gain of the APD is controlled by varying the reverse bias voltage applied to the diode. However, as indicated above, an optical preamplifier and PIN diode receiver are able to achieve a wider bandwidth than an APD receiver, becoming more and more attractive as communication systems move to higher bit rates.

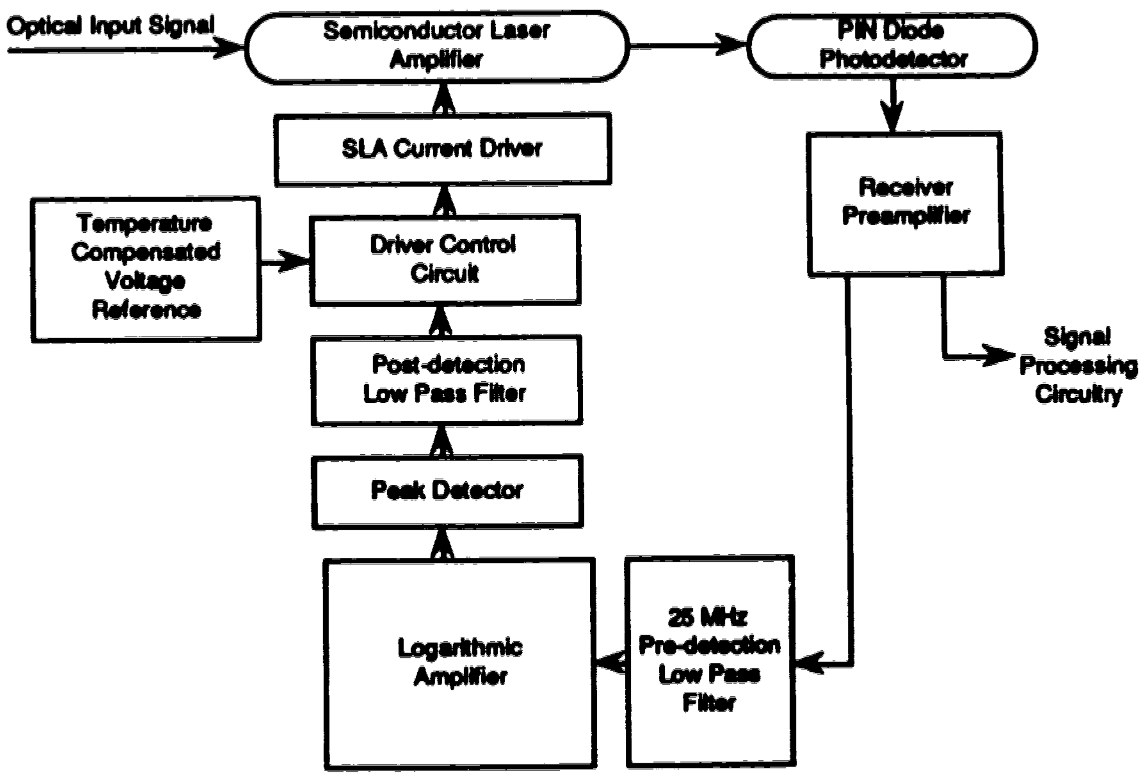

Figure 6.1 Receiver Preamplifier Output Power Control Configuration

The purpose of optical preamplifiers is to increase the overall sensitivity of optical receivers, particularly at high bit rates. Although the laser amplifier used in this experiment has very poor noise characteristics, the ability of this device to improve receiver sensitivity demonstrates the sensitivity improvement which can be realized by using optical preamplifiers. In order to achieve a 15.6 dB signal to noise ratio in a 7 GHz noise bandwidth, corresponding to 10^{-9} bit error rate in a 10 Gbit/s digital communication system [17], an input signal power of

-26.5 dBm and -23.8 dBm is required, with and without a 0.5 nm commercially available optical filter, respectively. For a PIN diode receiver under the same conditions, the base sensitivity without an optical preamplifier is -19.6 dBm. This result indicates the substantial sensitivity increase which may be achieved through use of an optical preamplifier. Appendix C contains the details of the noise calculations which have been performed to obtain the above results.

6.1.3 Active Fiber Amplifier Control

The gain control system implemented in this project to control semiconductor laser amplifiers may also be used to stabilize the gain or output power of an active fiber amplifier, using the configuration shown in Figure 6.2. The control system functionality does not change when an active fiber amplifier is employed in place of a semiconductor laser amplifier. The only difference between the two systems is the method that is used to vary the gain of the optical amplifier. When an active fiber amplifier is employed, gain or output power control is achieved by modifying the bias current applied to the copropagating fiber amplifier pump laser. The pump laser output is coupled into the fiber amplifier through the input WDM coupler, in this way controlling the optical gain of the amplifier. The output fiber coupler is also a WDM coupler, acting as an optical filter. This coupler reduces the amount of pump power which is transmitted down the output fiber to the remainder of the system.

Active fiber amplifiers are particularly well suited for use in receiver preamplifier applications, because of their low noise figure. In particular, active fiber amplifiers have been reported with noise figures as low as 3.2 dB [48], much lower than has been achieved using semiconductor laser amplifiers. The configuration above employs a copropagating pump, generating the highest gain at the input of the fiber amplifier. This tends to maximize the noise performance of the amplifier. Thus, a system similar to the one shown in Figure 6.1 may be used to stabilize the output power focused onto a receiver photodiode, when a fiber amplifier is used as an optical preamplifier. The result is a high speed receiver with excellent noise performance and increased sensitivity.

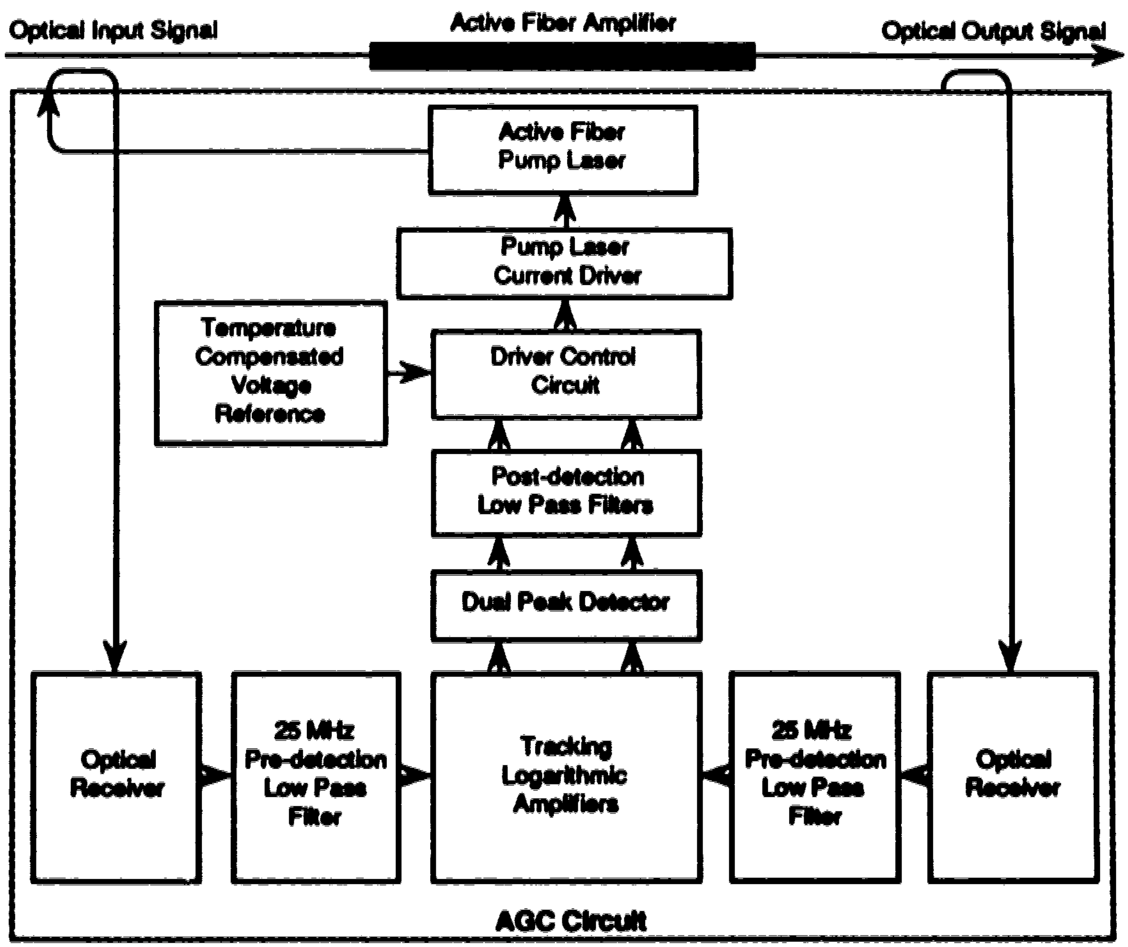

Figure 6.2 Active Fiber Amplifier Control System

6.1.4 Performance Monitoring System

When the control system is used to stabilize the gain or output power of a laser amplifier repeater, it may also be used as a remote node in part of an overall performance monitoring system. The monitoring system oversees the operation of the link, with the control system transmitting a specified optical signal down the link in the event of a span failure. Span breaks may be quickly detected at the receiving end of the link by searching for this key signal, allowing traffic rerouting and span repair to begin. The modifications which must be applied to the control system to permit system monitoring are shown in Figure 6.3.

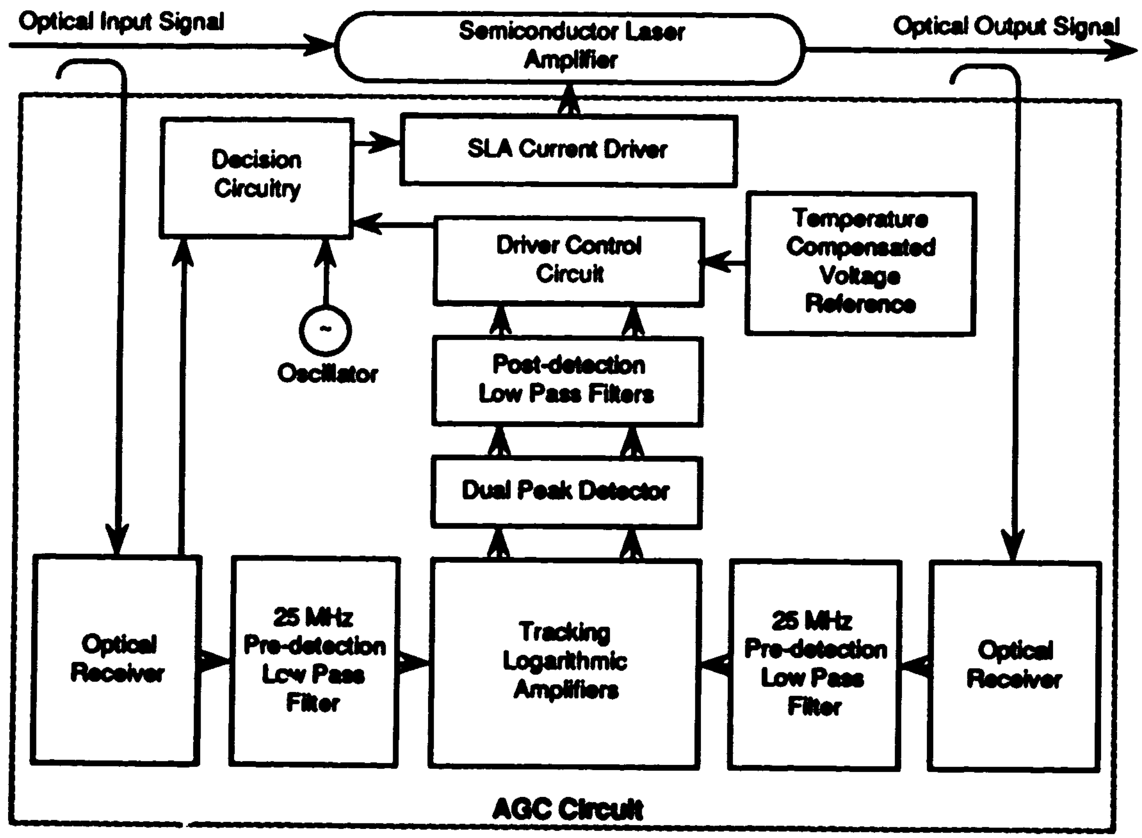

Figure 6.3 Control Circuit Configuration in Performance Monitoring System

The modifications in the control system allow the laser amplifier to function in one of two distinct modes depending on the presence or absence of an input optical signal. If an input signal with a magnitude greater than the preselected threshold is present at the laser amplifier input, the decision circuitry becomes transparent and does not affect the operation of the control loop. The laser amplifier stabilization circuitry functions normally, ensuring that the gain or output power of the amplifier is held constant. However, if the input optical signal level drops below the preassigned threshold, possibly due to a failure somewhere within the input span, the decision circuitry breaks the feedback loop of the control system. In this case, the laser amplifier is driven by a current waveform which has an AC component at a selected frequency. The output from the laser amplifier is then wideband spontaneous emission, intensity modulated at the chosen frequency. This frequency is different for each repeater within the link, and lies within the passband of the control circuitry. At the receiver, detection of a tone at a particular frequency, in place of the expected data stream, indicates not only a failure within the link but also allows the performance monitoring system to determine which span has failed. An example of this type of monitoring system is shown in Figure 6.4.

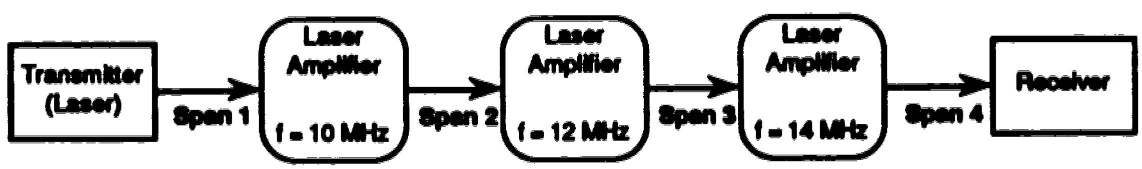

Figure 6.4 Performance Monitoring System

In this system, if span 1 fails for some reason, the first laser amplifier within the link will detect a loss of input signal and will produce an output optical signal which is intensity modulated at 10 MHz. The other laser amplifiers in the link simply detect this signal, as it lies within the passband of the control system, and function in a normal gain or output power control mode. At the receiver, a 10 MHz tone is detected in place of the expected data stream, indicating to the monitor system that a failure has occurred within span 1. Operation of the system is identical for failures within spans 2 and 3. However, if a failure occurs within span 4, no signal will be detected by the optical receiver, indicating a failure within the final span.

A supervisory system of this type has been investigated by BTRL in conjunction with their control system [49]. However, neither that system nor the one presented here is capable of detecting multiple span failures. For example, if spans 1 and 3 fail, the receiver will observe a 14 MHz tone indicating a failure somewhere within span 3. The 10 MHz tone generated by the first laser amplifier to indicate a failure within span 1 is lost due to the failure in the third span. As a result, span 3 must be repaired before the failure in the first span can be detected. One method which may be used to combat this problem is to install a parallel overhead processing system which connects each remote laser amplifier node to a centralized performance monitoring system. The remote nodes simply send a failure signal over the processing link to the central node, thereby indicating span failures and allowing detection of multiple span failures.

6.2 Conclusions

This work has presented the design details and performance specifications of an automatic gain control circuit which is capable of stabilizing the gain or output power of a semiconductor laser amplifier. Specifically, the control circuit which has been introduced is able to reduce environmentally induced fluctuations in laser amplifier gain or output power to less than 0.1 dB. Use of this system allows laser amplifiers to be employed as stable gain elements in fiber optic communication systems.

In order to demonstrate the motivation behind the control system, the theory of semiconductor laser amplifiers has been investigated. The results that were presented indicated that the optical gain of a laser amplifier is sensitive to the bias current of the amplifier, as well as several environmental parameters. The high sensitivity exhibited towards the drive current of the device demonstrates that tight bounds must be placed on amplifier bias in order to maintain a constant optical gain. However, gain fluctuations induced by effects such as device aging and variations in environmental parameters disallow open loop control of the amplifier bias. The drive current must be modified to obtain accurate control of the device gain or output power as opposed to simply generating a stable value of drive current. This implies that some form of closed loop feedback control system is required in order to stabilize the gain or output power of a laser amplifier, where the laser amplifier is contained within the control loop. A system of this type has been introduced in this work, and results have been presented which indicate that this system is able to ensure gain or output power stabilization independent of the environmental mechanism which is responsible for the original gain or output power variation.

The first environmental parameter to be considered was the polarization of the input signal applied to the laser amplifier. The sensitivity of laser amplifier gain towards polarization is induced as optical mode confinement factors within the laser amplifier are different for the two orthogonal polarizations. In addition, the residual facet reflectivities differ for TE and TM modes. As a result, laser amplifier gain varies with changes in the input signal polarization, as does the amplitude of the Fabry-Perot cavity resonances which are present in the gain profile.

The second environmental parameter which was investigated because of the effect it has on laser amplifier gain was the temperature of the amplifier. The temperature sensitivity of laser amplifier gain is produced by changes in the material gain coefficient with temperature. These changes are induced by changes in the carrier density required to achieve an amplifier gain of unity, as well as changes in the gain coefficient which converts carrier density to material gain. As a consequence, the gain of a laser amplifier exhibits a complex dependence on temperature.

Finally, laser amplifier sensitivity with respect to the wavelength of the input signal has been considered. On a broad wavelength scale this sensitivity is induced by the parabolic wavelength profile of the material gain coefficient, degrading the optical gain of the amplifier about the peak gain wavelength. On a finer scale, however, the gain of the laser amplifier traverses Fabry-Perot resonances created as a result of nonzero residual facet reflectivities. Hence, the gain of a laser amplifier varies with input signal wavelength, on both a coarse and a fine wavelength scale.

The sensitivity of laser amplifier gain to the above environmental parameters has been demonstrated. For the device tested in this project a polarization sensitivity of 5 dB was found to exist, along with a temperature sensitivity of 2 dB, and a wavelength sensitivity of 2 dB. Although the magnitude of these gain fluctuations varies from one laser amplifier to another, the gain of all laser amplifiers is affected by these parameters to some degree. It is for this reason that a control circuit was constructed, one that corrects for gain or output power fluctuations induced by changes in these parameters, or by swings in the laser amplifier input power.

The control system which was constructed has been outlined in Chapter 4. As indicated earlier, this system is capable of stabilizing both the gain and output power of a laser amplifier to within 0.1 dB of the desired value, independent of the parameter which caused the original gain variation. This accurate control is achieved through use of a closed loop integral type feedback control system. The control system compensates for gain and output power fluctuations occurring at up to 6 kHz, and achieves stabilization independent of the optical system transmission bit rate. In addition, control is obtained over an input optical signal range from -20 dBm to -40 dBm. This wide dynamic range is ensured through use of tracking logarithmic video amplifiers within the control loop, which compress the dynamic range of the electrical signals within the loop, thereby allowing gain or output power control over a wide dynamic range.

The configuration of two optimum control systems have also been proposed, indicating possible control system layouts which are capable of achieving both laser amplifier gain or output power stabilization, as well as laser amplifier linearization aimed at reducing interchannel crosstalk. Several practical applications of the control system have been introduced, indicating the wide range of possible uses of a controlled optical amplifier in fiber optic communication systems. The control system introduced in this project helps to make optical amplifiers technologically viable components which may be employed in fiber optic systems. Laser amplifiers are no longer restricted to operating in controlled environments in research laboratories.

6.3 Recommendations for Further Research

As a consequence of the work performed in this project, several new research topics have become available. One of the most obvious research thrusts would be aimed at implementing the optimum control systems presented earlier. A project in this area would involve construction and testing of a combined laser amplifier gain and linearization control scheme. Although the linearization method introduced by AT&T has been shown to achieve laser amplifier linearization, the use of a laser amplifier voltage driver which maintains a constant amplifier junction potential offers possibly greater returns.

One research project may be a study focusing on the feasibility of a wideband voltage source which has an impedance low enough to ensure that the laser amplifier junction potential does not vary. This may be followed by a project centering on the implementation and testing of a voltage source design aimed at fulfilling this goal, and hence construction of one of the optimum control systems.

A second avenue of research involves testing the control system in the fiber optic system applications introduced above. For example, the ability of the control circuit to stabilize the gain or output power of active fiber amplifiers may be investigated. Alternative configurations could be tested not only to ensure that the control system is capable of regulating fiber amplifiers with the same degree of accuracy as has been obtained for semiconductor laser amplifiers, but also to determine an optimum control system configuration. In addition, use of the control system in receiver preamplifier applications may be investigated. A rigorous theoretical analysis of an optical preamplifier and PIN diode receiver system, including a thorough noise analysis, may prove interesting. In particular, a comparison between this type of receiver and APD receivers, especially at speeds approaching 10 Gbits/s, may be undertaken.

Link testing of the performance monitoring system presented above indicates another possible area of research. Alternative system configurations could be tested, in terms of their ability to detect and monitor single or multiple span failures. In addition, optimum placement of the amplifiers within the system could be investigated, as well as the best choice of error detection oscillation frequencies.

Another possible area of research may center around optimization of the circuit blocks contained within the control system for monolithic integration. The outcome of this exercise would be the development of an application specific integrated circuit (ASIC) laser amplifier control chip. The complete gain or output power control function would then be implemented on a single integrated circuit chip. The feasibility of integrating the control circuit and laser amplifier on the same substrate may also be investigated. This could result in reducing the size of a fiber optic repeater to a single integrated circuit chip.

These research topics present a sampling of the possible projects which become viable as a result of this work. The range of applications of optical amplifiers, combined with the control system implemented in this project, are limited only by the imagination of the fiber optic system designer. This work not only allows the range of projects introduced above to proceed, but also helps to make optical amplifiers economically and technically viable components for general use in fiber optic communication systems.

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APPENDIX A

BT&D Semiconductor Laser Amplifier

Specification Sheet

T E C H N O L O G I E S

SOA1100 / SOA3100
SEMICONDUCTOR OPTICAL AMPLIFIER

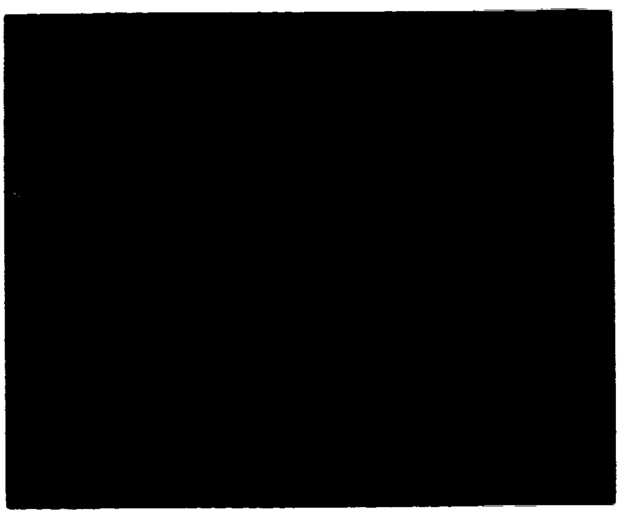
Features

- 1300 or 1550 nanometer Bands
- Direct amplification of the optical signal - no need to convert to the electrical domain
- 10 dB minimium TE mode gain
- 40 nanometer bandwidth
- Bi-directional - amplifies in either direction
- Compact package
- Low power consumption

Applications

Research and Development of:

- Fiber optic telecommunication systems
- Advanced local area and metropolitan area networks
- Instrumentation
- Military communications and control systems
- Advanced sensor systems



SOA3100

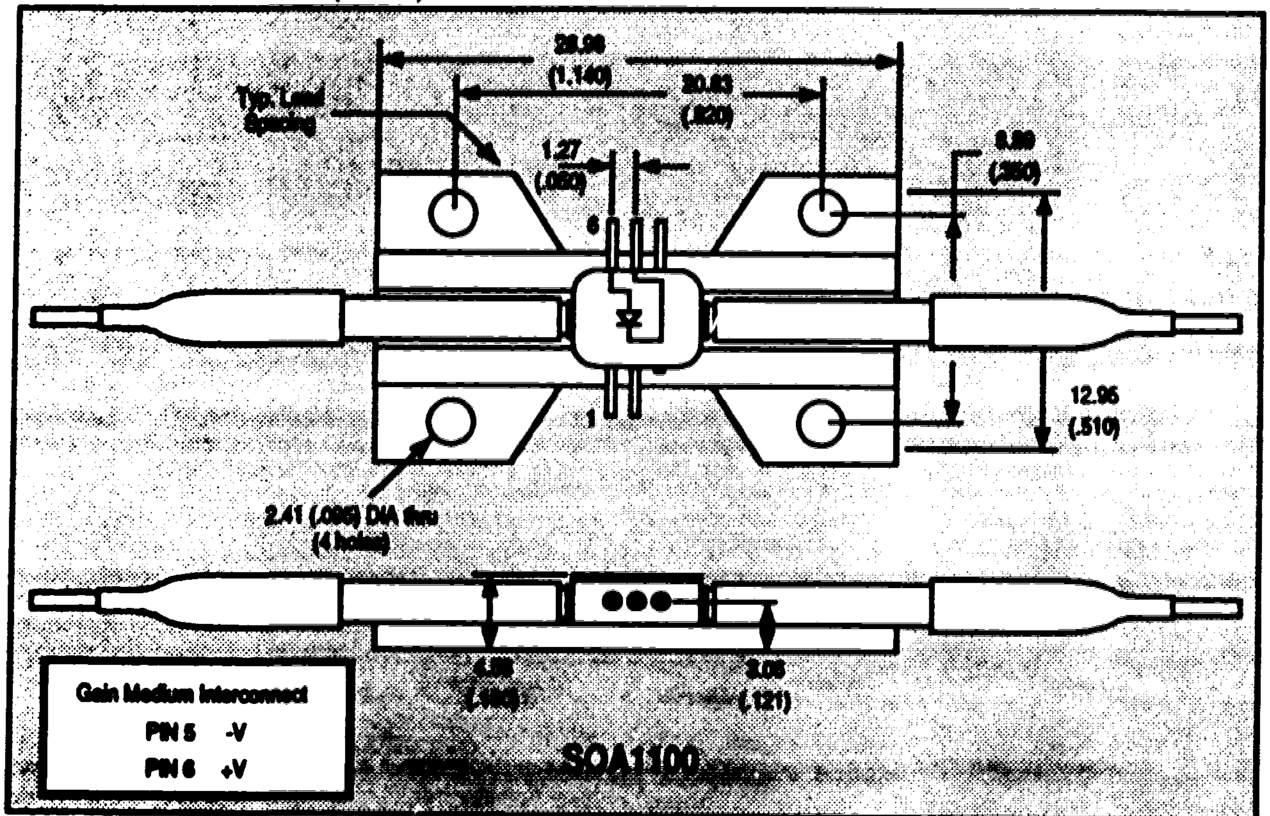
Description

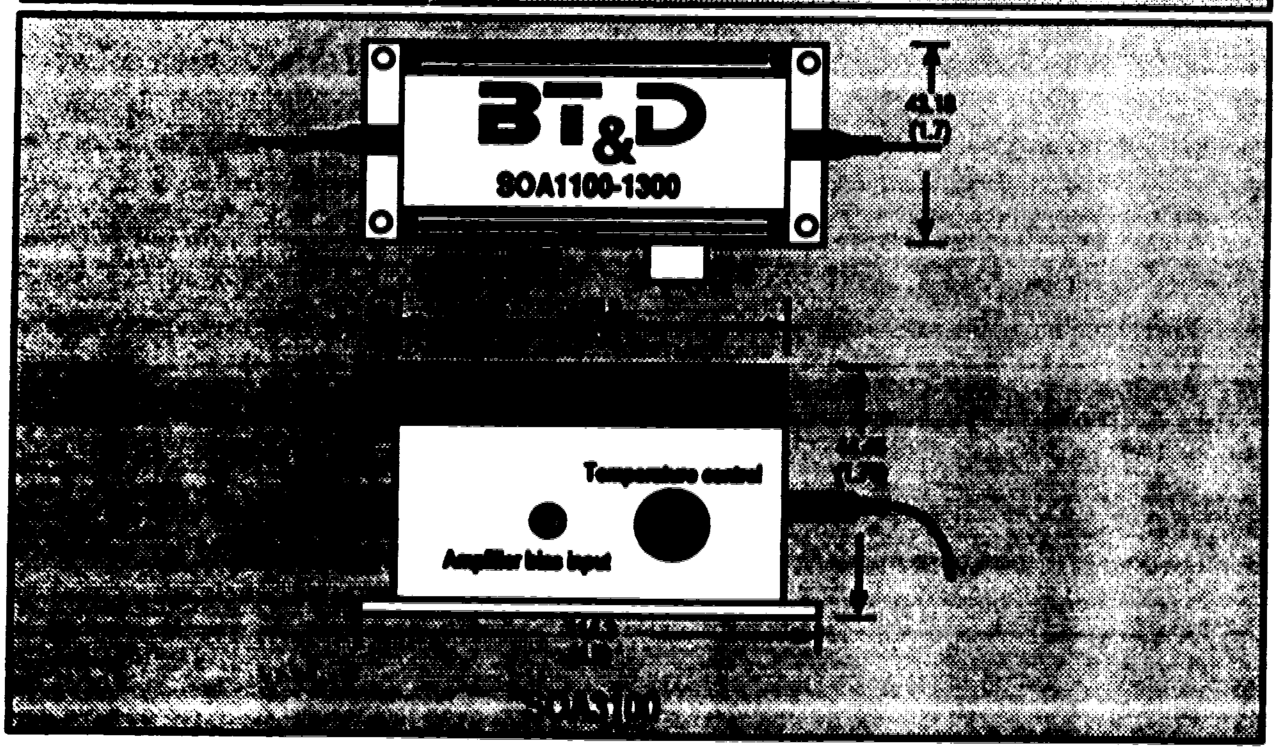
The SOA1100/3100 family of semiconductor optical amplifiers consist of an optical gain medium manufactured by BT&D's MOVPE (metal organic vapor phase epitaxy) process. The gain medium is anti-reflection coated at each end and coupled to single mode fiber. The SOA1100 is packaged in a sealed, miniature module.

Two single mode fiber pigtails allow easy connection to other fiber optic components. The SOA3100 consists of the SOA1100 mounted in a module containing a thermoelectric cooler, electrical connectors and heat sink.

Package Dimensions

dimensions in millimeters (inches)





SPECIFICATIONS

ABSOLUTE MAXIMUM RATINGS

PARAMETER	MIN	TYP	MAX	UNITS
Gain Medium Reverse Voltage	—	—	0.5	V
Gain Medium Forward Current	—	—	100	mA
Operating Temperature (in free air)	10	20	30	°C
Storage Temperature	-40	—	60	°C
Fiber Pull Strength	—	—	10	N
Relative Humidity	0	—	non - condensing	
Mechanical Vibration and Shock	The SOA1100/3100 family have not been characterized for vibration and shock at the time this specification was printed. Contact BT&D for specific recommendations before using this component in demanding applications.			

PERFORMANCE SPECIFICATIONS [1]

Optical

PARAMETER	MIN	TYP	MAX	UNITS
Peak Gain (TE mode, Polarization Dependent)	10	12	—	dB
Center Wavelength, λ_o (SOA1100/3100-1300)	1270	1290	1300	nm
(SOA1100/3100-1550)	1490	1535	1580	nm
Optical Bandwidth [2]	30	50	—	nm
Input Fiber Power for 3 dB Gain Compression	—	-20	—	dBm
Difference between peak of TM Gain Envelope and Peak of TE Envelope	—	5	—	dB
Fiber to Fiber Loss with Zero Drive Current	19	25	31	dB

Notes:

1 All measurements (except Peak Gain) are made at 20 C and at a 3dB residual reflection ripple measured at λ_o.

2 Measured at mean TE gain less 3 dB.

SPECIFICATIONS (cont'd.)

Electrical

PARAMETER	MIN	TYP	MAX	UNITS
Operating Current [3]	—	100	—	mA
Forward Voltage at 50 mA Operating Current	—	1.2	—	V
Amplifier Switch-on Time (10-90%) from 0 to I th -20mA	—	—	10	ns
Amplifier Switch-off Time (90-10%) from I th -20mA to 0	—	—	10	ns
Optical Power at I th - 20 mA (no optical input)	—	25	—	microwatts
Temp. Coeff. of Thres. Current, -20°C to +65°C	—	2.5	—	%/ °C
Differential Resistance	—	10	—	Ω (dv/di)

Fiber Pigtails

PARAMETER	MIN	TYP	MAX	UNITS
Type	Corning SMF 21 with CSB4 UV acrylate buffer and NX912 nylon jacket.			—
Length	1	1.5	—	m
Mode Field Diameter	9.0	10.0	11.0	µm
Cladding Diameter	122	125	128	µm
Core Cladding Concentricity	—	—	1.0	µm
Secondary Jacket Diameter	850	900	950	µm
Effective Cutoff Wavelength (1m straight)	1150	—	1200	nm

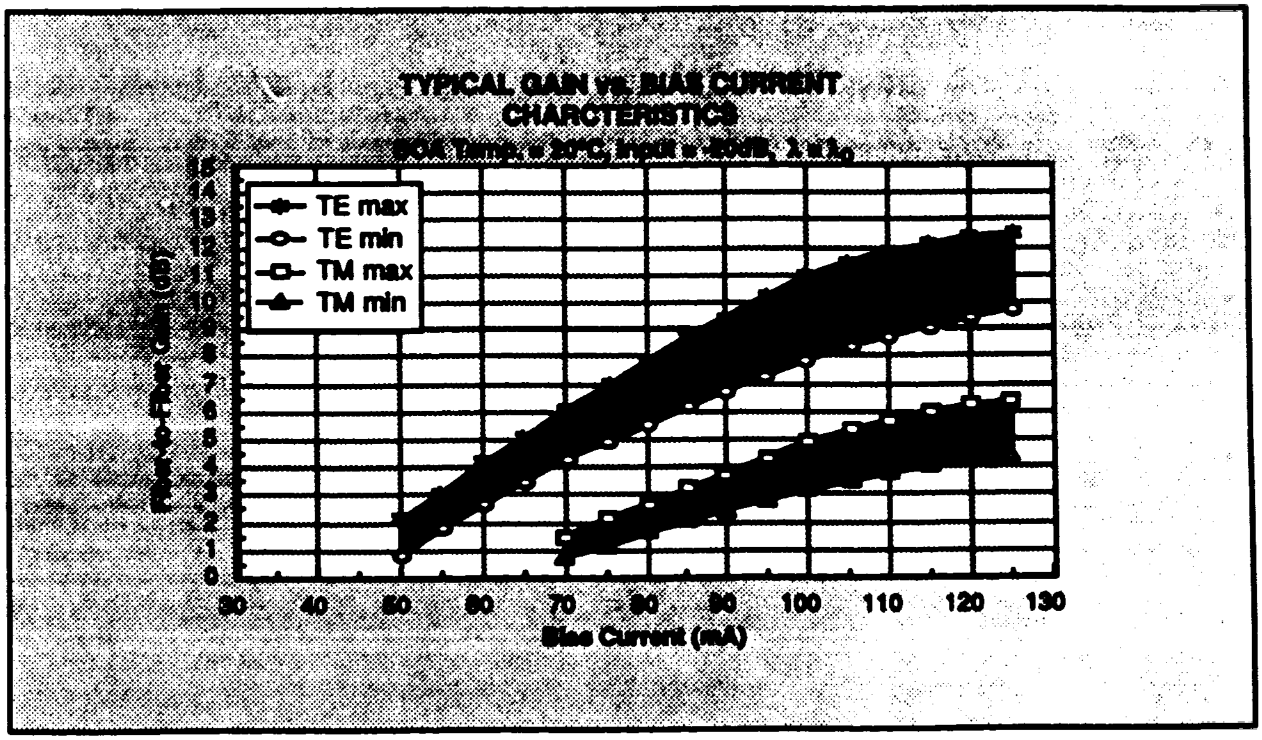
General

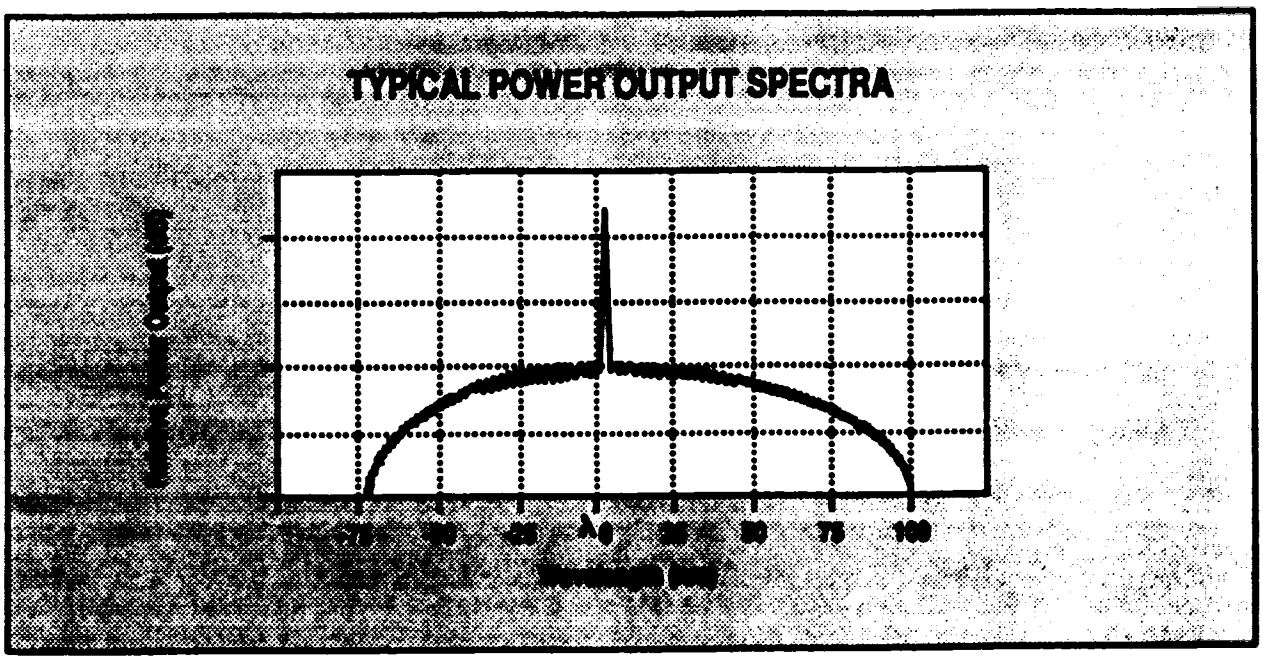
Reliability	The SOA1100/3100 family is constructed of reliable components, including BT&D's MOVPE grown laser chip which is the basis for the gain medium. However, the complete unit has not been tested for reliability at the time of printing of this data sheet. The user should check with BT&D for the latest test data before deploying the part where high reliability performance is paramount.

Notes:

[3] These devices are always operated below threshold.

[4] Further information on specific characteristics may be found in the SOA1100 Application Notes. Contact your BT&D representative for details.


TYPICAL GAIN vs. BIAS CURRENT
CHARCTERISTICS
TE max
TE min
TM max
TM min
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
30
40
50
60
70
80
90
100
110
120
130
Bias Current (mA)


TYPICAL POWER OUTPUT SPECTRA
-75
-50
-25
λ_0
25
50
75
100

ORDERING INFORMATION

Please order part number:

SOA1100-1300 or SOA3100-1300 for operation in the 1300 nanometer band
SOA1100-1550 or SOA3100-1550 for operation in the 1550 nanometer band

---

HANDLING PRECAUTIONS

Normal handling precautions for electrostatic-sensitive devices should be taken

Invisible LASER Radiation -
Avoid direct exposure to beam

Peak power	10 mW
Wavelength	1300 nm

Class III b LASER Product

Invisible LASER Radiation -
Avoid direct exposure to beam

Peak power	10 mW
Wavelength	1550 nm

Class III b LASER Product

To place an order or to obtain more information, contact:

U.S.A.
BT&D Technologies
Delaware Corporate Center II
Suite 200
2 Righter Parkway
Wilmington, DE 19803
Tel: (800) 545-4306 USA only
(302) 479-6300
Fax: (302) 479-6560

Japan
BT&D Technologies
DuPont Japan Technical Center
4997 Shin-Yoshida-Cho
Kohoku-ku, Yokohama-shi
Kanagawa 223, Japan
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Ipswich
IP1 5PB
England
Tel: UK 0473 42250
Int: +44 473 42250
Fax: +44 473 241110

APPENDIX B

Semiconductor Laser Amplifier
Gain Modelling Program

```
/**********************************************************************/
/*                                                                    */
/*                  Laser Amplifier Modelling Program                 */
/*                                                                    */
/**********************************************************************/
/* File    : SLAMODEL.C                                               */
/* By      : R.A. Morris, B.Sc.                                       */
/* Version : 1.00                                                     */
/* Date    : May 3, 1990                                              */
/*--------------------------------------------------------------------*/
/*   This program models the gain characteristics of a                */
/* semiconductor laser amplifier, including dependence on carrier     */
/* density, wavelength, temperature, and residual facet               */
/* reflectivities.                                                    */
/**********************************************************************/

/**************************/
/* Include Library Files */
/**************************/

#include    <math.h>
#include    <stdio.h>

/***********************/
/* Physical Constants */
/***********************/

#define     H     6.626176E-34          /* Planck's Constant      */
#define     C     2.99792459E8          /* Speed of Light         */
#define     Q     1.6021892E-19         /* Electronic Charge      */
#define     PI    3.141592654           /* PI                     */

/***********************/
/* Material Constants */
/***********************/

#define     AR    1E8                   /* Recomb Coefficient A   */
#define     BR    8E-17                 /* Recomb Coefficient B   */
#define     CR    4E-41                 /* Recomb Coefficient C   */
#define     DWAVE -1.61E-32             /* Wavelength Shift Coeff */
#define     NTH   2.77E24               /* Threshold Density      */
#define     NOTO  2.18E24               /* Transparency Density To */
#define     DNO   6.1E21                /* No Shift Coefficient   */
#define     TO    300                   /* Reference Temperature  */
#define     ATO   2.2E-20               /* Gain Coefficient at To */
#define     DA    -8.6E-23              /* Gain Coeff Shift       */
#define     B     3.3E19                /* Gain Constant          */

/*******************/
/* Loop Parameters */
/*******************/

#define     OLOOP 3                     /* Outer Loop Count       */
#define     ILOOP 400                   /* Inner Loop Count       */

/******************************/
/* Calculated Gain Parameters */
/******************************/
```

```
double      again[OLOOP];                 /* Gain Coefficient          */
double      no[OLOOP];                    /* Transparency Density      */
double      gaincf[OLOOP][ILOOP];         /* Material Gain Coeff       */
double      gainsp[OLOOP][ILOOP];         /* Single Pass Gain          */
double      phassp[ILOOP];                /* Single Pass Phase Shift */
double      gain[OLOOP][ILOOP];           /* Resonant Gain             */
double      gaindb[OLOOP][ILOOP];         /* Resonant Gain (dB)        */

/**********************************************************************/
/* MAIN(argc,argv):                                                   */
/*                                                                    */
/* Purpose: Calculates Desired Data                                   */
/*            Writes Data File                                        */
/*            Prints Completion Percentage                            */
/*                                                                    */
/* Inputs: Output File Name                                           */
/*                                                                    */
/* Returns: Integer Exit Code                                         */
/**********************************************************************/

int main(argc, argv)

int argc;
char **argv;

{

      FILE  *outfile;                     /* Output File Name          */

      /*********************************/
      /* Laser Amplifier Parameters */
      /*********************************/

      double l=250E-6;                    /* Amplifier Cavity Length */
      double w=2.05E-6;                   /* Amplifier Cavity Width  */
      double d=0.2E-6;                    /* Amplifier Cavity Depth  */
      double R1=0.0008;                   /* Input Facet Reflect     */
      double R2=0.0008;                   /* Output Facet Reflect    */

      double peak=1.3E-6;                 /* Peak Gain Wavelength    */
      double neff=4;                      /* Refractive Index        */
      double confine=0.47;                /* Confinement Factor      */
      double loss=2000;                   /* Loss Coefficient        */

      /**************************/
      /* Simulation Parameters */
      /**************************/

      register int oloop;                 /* Loop Counter: Outer     */
      register int iloop;                 /*               Inner     */
      register int carrloop;              /* Carrier Density Loop    */
      long percount;                      /* Percentage Counter      */
      float percent;                      /* Completion Percentage   */

      double current=71.5E-3;             /* Bias Current            */
      double wave[ILOOP];                 /* Wavelength              */
      double temp[OLOOP];                 /* Temperature             */
```

```
/*************************************/
/* Intermediate Simulation Results */
/*************************************/

double j;                          /* Current Density         */
double n;                          /* Carrier Density         */
double nright;                     /* Root Finding: Right     */
double nleft;                      /*               Left      */

/********************/
/* Check Arguments */
/********************/

if (argc != 2) {

      printf("Usage: SLAMODEL outfile\n");
      exit(1);

}

/********************/
/* Open Output File */
/********************/

if ((outfile = fopen(argv[1], "w")) == NULL) {

      printf("Error Opening Output File: %s\n", argv[1]);
      exit(2);

}

/*************************/
/* Print Startup Message */
/*************************/

printf("#################################################\n");
printf("# SLAMODEL - Laser Amplifier Modelling Routine #\n");
printf("#################################################\n\n");

/*****************************/
/* Calculate Carrier Density */
/*****************************/

j = current/(l*w*d*Q);

nleft = NTH/100;
nright = NTH*100;
n = (nleft + nright)/2;

for (carrloop = 0; carrloop < 50; carrloop++) {

      if ( ((j - n*(n*(n*CR + BR) + AR)) *
            (j - nleft*(nleft*(nleft*CR + BR) + AR))) < 0)

            nright = n;

      else
```

```
            nleft = n;

        n = (nleft + nright)/2;

        if ( (nleft/nright) < 1E-7)
            break;

}

printf("Operating Point Information: \n");
printf("   Bias Current         :   %5.1f mA\n", 1000*current);
printf("   Carrier Density      : %9.5e\n", n);

peak += DWAVE*(n - NTH);
printf("   Peak Gain Wavelength : %9.5e\n\n", peak);

/***************************/
/* Calculate Gain Values */
/***************************/

percent = 0;
percount = 0;

printf("Performing Gain Calculations ... \n");
printf("   Completed: %5.1f%%\r", percent);
fflush(stdout);

for (oloop = 0; oloop < OLOOP; oloop++) {

        temp[oloop] = TO + (oloop-1)*20;

        again[oloop] = ATO + DA*(temp[oloop] - TO);
        no[oloop] = NOTO + DNO*(temp[oloop] - TO);

        for (iloop = 0; iloop < ILOOP; iloop++) {

            wave[iloop] = 1.265E-6 + iloop*((40E-9/ILOOP));

            gaincf[oloop][iloop] = again[oloop]*(n - no[oloop])
                - B*(sqr(wave[iloop] - peak));
            gainsp[oloop][iloop] = exp((confine*
                gaincf[oloop][iloop] - loss)*1);
            phassp[iloop] = (2*PI*1)/(wave[iloop]/neff);

            gain[oloop][iloop] = ((1-R1)*(1-R2)*
                gainsp[oloop][iloop])/(sqr(1-
                gainsp[oloop][iloop]*sqrt(R1*R2)) + 4*
                gainsp[oloop][iloop]*sqrt(R1*R2)*sqr(sin(
                phassp[iloop]))));
            gaindb[oloop][iloop] = 10*log10(gain[oloop][iloop]);

            percount++;
            if (100*(float)percount/(float)(OLOOP*ILOOP)
                - percent >= 1) {

                percent = 100*(float)percount/
                        (float)(OLOOP*ILOOP);
```

```
                    printf("   Completed: %5.1f%%\r", percent);
                    fflush(stdout);

                }

            }

        }

        /****************************/
        /* Calculations Completed */
        /****************************/

        percent = 100;
        printf("   Completed: %5.1f%%\n", percent);
        printf("Calculations Completed.\n\n");

        /**************************/
        /* Store Results to Disk */
        /**************************/

        percent = 0;
        percount = 0;

        printf("Writing Results to Disk ... \n");
        printf("   Completed: %5.1f%%\r", percent);
        fflush(stdout);

        for (iloop = 0; iloop < ILOOP; iloop++) {

            fprintf(outfile, "%9.5e\t%9.5e\t%9.5e\t%9.5e\n",
                wave[iloop],
                gainsp[0][iloop], gainsp[1][iloop],
                gainsp[2][iloop]);

            percount++;
            if (100*(float)percount/(float)(ILOOP)
                - percent >= 1) {

                percent = 100*(float)percount/
                          (float)(ILOOP);
                printf("   Completed: %5.1f%%\r", percent);
                fflush(stdout);

            }

        }

        /*************************/
        /* File Write Completed */
        /*************************/

        percent = 100;
        printf("   Completed: %5.1f%%\n", percent);
        printf("File Writing Completed.\n\n");

        fclose(outfile);
```

```
    /**************************/
    /* Terminate Execution */
    /**************************/

    printf("Execution Completed.\n\n");

}
```

APPENDIX C

Semiconductor Laser Preamplifier
Noise Calculations

The improvement in receiver sensitivity which may be achieved using a semiconductor optical preamplifier, in conjunction with a PIN diode receiver, may be demonstrated by applying the results of the laser amplifier noise analysis presented in [9] to the optical receiver model shown in Figure C.1. This system contains a semiconductor laser preamplifier with an applied optical signal power of P_{in}. The laser amplifier has an internal optical power gain of G, and input and output coupling efficiencies κ_1 and κ_2, respectively. An optical bandpass filter of noise bandwidth B_o follows the laser amplifier. This filter is centered at the operating wavelength, and is used to reduce the amount of spontaneous emission incident on the photodetector. The insertion of this filter does not reduce the generality of the sensitivity derivation as B_o may simply be replaced by the noise bandwidth of the laser amplifier when analyzing systems which do not contain an optical filter.

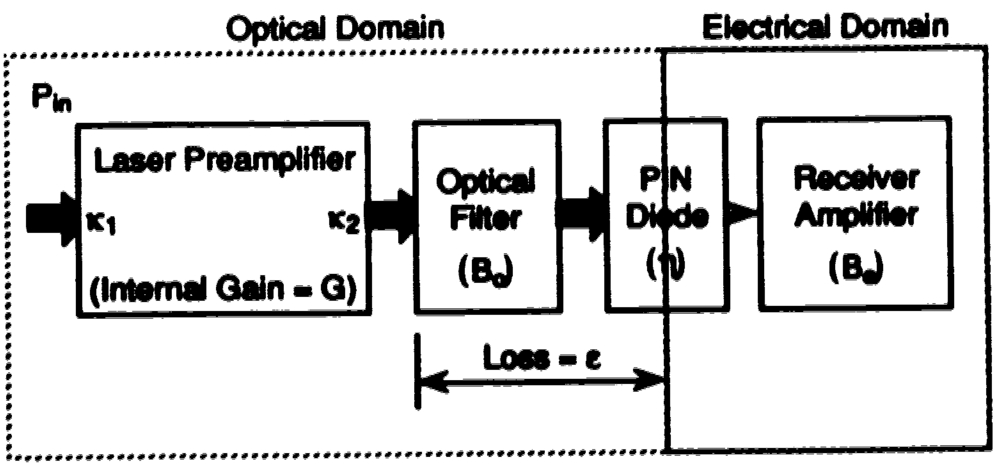

Figure C.1 Optical Receiver Model

The light at the output of the optical filter is focused onto an infinite bandwidth PIN diode of quantum efficiency η. The transmission loss incurred due to optical filtering and PIN diode coupling is denoted by ε. The assumption of infinite PIN diode bandwidth permits derivation of the non-bandlimited form of the power spectral densities of all shot and beat noise components which are generated by the PIN diode. The electrical noise components produced are subsequently filtered by the unity gain receiver amplifier which has a baseband bandwidth of B_e. The infinite PIN diode bandwidth assumption does not reduce the generality of the analysis as the receiver bandwidth, B_e, in the following noise calculations may be taken to be the bandwidth of the combined photodetector and receiver amplifier.

Using the model presented above, the photocurrent equivalents of the signal and noise components which are present at the receiver amplifier output are calculated in [9]. The results that have been derived are simply reiterated here in order to avoid the lengthy derivation which is required to generate the photocurrent expressions.

Two "signal" components exist at the receiver amplifier output. The first of these components is the transmitted data signal, which has an electrical power, on a per ohm basis, of

$$I_{sig}^2 = \left(P_{in}(\kappa_1 G \kappa_2) \cdot \varepsilon \frac{e\eta}{hf}\right)^2 \qquad \text{(C.1)}$$

where e is the electronic charge and hf is the energy of a photon of light at the operating wavelength. The conversion to a per ohm basis represents an assumption of a 1 ohm input resistance for the receiver amplifier, or equivalently a 1 ohm PIN diode load resistor.

The second "signal" component present in the laser amplifier output flux represents the spontaneously emitted light which is coupled into the guided mode. The spontaneous emission electrical power present at the receiver amplifier output may be expressed as,

$$I_{sp}^2 = \left(\Gamma'_{sp} \cdot \varepsilon \frac{e\eta}{hf}\right)^2 \qquad \text{(C.2)}$$

where P_{sp} is the output fiber coupled spontaneous emission optical power of the laser amplifier. This result is again given on a per ohm basis.

These two components represent the photocurrent equivalents of the total "signal" content present in the laser amplifier output flux. One portion corresponds to the amplifier input signal, while the other is the amplified spontaneous emission generated by the laser amplifier. It should be noted that the spontaneous emission signal component simply produces a DC offset at the input of the receiver, and may be removed by the addition of a DC blocking capacitor. More important, however, are the shot and beat noise components which this optical signal generates in the photodetector output current.

Four noise components are present at the receiver amplifier output, two shot noise components and two beat noise products. The shot noise components are generated due to the nonzero average values for the signal and spontaneous emission photocurrents, and are bandlimited to an electrical bandwidth of B_e by the receiver amplifier. The electrical power of the signal and spontaneous emission shot noise components is given by,

$$\left(I_{shot_{sig}}\right)^2 = 2eB_e \cdot I_{sig} \tag{C.3}$$

$$\left(I_{shot_{sp}}\right)^2 = 2eB_e \cdot I_{sp} \tag{C.4}$$

where e is again the electronic charge.

In addition to the shot noise components, two beat noise products exist at the output of the photodetector. These components are present because the photocurrent generated by the PIN diode is proportional to the incident light power, which is the square of the electric field. This indicates that the photodetector performs square law detection of the input electric field and causes beating to occur between the electric fields of the various signal components present in the incident light flux.

The signal-spontaneous beat noise power generated at the receiver amplifier output is, from [9],

$$I_{sig\text{-}sp}^2 = \begin{cases} 2\sqrt{I_{sig}^2 I_{sp}^2} & , 2B_e \geq B_o \\ 2\sqrt{I_{sig}^2 I_{sp}^2} \cdot 2\dfrac{B_e}{B_o} & , 2B_e < B_o \end{cases} \tag{C.5}$$

while the spontaneous-spontaneous beat noise power present at the receiver amplifier output is,

$$I_{sp\text{-}sp}^2 = \begin{cases} I_{sp}^2 & , B_e \geq B_o \\ I_{sp}^2 B_e \dfrac{2B_o - B_e}{B_o^2} & , B_e < B_o \end{cases} \tag{C.6}$$

The above results demonstrate that four noise components exit at the output of the receiver amplifier, namely shot noise terms induced due to nonzero signal and spontaneous emission average values, and beat noise products generated as a result of square law detection. It is constructive to note that the beat noise components generally dominate the shot noise components in typical system applications. In addition, the signal and noise terms presented above are derived based on a unity gain receiver amplifier and a one ohm PIN diode load. The components may be corrected to account for the chosen optical receiver implementation by multiplying all signal and noise powers by $G_{amp}R$, where G_{amp} is the receiver amplifier power gain and R is the amplifier input impedance, or equivalently the PIN diode load resistor.

The signal to noise ratio in an analog system may be calculated from the signal and noise power terms introduced above. The various noise components are uncorrelated and may therefore be added on a power basis, resulting in a total noise power of,

$$I_n^2 = I_{shot_{sig}}^2 + I_{shot_{sp}}^2 + I_{sig\text{-}sp}^2 + I_{sp\text{-}sp}^2 + I_{rec}^2 \tag{C.7}$$

where I_{rec}^2 is the receiver amplifier electrical noise power. The analog signal to noise ratio is simply the ratio of the total received electrical signal power to the total noise power, given by,

$$SNR = \frac{I_{sig}^2}{I_n^2} \tag{C.8}$$

Using the expressions introduced above for the electrical noise powers present at the receiver amplifier output, the relative magnitudes of the noise components generated by a laser amplifier may be examined. These results are presented in Figures C.2 and C.3, as a function of the laser amplifier input signal power. The figures indicate the noise component magnitudes present at the receiver amplifier output with and without a wavelength tunable optical filter which has an optical bandwidth of 0.5 nm and an insertion loss of 1.5 dB. The analog signal to noise ratio that is achieved in the two cases is indicated in Figure C.4. The receiver parameters that have been used to calculate the results presented in the three plots are listed in Table C.1. These values represent the measured parameters of the laser amplifier used in this experiment.

Table C.1 Laser Amplifier Noise Modelling Parameters

Parameter	Description	Value
G_{ff}	Laser Amplifier Fiber to Fiber Gain	12.5 dB
P_{sp}	Laser Amplifier Spontaneous Emission	172.0 μW
λ	Operating Wavelength	1293.0 nm
$\frac{e\eta}{hf}$	PIN Diode Responsivity	1.00 A/W
B_e	Receiver Bandwidth	7.0 GHz
NF_{Rec}	Receiver Noise Factor	2.50

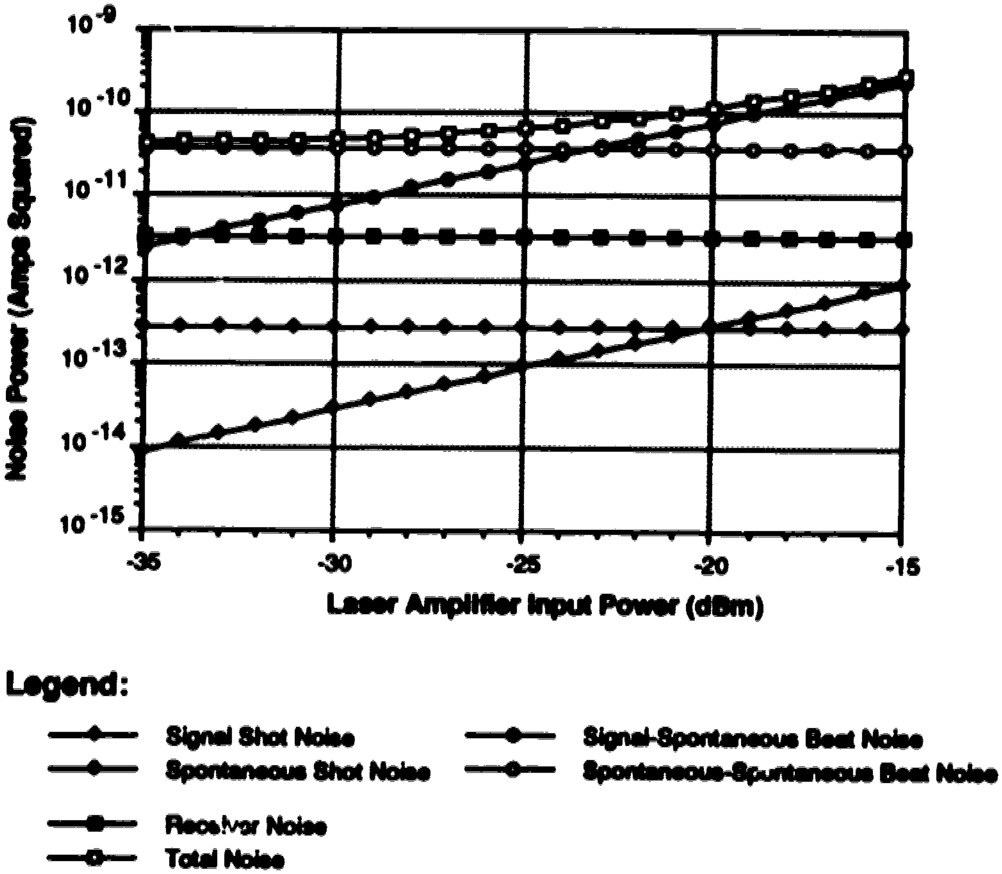

Figure C.2 Laser Amplifier Noise Components with No Optical Filter

Figures C.2 and C.3 demonstrate that the laser amplifier noise components generally dominate the receiver amplifier noise, particularly when no optical filter is employed. This does not reduce the sensitivity of the overall receiver, because the optical preamplifier provides signal gain in front of the receiver amplifier. Thus, the noise generated by the receiver amplifier is reduced by the gain provided by the optical preamplifier. As a result, the overall system is able to achieve a higher sensitivity, while easing the design of the electronic amplifier, as a result of the relaxed noise constraints placed on the amplifier.

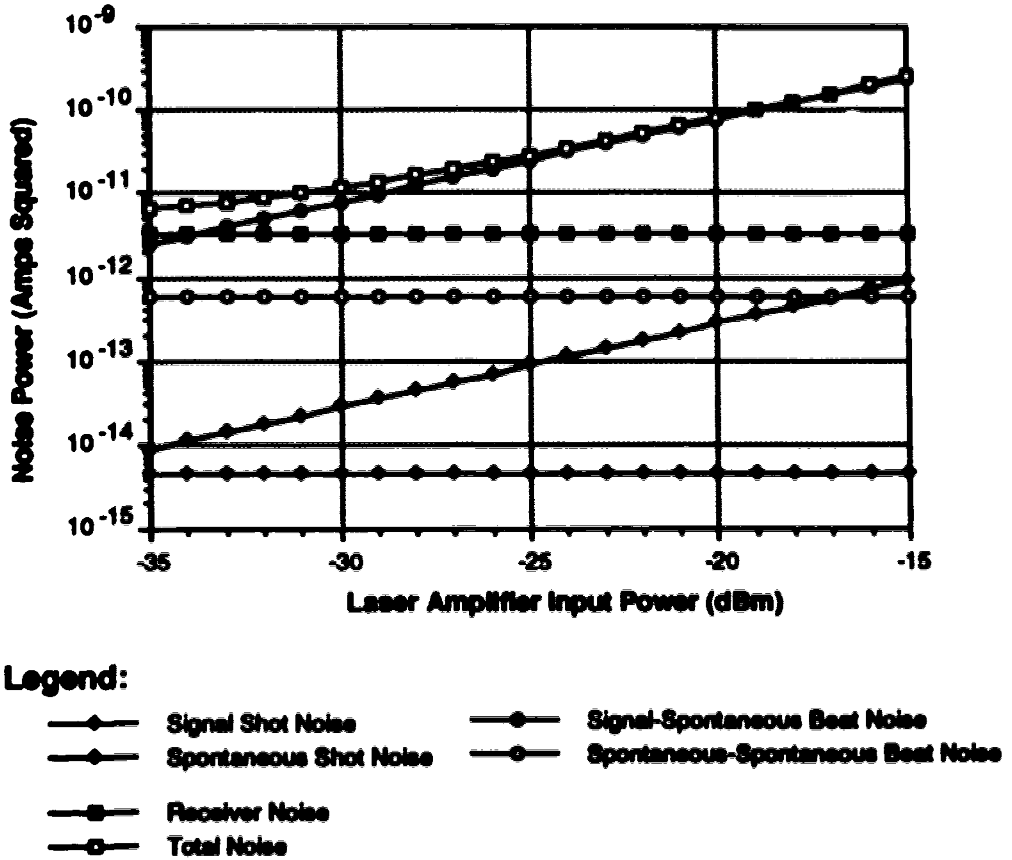

Figure C.3 Laser Amplifier Noise Components with 0.5 nm Optical Filter

The two graphs indicate that the beat noise components dominate the shot noise components, and therefore determine the performance achieved by the laser preamplifier and PIN diode receiver combination. The spontaneous-spontaneous beat noice is the larger of the two beat noise terms at low signal powers, with the signal-spontaneous beat noise becoming dominant at higher signal powers. The point at which the receiver becomes signal-spontaneous beat noise limited depends on the optical filter bandwidth, as the filter reduces the spontaneous-spontaneous beat noise term and has no effect on the signal-spontaneous term. This fact is demonstrated by comparison of Figures C.2 and C.3.

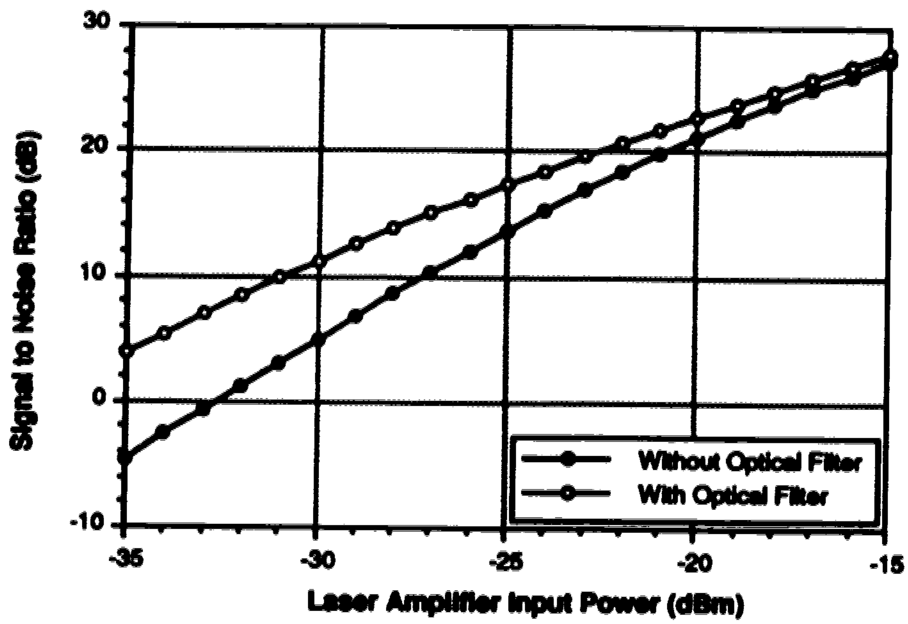

Figure C.4 Signal to Noise Ratio at Receiver Amplifier Output

Figure C.4 indicates the improvement in signal to noise ratio that is offered by the insertion of an optical filter. This improvement is most pronounced at low signal powers where the receiver is spontaneous-spontaneous beat noise limited. The insertion of the optical filter reduces this dominant noise component and a significant reduction in the total noise power results. However, as the system becomes signal-spontaneous beat noise limited, the optical filter does little to improve signal to noise ratio as it has no effect on the dominant noise source, and the two curves converge on each other. In addition, both curves indicate a reduced signal to noise ratio improvement with increasing signal power at higher power levels. This effect is again due to the nature of the dominant noise source. At low power levels, increasing signal power does not increase the dominant noise source, spontaneous-spontaneous beat noise, while it does at high power levels when the receiver is signal-spontaneous beat noise limited.

The device used in this experiment has very poor noise characteristics, and the overall receiver performance could be improved through the use of a true laser amplifier as opposed to an antireflection coated laser. Nevertheless, this amplifier may be used as an optical preamplifier to increase receiver sensitivity, as indicated in the above figures. With the laser amplifier in place the signal to noise ratio is 15.6 dB, corresponding to a 10^{-9} bit error rate in a digital communication system [17], at an input signal power of -26.5 dBm and -23.8 dBm, with and without an optical filter, respectively. The difference in power levels indicates that the spontaneous-spontaneous beat noise component contributes a significant portion of the total receiver noise power, and hence the total noise power is reduced due to the insertion of an optical filter. For the same PIN diode receiver, without a laser preamplifier, the receiver sensitivity is -19.6 dBm. This indicates the substantial sensitivity increase which may be achieved through use of a semiconductor optical preamplifier. This improvement becomes more pronounced at higher bit rates, where B_e is larger.