Order Number 1351355

Design of an optimum driver circuit for CW laser diodes

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The University of Arizona, 1992

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DESIGN OF AN OPTIMUM DRIVER CIRCUIT

FOR CW LASER DIODES

by

Kazem Hajiaghajani

A Thesis Submitted to the Faculty of the

ELECTRICAL and COMPUTER ENGINEERING DEPARTMENT

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN ELECTRICAL ENGINEERING

In the Graduate College

The UNIVERSITY OF ARIZONA

1992

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Date

ACKNOWLEDGMENTS

I am very grateful to Dr. Ming-Kang (Max) Liu who was a tremendous source of insight and inspiration on this thesis. No less is my thanks to Drs. John Wait and Tom Milster for their immense generosity in offering their time, support, and valuable suggestions.

Last but not least, there are no adequate words to express my thanks to my life companion Pamela and my daughter Roxana whose love and support enabled me to recover from a two-year long illness and pursue this thesis at the same time. When the world seemed dark and empty, they were there to bring light and life back to it.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

ABSTRACT

The drive circuit of a laser diode plays a critical role in the diode's performance and life time. A poorly designed drive circuit leads at best to unstable optical output power and/or frequency and at worst to permanent damage to the laser diode. Thermal stress on the laser diode junction and noise from various sources degrade the diode's performance and may result in its damage, and transients may destroy the laser diode outright. This thesis explores all failure mechanisms of a laser diode, and offers solutions to prevent and/or control them. General drive circuit considerations and requirements of various demanding applications of a CW laser diode are discussed. Finally, a fully functional drive circuit is presented.

CHAPTER ONE

LASER DIODE APPLICATIONS AND PROBLEMS

1.1 Introduction

Since the first emergence of commercial laser diodes in the late 1970s, there has been an explosive growth in their technology and applications. Once confined to the realm of laboratories and an object of abstract curiosity of scientists, laser diodes today have found applications in many scientific, military, industrial, and commercial areas, and new applications continue to be explored as their performance improves and their cost declines.

Laser diodes today are mass-produced with very high yields. They are built in many different structures and semiconductor compounds to achieve desirable properties. Wavelengths of laser diodes are available from the 650 nm to 30 microns range, although the majority fall between 650 nm and 1.6 micron [16]. CW optical output power is from a few mW to tens of mW for a single diode (the single layer type), to nearly a watt for the laser diode arrays. The pulsed output peak can be as high as hundreds of watts. Many laser diodes have integrated photo-detectors known as monitor diodes used in a feedback loop to stabilize laser diode's output power. Many also come in pen-like housings with collimator and focusing lenses in the package ready to be used for many applications. Some are even available hermetically sealed in "a printed circuit board module, complete with heat sink, thermo-electric cooler, temperature sensor (thermistor), monitor diode, and fiber pig-tail" [16]. Of course, the more elaborate, the more substantial the price tag (in the thousands of dollars per unit). [43] provides a comprehensive listing of laser diode manufacturers and part numbers.

Until a few years ago it was impossible to produce visible-light laser diodes. The laboratory units worked only at cryogenic temperatures and tended to self-destruct quickly at room temperature due to the high current densities developing on the laser diodes' p-n junctions. Thanks to advances in producing direct band gap ternary and quaternary semiconductor compounds from III-V materials combined with a new laser diode structure known as double hetrostructure (DH), visible laser diodes have become a commercial reality. Designers have already begun using visible laser diodes instead of the expensive and bulky He-Ne lasers in applications where long coherence lengths of He-Ne lasers are not required. The increase in the output power of laser diodes in the 800-900 nano-meter range have enabled researchers to use frequency doubling to generate laser light in the 400-450 nano-meter range for applications that need small focal spots such as optical data storage. One recent exciting application for laser diodes is in the area of machine vision with a projected revenue of nearly half a billion dollars by 1995 [20]. Table 1 gives a partial list of the areas the laser diodes are being used today.

There are many different kinds of laser diodes. For different applications, different laser diode properties are needed. For example, high modulation bandwidths, narrow spectral widths, and high power are critical to high speed telecommunications, whereas in laser printers, compactness and high power capability are important [16]. A summary of laser diode features is given in table 2. [12] and [42] provide a more in-depth description of laser diode features.

<u>COMMUNICATION EQUIPMENT</u>	<u>CONSUMER PRODUCTS</u>
Fiber Optic Communications	CD Players
Atmospheric Communications	Video Disk Player
Satellite Communications	CD-ROM
<u>INFORMATION PROCESSING EQUIPMENT</u>	<u>MEDICAL APPARATUS</u>
Optical Disk Memories	Laser Treatment Equipment
Optical Floppy Disks	Biochemical Analyzers
Optical Memory Card	
<u>MEASUREMENT, ANALYSIS, AND CONTROL INSTRUMENTS</u>	
Laser Scanners	
Optical Micrometers	
Laser Gyroscopes	
Velocity Meters	
Infinitesimal Displacement Meters	
Photoelectric Switches	
Range Finders	
Interferometers	
Electrical Measurement Instruments	
Strain Gauges	
Rotary Encoders	
YAG Laser Pumping	
<u>OFFICE AUTOMATION EQUIPMENT</u>	
Laser Printers	
Laser Copiers	
Bar Code Readers	
Laser Pens	
POS Terminals	
Laser Printing Plate Engraving	

Table 1. Laser diode applications [40].

- **Commercial wavelengths from 650 nano-meter (visible red) to 30 microns (far infrared) [16].**
- **High radiance.**
- **High modulation bandwidth in the giga hertz range [42].**
- **Long coherence lengths in the tens of meters for single mode distributed-feedback laser diodes [12], [6].**
- **High electro-optical efficiencies over 20 times those of gas lasers [16].**
- **Compactness (small packages the size of a small signal transistor metal can)**
- **Easy to operate compared to gas lasers where high voltage power supplies or water cooling is needed.**
- **High power from a few mW to several tens of mW for single stripe units and several hundred mW to 1 W for laser diode arrays.**

Table 2. Laser diode features.

1.2 Why a Thesis on CW Drive Circuit Design?

The characteristics that have made laser diodes a darling of design engineers have also put stringent requirements on the drive circuitry design. The small size of the laser diode active region, typically a fraction of a micron thick and a few microns wide, makes it susceptible to damage by line transients, Electro-Static Discharge (ESD), and noise spikes in the drive circuitry. ESD requires careful consideration in laser diode handling, and has caused the destruction of hundreds of thousands of dollars worth of laser diodes [3]. Since there is a lot of literature dealing with ESD and describing how to create a safe and ESD-free work environment at both the production and at user levels, we will briefly touch on the ESD handling of bare laser diodes in this thesis, and show some design methods to isolate the laser diode and the drive circuitry from sources of ESD, mainly human touch.

There are several manufacturers such as ILX Lightwave, and Melles Griot who make universal laser drive systems for laboratory use. However, with a price tag of about a thousand dollars per unit, these general purpose laser drive units become impractical for use in new products incorporating laser diodes, especially those with a large quantity or certain mechanical restrictions. Thus the aim of this thesis is provide a methodical procedure to design inexpensive and reliable laser diode drive circuits.

In this thesis, we will deal only with small power (under 1 mW to 30 mW) and continuous wave (CW) laser diodes ranging from 650 nm to 900 nm in wavelength. Most consumer electronic laser diodes, as well as those suited for interferometry and machine vision fall in this category.

1.3 Definition of the Problem

Laser diodes have a long lifetime in the range of tens of thousands of hours when driven with stable circuits [3]. However, if driven by a poorly designed drive circuit, they can either fail prematurely or degrade over a period of time and then fail. Understanding the failure sources of laser diodes before launching into designing a product around them is paramount.

To prevent laser diodes from failures, the structure, lasing mechanism, and properties of a laser diode must be fully understood. Chapters 2 to 4 review the fundamentals and failure sources of laser diodes. Since the aim of this thesis is to demonstrate good drive circuit design, detailed quantum physics of semiconductor laser actions will not be presented. For a thorough discussion on this subject, refer to [42].

The low cost of low power laser diodes today (from a few tens of dollars per unit in small quantities to a few dollars each in large quantities) may deceive design engineers to forego a thorough circuit design phase and hastily put together something for the job. But this could be a very costly oversight. Laser diodes are hardly used bare because of their high beam divergence and non-circular beam profile. Usually the laser diodes are assembled in a system with collimated and cylindrical lenses, and mechanical jigs, with elaborate alignment procedures. Thus, an assembled laser diode becomes very expensive to replace if it fails. As a motivating example, in one application at Wyko Corporation, Tucson, Arizona, the laser diode used costs about 50 dollars, but once assembled into the system, and after having gone through alignment, tests, and burned-in, its replacement becomes a very expensive proposition in the range of seven hundred dollars. Thus, proper design of a laser diode drive circuit is a very critical task to avoid high costs of system repair. With a good drive circuit design and implementation, the longevity of the laser diode can be ensured.

CHAPTER TWO

LASER DIODE FUNDAMENTALS AND OPERATION

2.1 Semiconductor Light Emitting Devices

Laser diodes are the younger siblings of Light emitting diodes (LEDs). LEDs and laser diodes are photonic devices that transform electrical energy into optical radiation. More specifically, they are injection electroluminescent p-n junction semiconductors since they generate optical radiation (light) when minority carriers are injected into their respective p-n junctions. In both LEDs and laser diodes the emitted wavelength is related to the band-gap energy of the p-n junction where lasing occurs through forward biased injection current.

The process of photon-electron interaction in a semiconductor is classified into three categories as shown in Fig. 1: (a) *Absorption* (or *excitation*) where a photon is absorbed by the transition of an electron from a filled state in energy level E_1 (valence band) to an empty state in energy level E_2 (conduction band, $E_2 > E_1$), or (b) *spontaneous emission* where a photon is generated when an electron from a state at energy level E_2 returns spontaneously to a state in energy level E_1, or (c) *stimulated emission* where a photon can stimulate the emission of a similar photon (same energy and phase) by transition of an electron from a state at energy level E_2 to a state in energy level E_1.

In LEDs and laser diodes, when the p-n junction is forward biased, electrons from the n-type material at energy level E_2, recombine with holes from the p-type material at energy level E_1. These electron-hole recombination generate photons with an intensity directly proportional to the drive current and a wavelength inversely proportional to the band-gap energy as shown in (1).

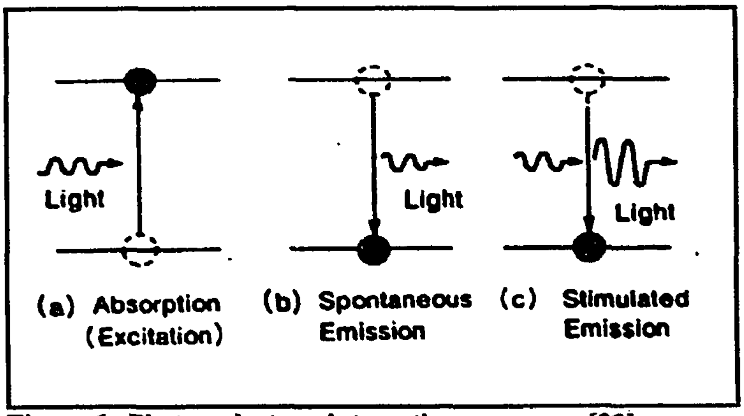


Figure 1 Photon-electron interaction processes [23].

$$\lambda = \frac{C}{\frac{(E_2 - E_1)}{h}} \qquad (1)$$

where
C: Velocity of light (2.998 X 10^8 cm/sec)
h: Planck's constant (6.625 X 10^{-34} Joule-sec)

Since the band-gap energy depends on the composition of the semiconductor compound, it can be manipulated to obtain light of different colors (wavelengths).

In an LED the optical radiation is the result of *spontaneous emission.* The LED beam is incoherent and out of focus. The beam consists of many closely spaced wavelengths corresponding to the difference between the energy levels of the valence band and the higher energy states of the conduction band. A lens or some other structure is integrated in the LED package to concentrate the emerging output light.

The LED beam has no specific direction. As a result a significant part of it is absorbed by the semi-conductor material itself. In surface-emitting LED's the efficiency is increased by making the junction close to the surface of the device to reduce absorption by other parts of the semiconductor.

The LED technology is in a very advanced stage and the manufacturing processes involved are very efficient and cost effective. The light emitted by commercial LED span from the ultra violet to visible to infrared regions of the electromagnetic spectrum.

Laser diodes produce *stimulated emission* when forward biased. The optical radiation, like any laser beam, has both spatial and temporal coherence.

The first laser diodes were produced in early 60's, had a very short life time, could only be operated in a pulsed mode, and needed to be cooled by liquid nitrogen. Great achievements in material sciences and process technologies have enabled laser diode manufacturers to produce devices that have tens of thousands of hours of lifetime and operate continuously at room temperatures.

2.2 Direct and Indirect Band Gap Materials

The elements predominantly used in the manufacture of laser diodes belong to groups IIIa and Va of the periodic table. The semiconductor compounds use equal amounts of each group to form the laser diode material and hence are called the III-V semiconductors. Table 3 lists the most important elements of III-V semiconductor compounds.

The III-V materials for lasing semiconductors are chosen so that the compound has a direct band gap as opposed to an indirect band gap. The energy-momentum plots of direct band gap alloys show a direct minima for the conduction band with the same momentum as the maxima

Group IIIa	**Group Va**
Aluminum (Al)	**Phosphorous (P)**
Gallium (Ga)	**Arsenic (As)**
Indium (In)	

Table 3. Elements used in laser diodes [12]

of the valence band, so the electrons in the conduction band minima and holes in the valence band maxima have the same momentum (Fig. 2). This means that the electron-hole recombination producing photon is a first order transition process in which momentum is conserved and transition probability is high. In an indirect band gap material the minima of the conduction band and the maxima of the valence band do not have the same momentum and the recombination process requires intermediate stages where phonons or other scattering agents are involved to conserve momentum and energy. First order recombination means shorter radiative lifetime. Therefore, the quantum efficiency of a direct band gap semiconductor is expected to be much higher than that for an indirect band gap semiconductor [42].

GaAs compounds were the first semiconductors to lase and are the most widely used materials for laser diodes especially those used in digital compact disk players [12],[42]. The lasing wavelength depends on the bandgap energy which itself is dependant on semiconductor lattice spacing and composition. Usually ternary or quaternary compounds expressed as $A_xB_{1-x}C$ or $A_xB_{1-x}C_yD_{1-y}$, where A and B may be group III elements and C and D group V elements, are grown on a binary substrate made up of an element from group III and one from group V by epitaxial growth processes. The choice of materials is very critical in order to create lattice-

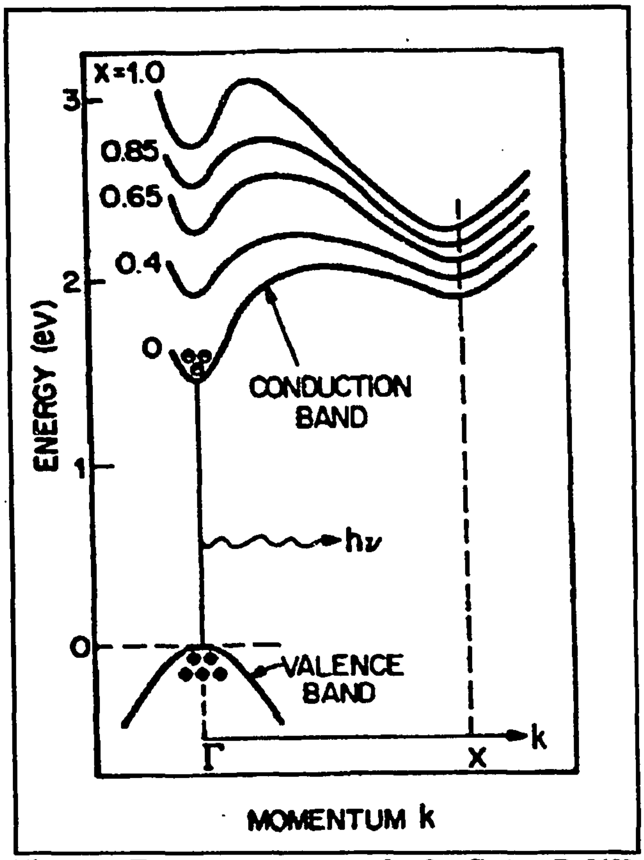


Figure 2 Energy-momentum plot for $GaAs_{1-x}P_x$ [42].

matched layers of compounds grown over each other. Otherwise fatal flaws will occur in the resulting device. Figure 3 shows the energy bandgap and lattice constant plots for different compositions of $In_xGa_{1-x}As_yP_{1-y}$ whose wavelength falls within the shaded area defined by the properties of InAs, InP, GaAs, and GaP [12]. GaAs is usually used as the substrate for laser diodes in the 600 to less than 1000 nm range and InP is the preferred substrate for the 1000 to

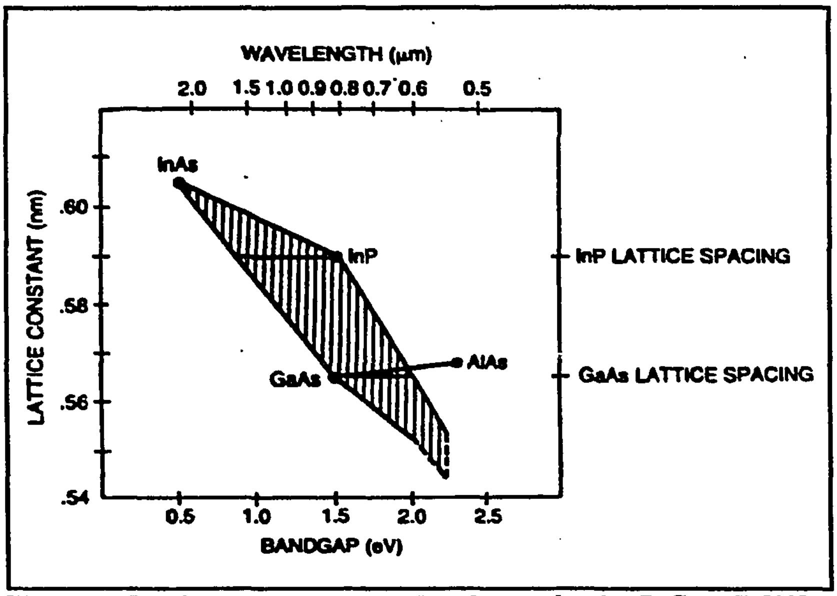


Figure 3 Lattice constant versus band gap plot for InGaAsP [12].

1700 nm range [12]. The other layers are grown with the gradual introduction of another group III element or a group III and a group V element such that the lattices between the semiconductors are closely matched, typically by less than 0.1% [42].

2.3 Principals of Laser Oscillation

A laser device consists of an active medium, called a Fabry-Perot resonator, in which the generated photons have equal or nearly equal energies (wavelength), and their phase relationship is constant. This coherent light is the result of *stimulated* emission as mentioned before. To achieve coherent light or laser, the stimulated emission must dominate over spontaneous emission, a condition known as *population inversion.*

The laser beam has to be amplified and sustained. The Fabry-Perot resonator achieves both objectives with a basic structure shown in Fig. 4. The light oscillation inside the active medium is confined by two mirrors to reflect the light back in. The beams are returned back and forth by the mirrors and add constructively to produce the necessary amplification of light, part of which is emitted from one mirror.

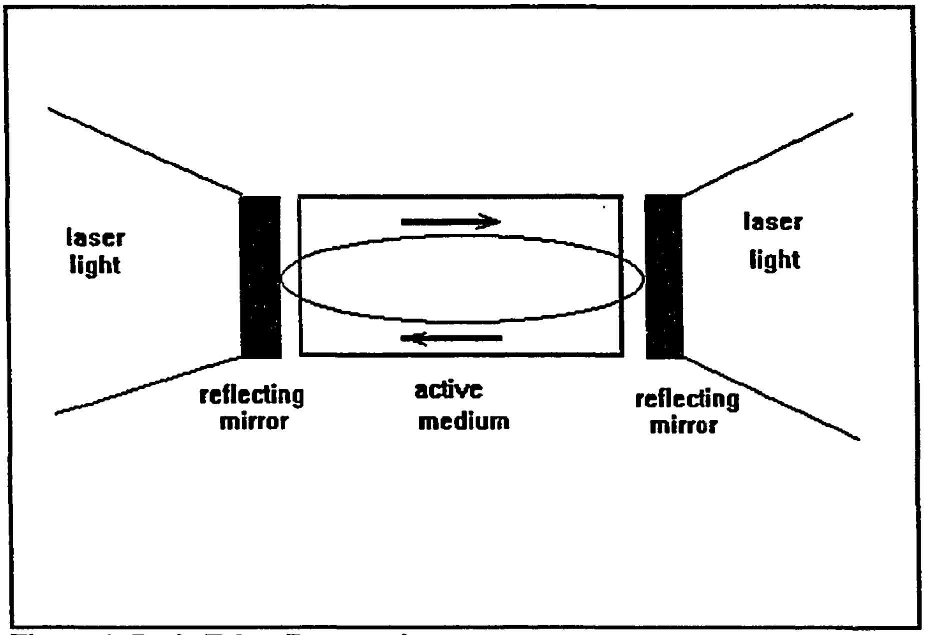


Figure 4 Basic Fabry-Perot cavity.

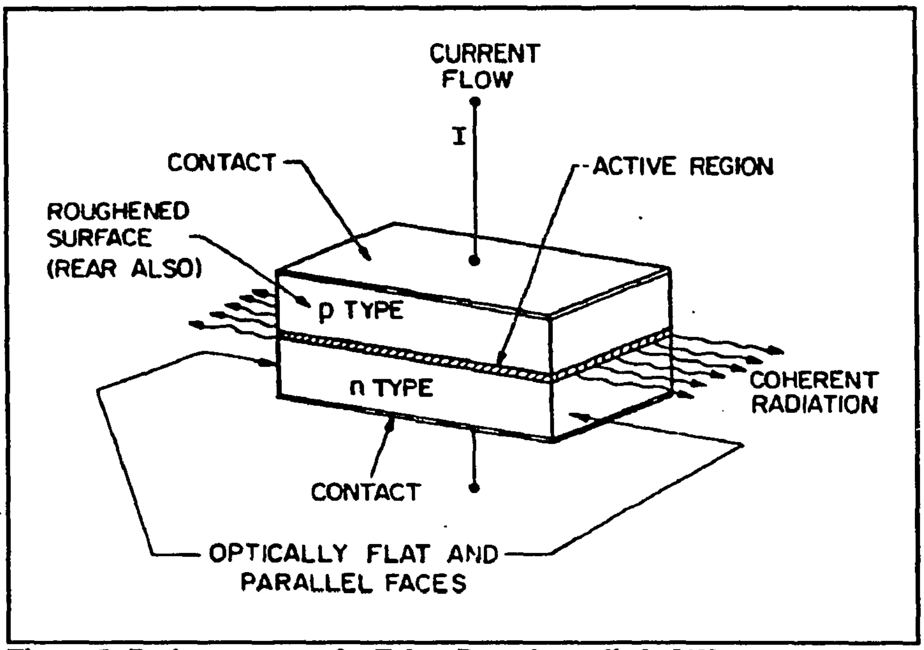


Figure 5 Basic structure of a Fabry-Perot laser diode [42].

To create a Fabry-Perot cavity inside a laser diode, an active layer is formed over a n-type substrate such as GaAs, and a p-doped layer of GaAs is grown over it. Figure 5 shows a basic Fabry-Perot laser diode. The layers on the top and bottom of the active layer have lower refractive indices than that of the active layer to confine the beam inside the cavity. The ends of the semiconductor crystal are cleaved to form reflection facets. In some laser diodes the rear end is coated with a highly reflective material. The reflective ends provide the necessary feedback for light amplification.

Lasing begins after the injected current through the forward-biased junction passes a threshold level I_{th}. The beams inside the active region interfere constructively and form a

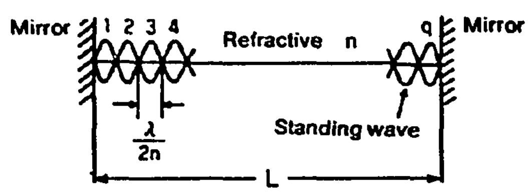


Figure 6 Standing Wave condition in the active layer [40].

condition known as *standing wave*, shown in Fig. 6. In the standing wave condition an integral number of half-waves is equal to the length of the active layer L, as given by (2),

$$q \cdot \frac{\lambda}{2n} = L \qquad (2)$$

where q is an integer called the *mode degree*, and n is the refractive index of the active layer.

The active region of a Fabry-Perot laser diode is between 200 to 500 microns long, and the refractive index n is a number between 3 and 4. At these values, the Fabry-Perot laser diode generates multiple longitudinal modes, with longitudinal mode separation given by (3) [16].

$$\Delta\lambda = \frac{\lambda^2}{2nL} \qquad (3)$$

For example, for a Sharp GaAlAs 780 nm laser diode, with L= 250 microns and n= 3.5, we get a q of 2343. Varying this number by 1 results in a slight variation of about 0.35 nanometer in the wavelength.

Figure 5, however is an oversimplified representation of the laser diodes. Practical laser diodes must achieve both carrier and light confinements within the active layer without stressing it with high current densities. The original laser diodes used a structure known as homostructure, similar to the one shown in Fig. 5. The layers over and under the active layer were GaAs binary compounds, like the active layer itself. The potential barriers developed were not large enough to confine carriers within the active layer efficiently. Also, the active layer area was nearly equal to the top and bottom layers. The result was the development of high threshold current densities from 50,000 Acm^{-2} to 100,000 Acm^{-2} at 300 °K in the active layer [18]. It was impossible to sustain such large current densities continuously without the laser diode being destroyed. To solve this problem, single- and then double-hetrostructure laser diodes were developed [42].

In a simple GaAs hetrostructure, an n-doped substrate of GaAs is developed. Then, by an epitaxial process, such as liquid-phase epitaxy, either the p-doped GaAs active layer is grown over the substrate followed by the ternary compound $Al_xGa_{1-x}As$ (p-doped) to form a single-hetrostructure, or an n-doped $Al_xGa_{1-x}As$ layer is grown over the substrate, followed by a p-doped GaAs active layer and finally a p-doped $Al_xGa_{1-x}As$ to form a double-hetrostructure laser diode. The latter structure, frequently referred to as DH laser diode, has superior carrier and light confinement in the active layer, achieves threshold current densities (J_{th}) as low as 1000 Acm^{-2}, and is the structure of choice in the majority of the commercial laser diodes in the 600 to 1000 nm wavelengths [42]. There are many variations in the DH laser diodes, such as stripe geometry laser diodes, to enhance its optical properties and reduce J_{th} even further. In complex DH laser

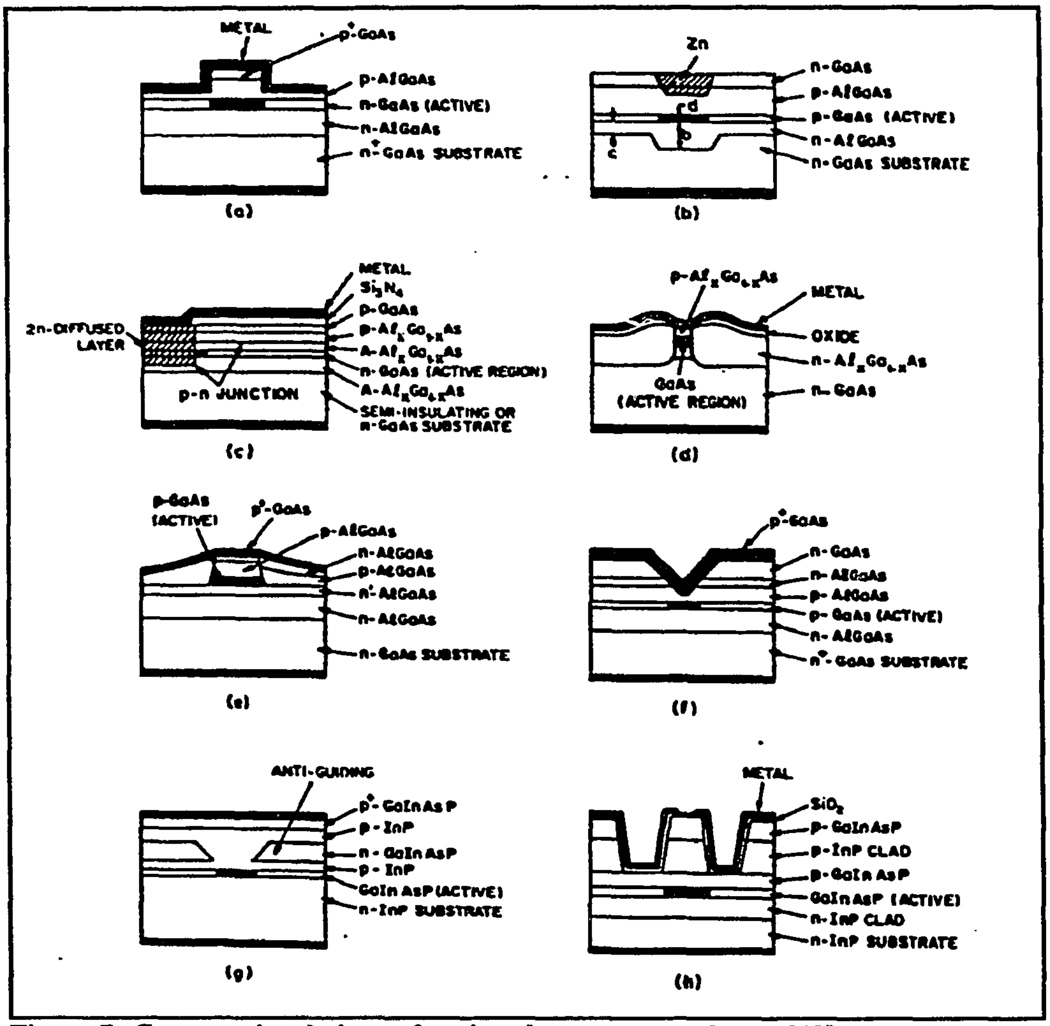


Figure 7 Cross-sectional views of various hetrostructure lasers [42].

diodes the active layer may also be made-up of a ternary or a quaternary compound. Figure 7 shows cross-sectional views of several hetrostructure laser diodes.

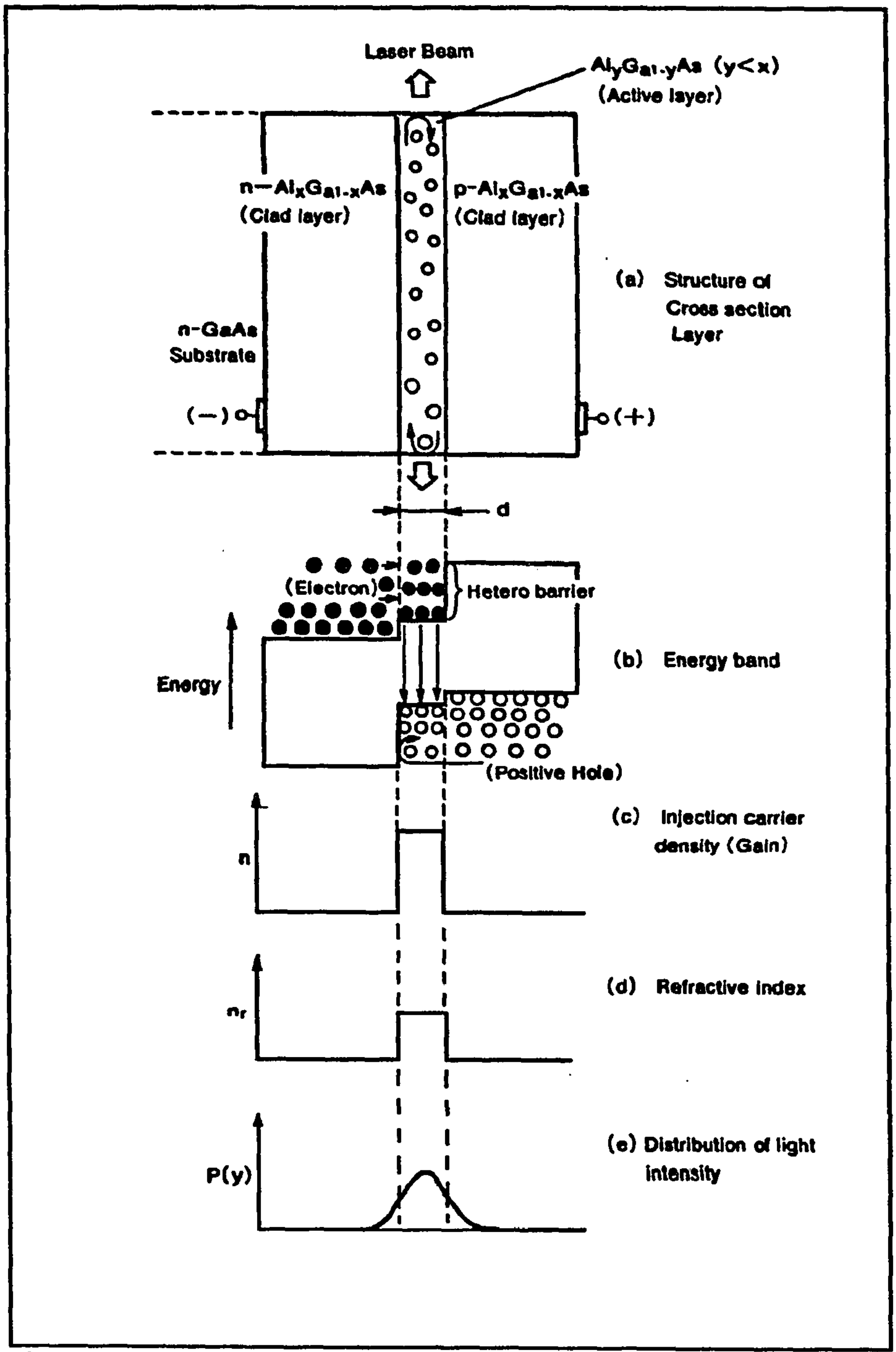


Figure 8 Lasing process in the active layer [23].

Laser diodes may have more than one active layer. Those with multiple active layers, called laser diode array, achieve CW output powers over one watt with the output beam consisting of several closely spaced wavelengths. Some laser diode arrays, like EBAC-240 series of devices by Ensign Bickford Aerospace Company, have CW output powers of 8 to 12 W [8].

Figure 8 shows a GaAlAs laser diode which is forward biased and lasing. The electrons from the n-cladding layer are injected into the active layer as are the holes from the p-cladding layer. In the active layer the recombination process produces the coherent beam, which is then confined and amplified as discussed before. The refractive index profile of the different layers is shown, along with the Gaussian distribution of light intensity.

2.4 Gain Guided and Index Guided Laser Diodes

To confine photons and minority carriers in the active layer of a laser diode, two different kinds of structures have been used, namely *gain guided* and *index guided* [12]. In both of these structures, the vertical light confinement in the active layer is achieved by total internal reflection due to the lower reflective indices of the cladding layers. What sets the two structures apart is the way light is horizontally confined in the active layer. In an index guided laser diode the

GAIN GUIDED	INDEX GUIDED
* Astigmatic	* Little or no astigmatism
* Multiple transverse modes	* Single transverse mode
* High threshold current	* Low threshold current
* Low fabrication process complexity	* High fabrication process complexity
* High yield (lower unit cost)	* Lower yields (higher unit cost)

Table 4. Index guided versus gain guided laser diodes [16].

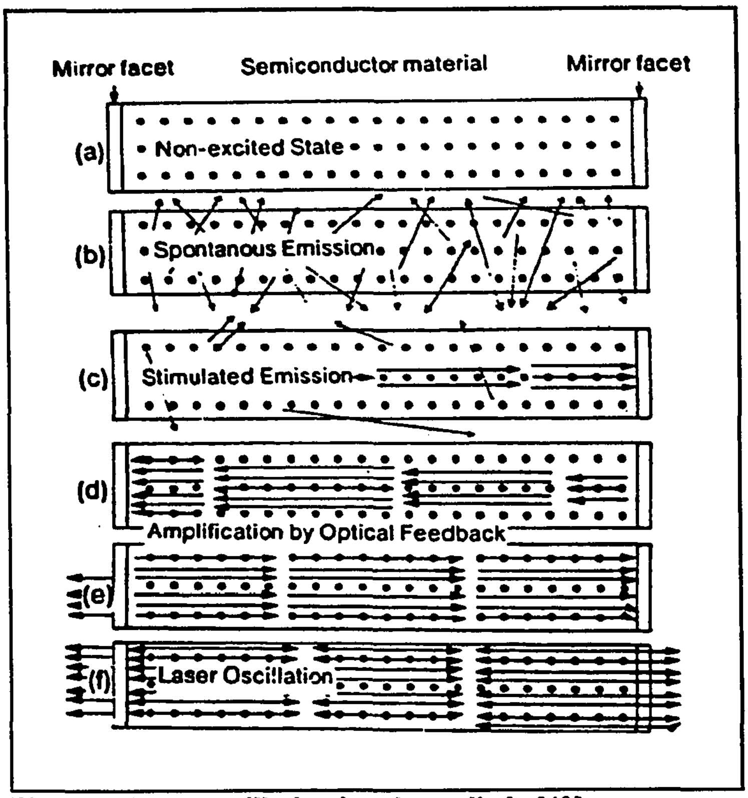


Figure 9 Laser oscillation in a laser diode [40].

horizontal light confinement is achieved by a horizontally built-in refractive index profile. The gain guided laser diode lacks this feature and achieves horizontal light confinement in the active layer simply by optical gain.

2.5 Power Output versus Drive Current

When biased below the threshold current, a laser diode behaves much like an LED, producing spontaneous emission. Beyond the threshold current, I_{th}, population inversion occurs, and stimulated emission from the electron-hole pair recombination dominates over the absorption at the junction, as shown in Fig. 9.

The threshold current I_{th} increases exponentially with temperature as

$$I_{th} \sim \exp\left(\frac{T}{T_0}\right) \tag{4}$$

where T is the heat sink temperature in °C, and T_0 is experimentally found [42]. For example, for a GaAs-$Al_xGa_{1-x}As$ stripe-buried hetrostructure laser diode T_0 is found to be 110 °C.

The plot of light output versus forward current for a laser diode (Fig.s 10 and 11) shows a steep increase of output light past the threshold current. In the operation region the light output increases almost linearly with drive current and the curve can be approximated by a straight line. As seen in Fig. 10, at high bias currents, a laser diode shows kinks which are due to non-linear carrier recombination in the active region. The drive current should be restricted to values below the point where the first kink occurs.

Associated with each laser diode is an output spectrum, consisting of one or more narrow line-width peaks as shown in Fig. 12. The output spectrum depends on the junction temperature and drive current. When there is only one wavelength, the device is called single mode laser diode. Single mode laser diodes are enhanced versions of DH laser diodes, with a built-in mechanism to restrict lasing to one wavelength. Examples of single-mode laser diodes are the distributed-feedback (DFB) laser diodes, shown in Fig. 13, which use a saw-tooth grating of the refractive index within the active layer to promote constructive interference of light beam for a

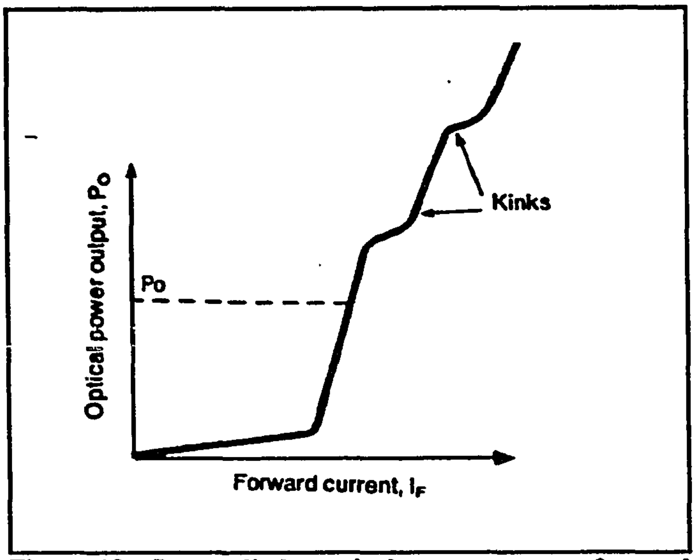


Figure 10 Laser diode optical output versus forward current [40].

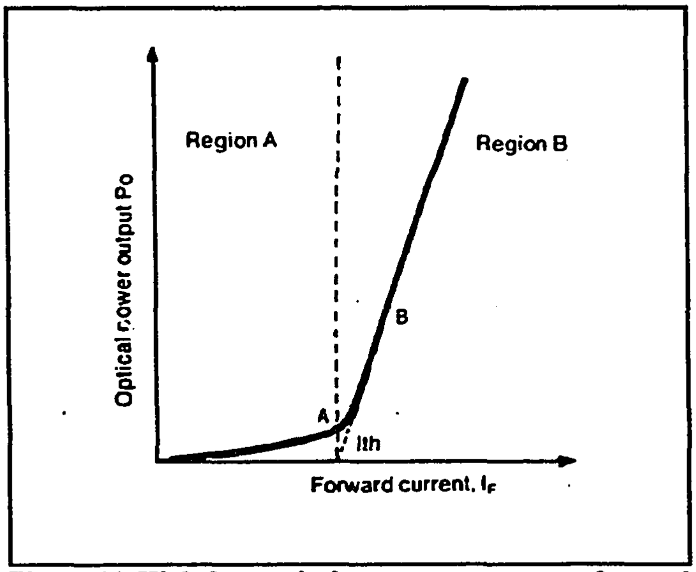


Figure 11 Kink-free optical output power versus forward current [40].

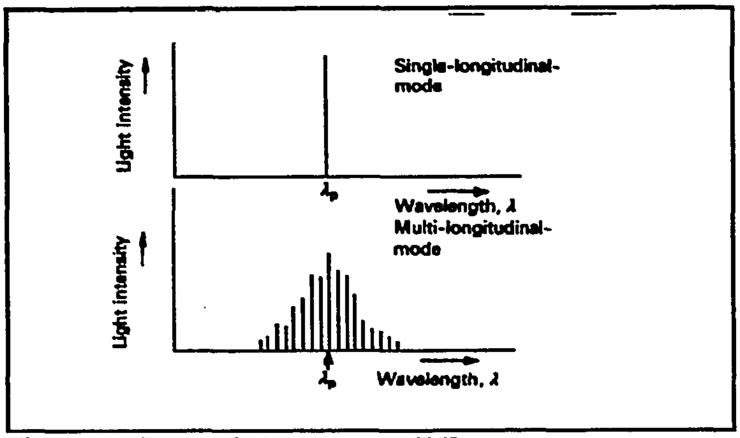


Figure 12 Laser diode spectrum [14].

given wavelength. The grating spacing D determines the laser wavelength. It depends on the refractive index n in the active layer and a positive integer m, called the order of the DFB coupling (with typical values of 1 or 2), as given by (5) [12].

$$D = m\lambda/2n \qquad (5)$$

The DFB laser diode is more stable than the Fabry-Perot laser diode over a wide temperature range. The reason is that the DFB laser wavelength depends on the refractive index which is less sensitive to the temperature range than the bandgap energy on which the Fabry-Perot laser wavelength depends. For the Fabry-Perot index guided laser diodes, however, as the output power increases, the side modes are reduced in amplitude and the main mode stands out as shown in Fig. 14.

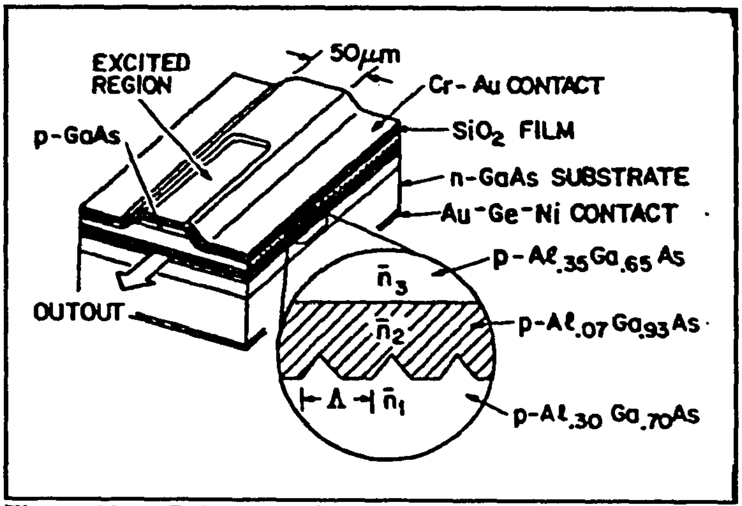


Figure 13 A DFB laser diode [42].

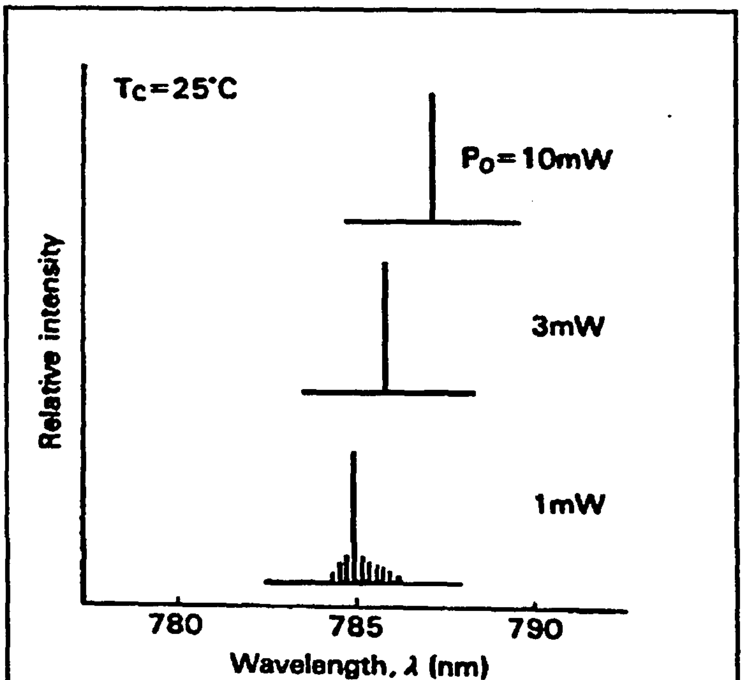


Figure 14 Output spectrum of Hitachi HL7802E laser diode [14].

2.6 Laser Diode Output Modulation

The narrow active layer of the DH laser diodes with stripe geometries provides a very low capacitance. This low capacitance in combination with the linear dependance of light output on drive current makes output modulation a very straightforward task. One can simply modulate the drive current to modulate the light intensity. Since laser diodes have large modulation bandwidths, direct modulation in the gigahertz range is very feasible, albeit with some problems in certain applications. For example, in optical fiber communications, direct modulation of the laser diode causes chirping and degrades transmission performance. Chirping comes from the carrier density change during modulation which causes the refractive index to change. From (2), we have

$$\lambda = n\frac{2L}{N} \qquad (6)$$

which shows the dependance of the light wavelength on the refractive index. Therefore chirping is the wavelength change during modulation. Although the change is not large, together with the fact that the propagation delay in optical fibers is a function of wavelength, received pulses will be spread out. This pulse spread phenomenon which is called *dispersion* or *chirping* degrades the laser diode's performance at very high speeds.

An alternative way to modulate light is to use an external modulator. Dispersion could be prevented if one could modulate the beam from a CW laser diode at ultra high speeds. The development of external modulators, however, is a field by itself and beyond the scope of this thesis. Suffice it to say that with the commercial development of external modulators, the CW laser diodes will replace direct modulation for ultra high speed communication.

2.7 Photodiode (Monitor Diode)

Many laser diodes are packaged with an internal photodiode, often referred to as *monitor diodes*, which can be used in a feedback loop to stabilize their output power. One such package is shown in Fig. 15. The laser and monitor diodes are configured in five different ways as shown in Fig. 16. Circuits using the monitor diode for output power stabilization are called *APC* for *Automatic Power Control.* The specific LD-PD configuration must be taken into consideration when an APC is designed.

Photodiodes, also known as semiconductor detectors, are electro-optical semiconductor devices that transform photon energies into electrical current and deliver this current to an external

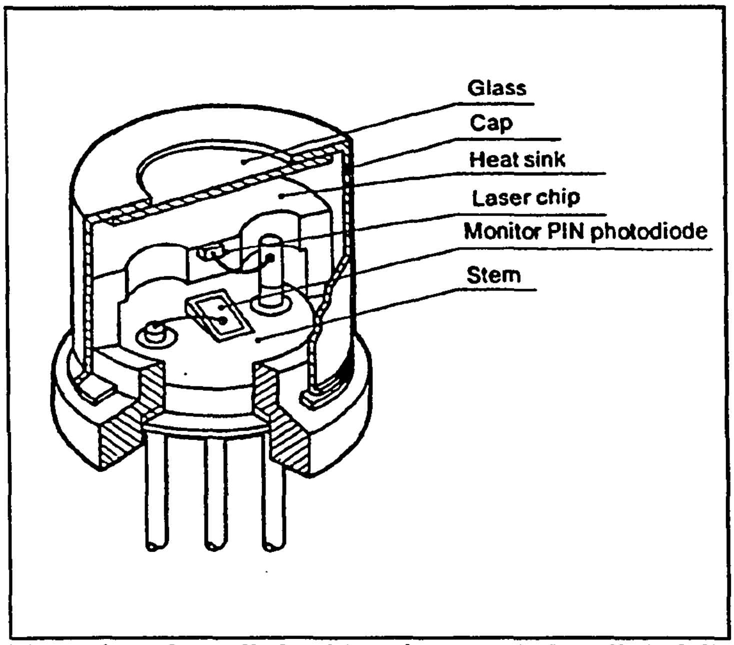


Figure 15 A laser diode with an integrated photodiode [40].

circuit. Photons with equal or higher energy than the photodiode's band gap energy are absorbed [42]. The photon absorption process generates electron-hole pairs. Under application of an electric field, the holes and electrons are drifted to the opposite poles, creating a net current which is proportional to the number of incident photons (light intensity).

A very important parameter to measure the performance of a photodiode is the *quantum efficiency*. The quantum efficiency or gain, which is the number of carriers generated per incident photon, depends, among other things, on the absorption coefficient of the photodiode material which is a strong function of the wavelength. The quantum efficiency is increased to a peak and then drops as the wavelength of the incident photons is increased. Indeed, the quantum efficiency and therefore the spectral response of a photodiode are restricted to a narrow wavelength range

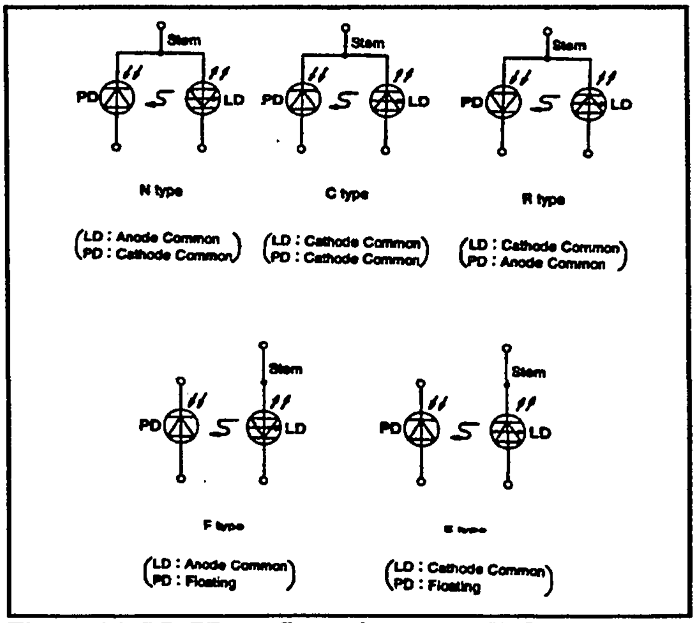


Figure 16 LD-PD configurations types [23].

centered around a certain optical wavelength. The peak in spectral response of a photodiode packaged with a laser diode should match the center wavelength of the laser diode.

Usually a large reverse-bias voltage (below the avalanche breakdown voltage) is applied to a photodiode used in the visible or near infrared range. The large reverse bias deepens the depletion layer, thus allowing the absorption of a larger fraction of light and improving the quantum efficiency. This reverse bias also lowers the photodiode capacitance and improves the photodiode's response time by reducing the carrier transit time in the depletion region.

The monitor diode current follows the incident optical power linearly. Figure 17 shows a typical monitor diode's current response to the laser diode's optical output power, referred to here as the I-P curve. In most cases, manufacturers provide the I-P curve for a specific device. At times, this information is not readily available or apparent as shown in Figures 18 and 19, and should be either obtained by contacting the manufacturer or found experimentally.

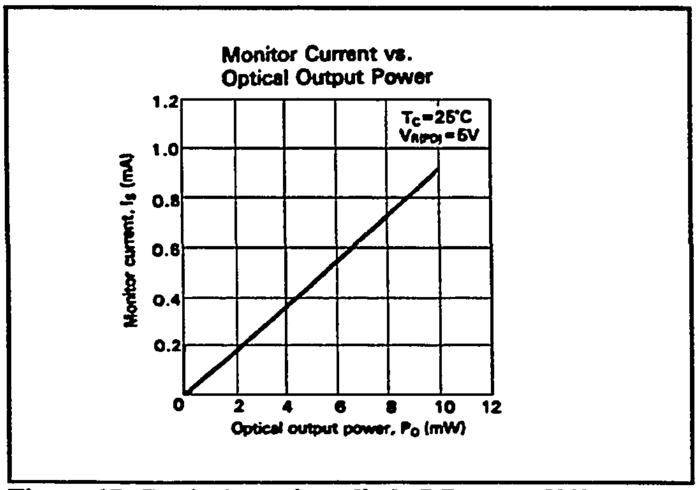


Figure 17 Typical monitor diode I-P curve [23].

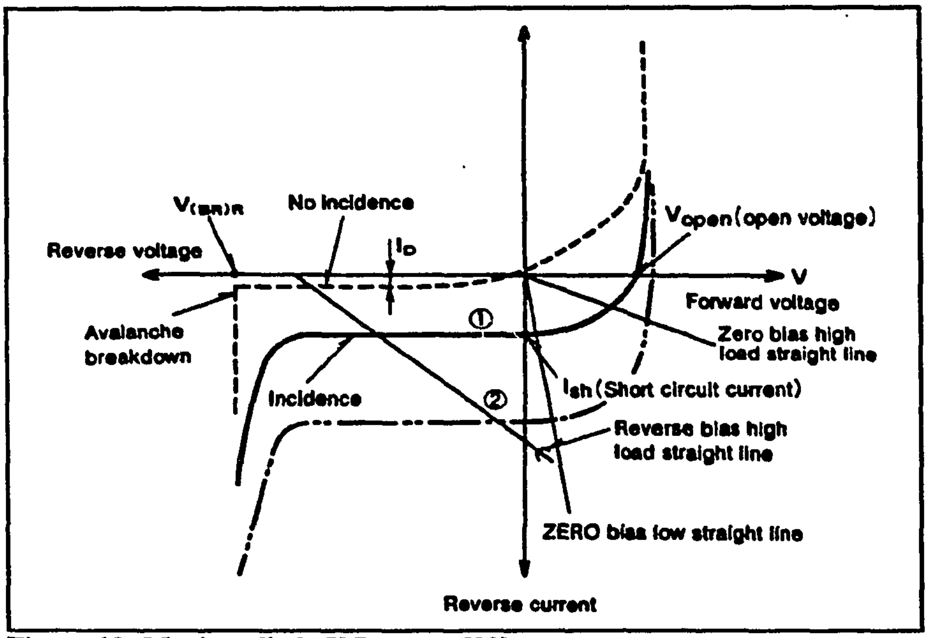


Figure 18 Monitor diode V-I curves [23].

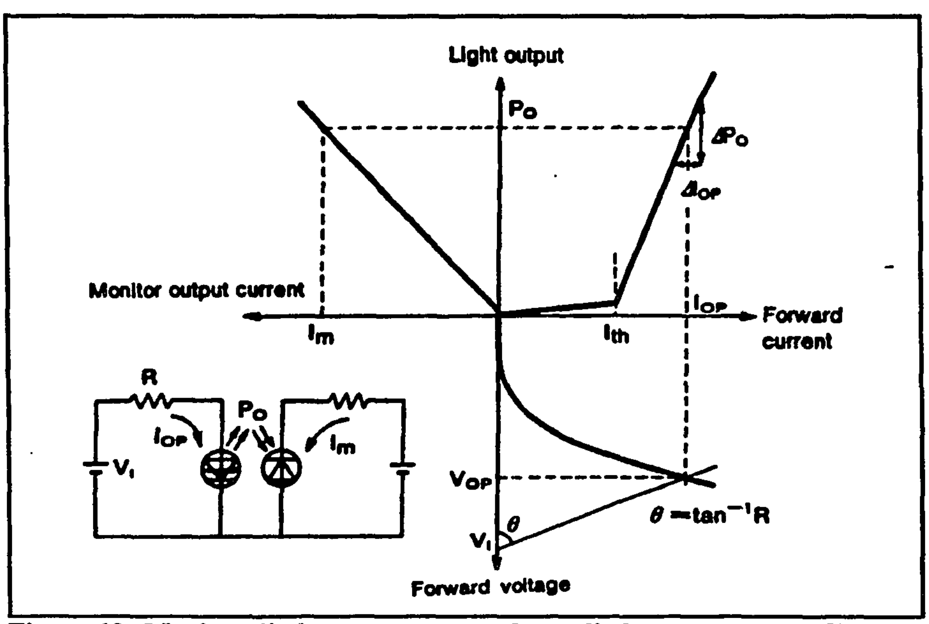


Figure 19 Monitor diode current versus laser diode output power [23]

CHAPTER THREE

A QUESTION OF LIFETIME AND DEATH

The operating lifetime of a laser diode is in the tens of thousands of hours and is being improved from process and design refinements. However, this longevity is only possible if the laser diode is handled and driven properly. As we shall show, thermal stress, current transients, and poor handling are laser diodes' deadliest foes.

A laser diode's lifetime or Mean Time To Failure (MTTF) can be defined according to specified parameters of a laser diode when thermal stress or current transients are applied to it. These parameters decrease or increase by a percentage of the initial value under such stress. Three most common definitions are as follows [16]:

1. **Constant Current Failure:** At a constant drive current, the optical output power falls below a specified fraction of the initial value (usually 1/2 or 1/e).
2. **Constant Light Failure:** At a constant optical output power, the drive current required increases above a specified factor of the initial value.
3. **Threshold Current Failure:** When the threshold current increases above a specified factor of the initial value.

In this thesis, we use the Constant Light Failure criterion to define the life time.

3.1 Definition of Lifetime

The laser diode lifetime of constant light failure is determined by measuring the change in optical output power P_o versus forward current I_F. In the measurement, the laser diode is biased to produce constant P_o at an operational current of I_{op} with an APC drive. Its P-I characteristics is monitored at different intervals. At some time $t=t_0$, the slope efficiency decreases from that of the initial condition. The decrease in efficiency signals a crystal degradation and is usually accompanied by higher threshold current requirement. Finally, the degradation reaches a point beyond which the P_o can not be kept constant (Fig. 20).

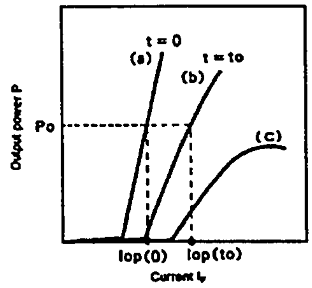


Figure 20 P-I curves for lifetime measurement [23].

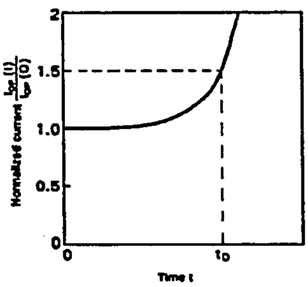


Figure 21 Normalized current versus time for lifetime measurement [23].

As time proceeds, the bias current I_{op} that maintains a constant light output is logged versus time. The time t_0 at which I_{op} is 1.5 times the initial I_{op} is defined as the *lifetime* of the laser diode as shown in Fig. 21.

The temperature rise of the laser diode case accelerates the degradation in lifetime according to the Arrhenius formula [23],

$$A_L = e^{\frac{\Delta E}{k}\left(\frac{1}{T_o}-\frac{1}{T_1}\right)} = e^{11606 \Delta E\left(\frac{1}{T_o}-\frac{1}{T_1}\right)} \qquad (7)$$

where A_L is the acceleration (or MTTF degradation) factor, T_0 and T_1 are case temperatures in Kelvin at times t_0 and t_1 respectively, k is Boltzmann's constant, and ΔE is the activation energy.

For example, with 1 eV of activation energy and 10 °C rise from the room temperature (300 K), the lifetime accelerates (MTTF is reduced) 2.8 times [23]. Figure 22 depicts this relationship.

Another factor determining a laser diode lifetime is its optical output power. The higher the optical output power, the higher is the optical power density in mW/cm^2 on the diode's facets, which accelerates their degradation. Although there is no exact formula for MTTF versus the optical output power, the acceleration factor between output powers P_2 and P_1, B_L, is experimentally shown to have the following approximate form:

$$B_L = \left(\frac{P_2}{P_1}\right)^n \qquad (8)$$

For example, when the optical output power is increased from 2 mW to 6 mW and with n = 2, the MTTF is reduced by a factor of 8 [23]. See Fig. 23.

As heat builds up in the active area, and the beam energy on the facets increases, the facets deform, and the Fabry-Perot resonating action disappears. Consequently, the diode stops lasing.

Since temperature and optical output power play important roles in the lifetime of a laser diode, it is prudent to take into consideration the situations that result in thermal stress and a rise in optical output power when we design the laser diode drive circuit. Sources of thermal stress will be presented next. Also, because any sudden current injection into the laser diode produces an almost instantaneous jump in optical output power, noise of sufficient amplitude, transients,

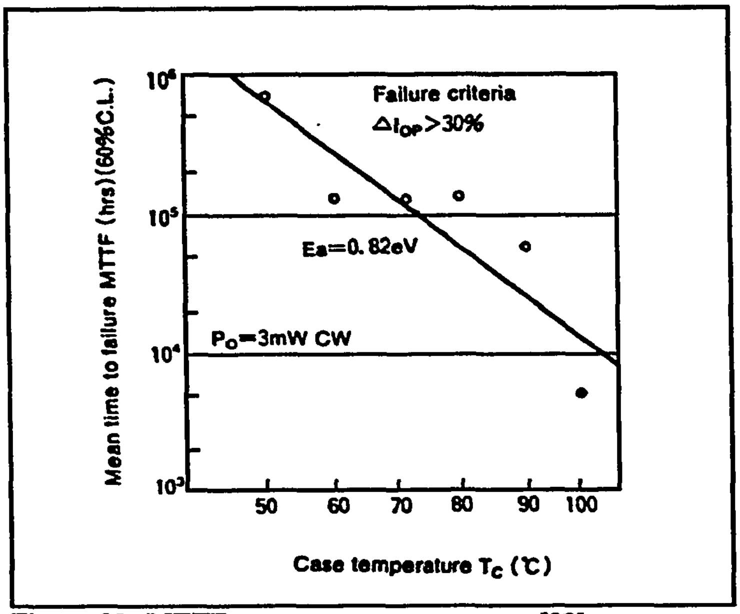


Figure 22 MTTF versus case temperature [23].

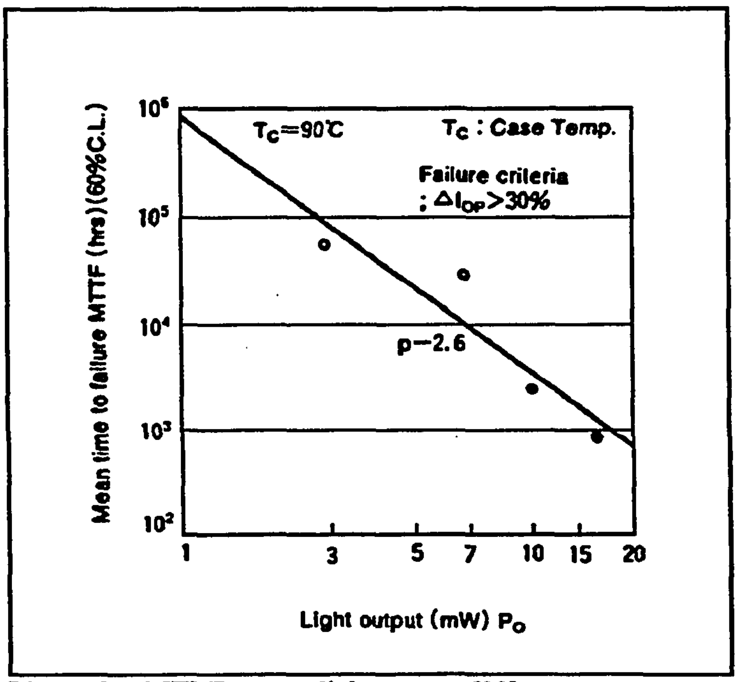


Figure 23 MTTF versus light output [23]

and ESD can all accelerate the lifetime to termination! We will take issue with them following the section on thermal stress.

3.2 Thermal Stress

Thermal stress is a result of the heat build-up due to poor heat sinking of the laser diode or a sudden big jump in the junction temperature. In essence, thermal stress is the mother of all enemies of laser diodes. At low levels, thermal stress affects performance parameters such as frequency stability of laser diodes, and at high levels, it destroys them. The heat build-up can be traced to either internal or external sources.

3.2.1 Internal Source of Heat

Below the threshold current, most of the injected energy is lost as heat. Thus, the higher the threshold current, the higher the thermal stress that the active area experiences before lasing begins. Considering that the active area is a narrow strip of a few microns wide by a few hundred microns long , current densities of several kilo Amperes per square centimeter are possible. In fact, one of the parameters that determines the life expectancy of a laser diode is the threshold current density J_{th} which is derived from dividing the I_{th} in amps by the active area in cm^2.

As the drive current increases, the junction temperature of the laser diode also increases. Temperature rise in the active region reduces the band gap energy, which causes the dominant wavelength to first increase at a slow slope and then suddenly *hop* to the next wavelength

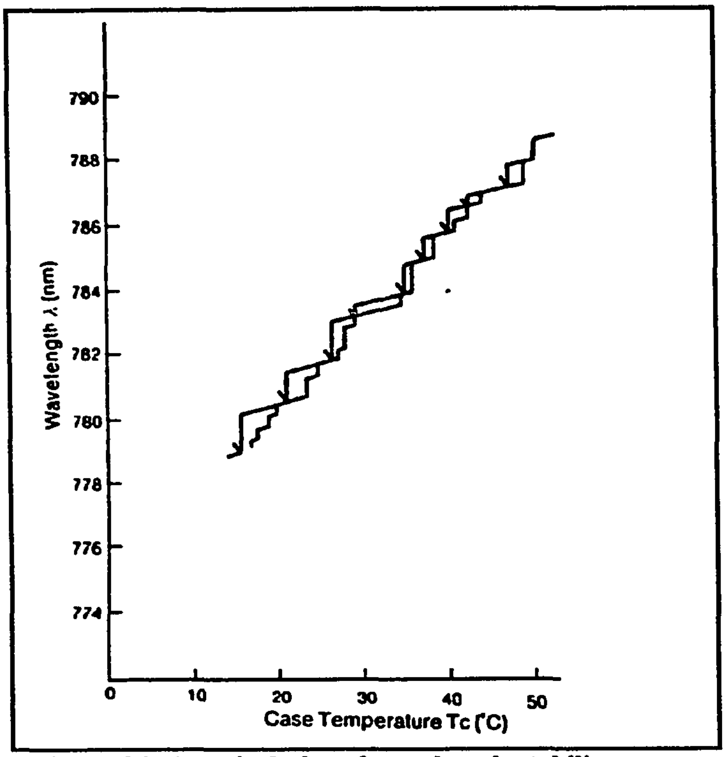


Figure 24 A typical plot of wavelength stability versus temperature for a laser diode [14].

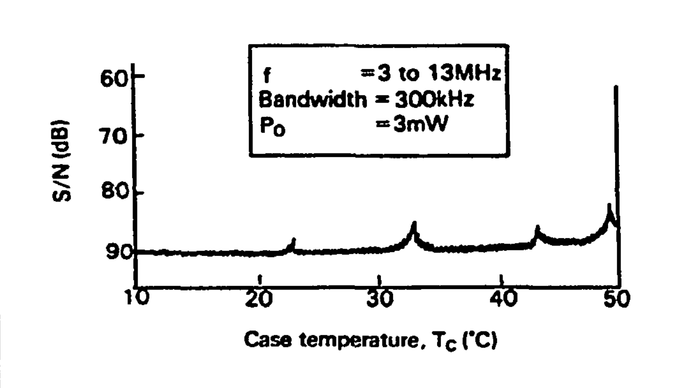


Figure 25 Mode hopping noise versus temperature [14].

(longitudinal mode). This is known as *mode hopping*. With a reduction in the case temperature a hysteresis effect is observed as shown in Fig. 24.

Mode hopping produces a brief period of noise, followed by a shift in the light output power to the next wavelength. The mode hopping noise increases with temperature rise as shown in Fig. 25. If the temperature rise is not controlled, the dominant wavelength keeps hopping to the next higher wavelength.

Mode hopping obviously is undesirable when a stable single frequency is required. The DFB laser diode as mentioned before suppresses side longitudinal modes and allows only one mode to dominate. However, even with a DFB laser diode, a well-designed drive circuit is needed to achieve better performance levels. It is because drive current instabilities result in fluctuations in the injection current density. Excessive current density fluctuations in the active region change the junction temperature. Although the DFB laser diode is extremely stable, the junction temperature change will affect its wavelength [42].

Another temperature related phenomenon is that with an increase in laser diode ambient temperature, a higher I_{th} is required as shown previously in (4). In a study done by ILX for example, a Mitsubishi ML4402 laser diode was tested at temperatures from -20 °C to +70 °C at 10 °C increments. The I_{th} went from 33.8 mA at -20 °C to 54.7 mA at +70 °C [17].

3.2.2. External Sources of Heat

External excessive heat applied to a laser diode can also degrade or damage it outright. One most frequently overlooked external heat source is the improper soldering practice during assembly.

Manufacturers' guidelines should be followed when soldering laser diode pins. Heat from the soldering iron tip to the active areas and the facets can destroy the diode. It is important to mount the laser diode to the heat sink before soldering the pins. A better solution is to use transistor sockets, such as the 8058 or 8059 series sockets made by Augat, Inc., Attleboro Falls, MA. The socket is either soldered to the printed circuit board or the cable assembly and then the laser diode is inserted in it.

3.2.3 Effect of Heat On the Monitor Diode Performance

For laser diodes with wavelengths below 1 micron, as temperature increases, the monitor diode's current, I_{MON}, decreases. This is because the laser longitudinal mode keeps hopping to higher wavelengths, but the spectral window of detection remains pretty much the same. Thus, the photo detector sees less power. If the monitor diode is used as feedback in the APC circuit, the reduction in its current deceives the APC circuit to pump more current into the laser diode, thus starting a vicious cycle of more laser diode current, higher temperature (more thermal stress), longer wavelength, lower power in the detection window, and lower monitor current until the thermal stress destroys the laser diode.

3.2.4 Combating Thermal Stress

From the previous discussion, keeping the junction temperature of laser diodes low is the prerequisite for maintaining good performance, high efficiency, and long lifetime. Depending on applications care, from simple heat sinking to more elaborate thermoelectric cooling (TEC) stabilization is needed to maintain a low junction temperature. For most applications heat sinking is sufficient and can be implemented inexpensively. The TEC method is more involved and expensive, and usually is a super-set of the heat sinking method.

3.2.5 Heat Sinking

CW lasers require an external heat sink, attached to the case to reduce the junction temperature. During operation, the absolute maximum case temperature should never be exceeded. It is recommended, when designing a heat sink or using off the shelf standard finned heat sinks for transistors, to leave a 10 °C cushion between the absolute maximum rating and the operating temperature. Since the junction temperature is always higher than the case temperature, ambient temperature rises can cause the violation of the absolute maximum rating. Also, it is recommended to select laser diodes with low thermal resistance, defined as the "incremental change in the junction temperature per incremental change in power dissipation." Low thermal resistance values are indicative of good junction to case thermal contact and heat transfer. Look for values less than 30 °C/W.

If the laser diode is to be mounted on or in a fixture without a separately built heat-sink, two preventive measures should be taken:

A. The contact area should be very thermally conductive, and the holding fixture should provide a means of transferring and dissipating the heat from the laser diode case. Usually, the part of the case that is in thermal contact with the active area is marked on the case. The contact between the holding fixture and the case should include the marked band.

B. During normal operation, the fixture may be touched by people. Therefore, it should be designed to have no ohmic contact between the laser diode case in general and the active area in particular to prevent ESD damage. There are commercially available materials with excellent insulating properties and thermal conductivity. One such material is Beryllium Oxide which is a superb electrical insulator but with thermal conductivity similar to metals [44]. However, it is extremely toxic and requires great care in handling.

3.2.6 Heat Sink Design

Special care should be given to the design of a proper heat sink attached to the laser diode case. The thermal resistance of the heat-sink is determined by the following equation:

$$\theta_f = \frac{T_c - T_a}{I_{op} \cdot V_{op}} - (\theta_s + \theta_c) \qquad (9)$$

where T_c and T_a are case and ambient temperatures (°C) respectively, I_{op} is the operating current in Amp, V_{op} is the operating voltage in volts, and θ_f , θ_s , θ_c are the thermal resistances of the heat sink, the insulator panel, and contact respectively.

For example, for T_c = 45 °C, T_a = 40 °C, I_{op} = 80 mA, V_{op} = 3.0 volts, θ_c =10 °C/W, and θ_s =0.5 °C/W (for a Delta Pad Thermally Conductive Insulator No. 173-9), we get θ_f =10.3 °C/W. Using Fig. 26, and choosing a 2 mm thick aluminum plate, we need about 35 cm^2 of heat sink area to keep the thermal resistance below 10.3 °C/W [46]. Section 15 of [25] provides a good tutorial on heat sink design.

3.2.7 Thermo-electric Cooling (TEC)

In addition to heat sinking, where stable wavelength is required, TEC provides another alternative. Many laser diode manufacturers provide laser diodes with integrated TEC and thermal sensors (thermistors) in the package. The signal from the thermistor is sensed in a feedback loop that directs the TEC to keep the case temperature at a constant safe value. With TE cooling, case

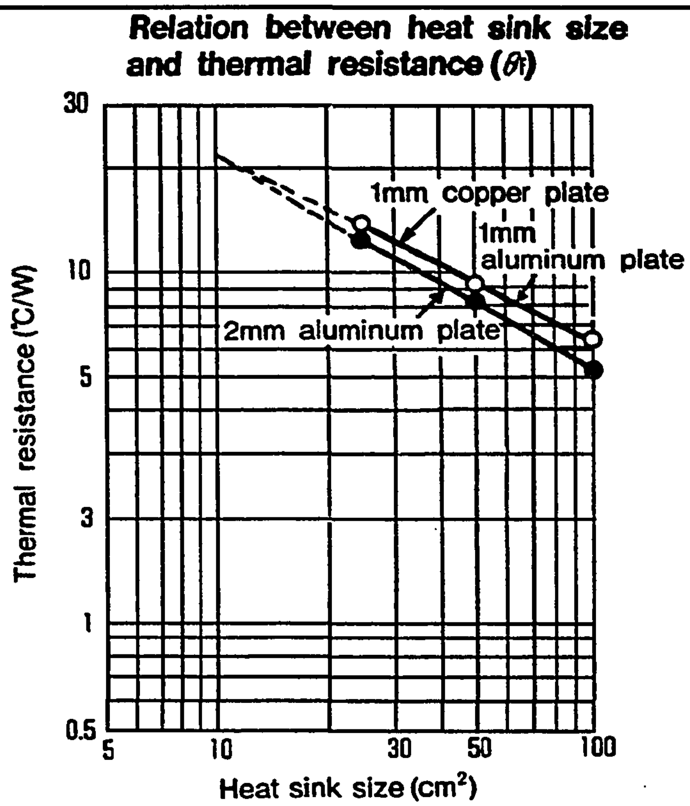


Figure 26 Heat sink size versus thermal resistance [45].

temperatures can be maintained within 0.05 °C [21]. External thermoelectric cooler and thermistors can also be used in a similar fashion to stabilize the laser diode.

A TEC is a solid state device that behaves as a small heat pump comprised of a Hot and a Cold plate, transferring heat energy from one plate to the other. TECs work based on the principal of Peltier Thermoelectric Effect demonstrated by J.C. Peltier in 1834. Peltier showed that when two conductors of the same material are connected to a third dissimilar conductor, and

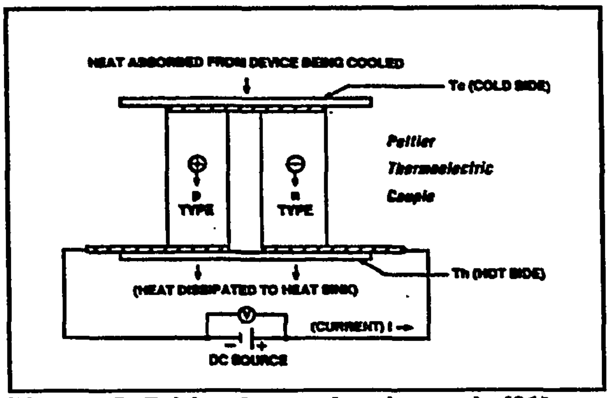


Figure 27 Peltier thermoelectric couple [21].

a current passes through them, one end of the third conductor will get cooler or warmer than the other end depending on the direction of the applied current [2].

In its most basic form, a TEC is made-up of a thermoelectric couple. Instead of dissimilar

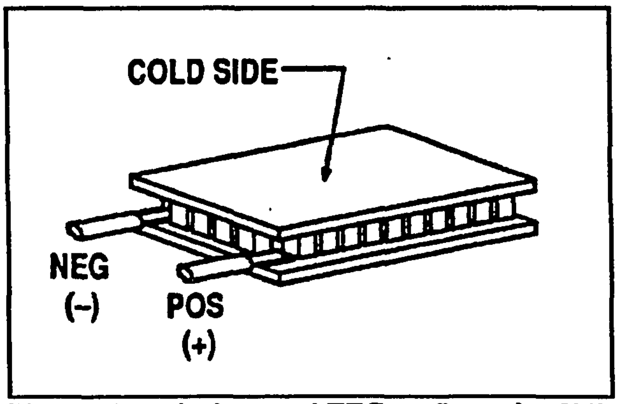


Figure 28 A single-staged TEC configuration [21].

conductors, a thermoelectric couple consists of a p-type and n-type semiconductor known as thermoelement as shown in Fig. 27. Electrons in the p-type thermoelement are at a lower energy level than electrons in the n-type thermoelement. With the n-type thermoelement biased positive relative to the p-type one, electrons from the p-type thermoelement pass through the n-type thermoelement, absorbing the heat from the Cold side in the process. The heat is then transferred to the Hot side by the n-type thermoelement, and dissipated as the electrons return to the p-type thermoelement back to a lower energy level. If the direction of the current is reversed, the Peltier thermocouple will act as a heat pump, warming up the Cold side relative to the Hot side. Thus, a TEC can be used to cool, warm, or temperature stabilize a device attached to it. Figure 27 shows the Peltier thermocouple in the cooling mode.

The cooling is proportional to the current and the number of Peltier thermocouples. A TEC may consist of one thermocouple to several hundred thermocouples connected in series electrically and in parallel thermally, sandwiched between two ceramic plates as shown in Fig. 28. The ceramic plates may or may not be metallized. TECs can be stacked up vertically to form a multi-stage TEC. Each descending stage has more Peltier thermocouples than the stage above it to be able to pump the heat dissipated by the upper stage as well as the heat from the cold plate (Fig. 29). With multi-stage TECs, cryogenic cooling to 150 degrees Kelvin and heat pumping of 50 W can be achieved for some loads [21].

Usually the Cold plate is attached to the device to be cooled and the Hot plate to a heatsink. The mounting method depends on the TEC size and the device it is to be attached to. One of three methods are in use: (a) bonding with thermal epoxy, (b) compression with a thermal compound, or (c) soldering to metallized ceramic(s).

As the discussion above shows, TEC can provide many advantages over simple heatsink

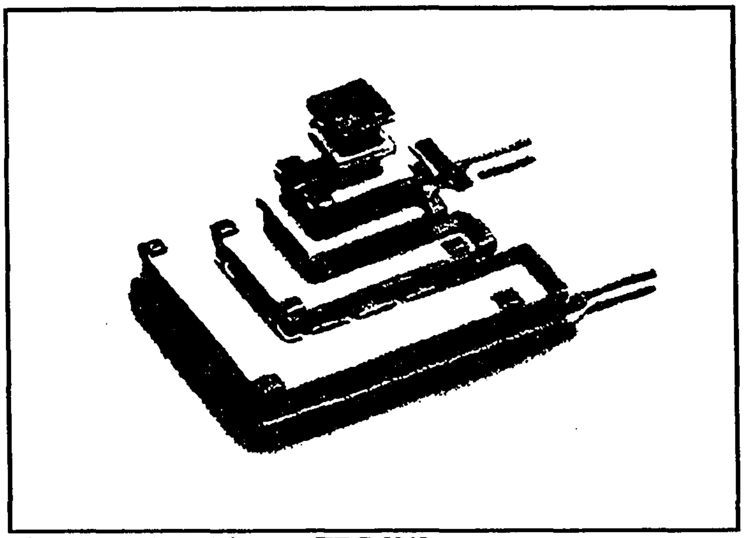


Figure 29 A multi-stage TEC [21].

cooling method such as:

(a) Precision temperature control to within 0.05 °C [21],

(b) Temperature control below and above ambient,

(c) Localized cooling, and

(d) Heating or cooling -- depending on the direction of the current.

3.3 Excessive Optical Output Power Density

As mentioned previously, due to the fast response of the laser diode light output to the drive current variation, transients and noise of sufficient amplitude can result in high optical output power densities inside the active layer and on the facets. The result is an overheating of the facets which, depending on the incident power density, will deform or destroy the facets. In any case, the laser diode is rendered useless. In this chapter, we will first discuss the sources of transients that can affect the laser diode. Noise, due to many sources generating it, will be discussed in the next chapter.

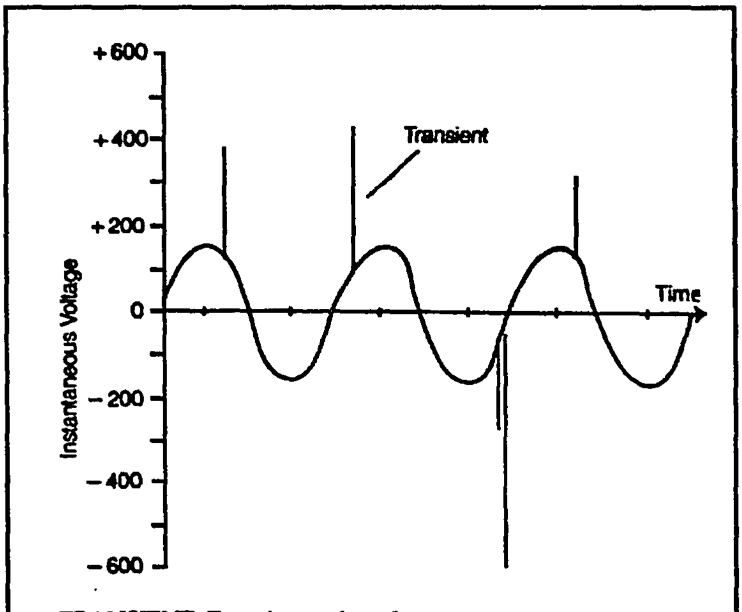
3.3.1 Transients

Transients are voltage or current surges that are super-imposed on signals with deadly consequences for the victim circuits. Two categories of transients are discussed here: (1) high peak voltage or current transients over several hundred volts or amps, and (2) low peak ones. Power line transients and ESD are in the former category; while dc power supply turn on spikes and interference from nearby AC or high frequency digital circuits are of the latter kind.

3.3.1.1 Power Line Transients

Power line transients are common high voltage spikes (several hundred volts) that occur very briefly on the power line. They are caused by lightning, power grid switching by the power company, or electric arcing from relay contact closures. One study [30] recorded 277,612 voltage and current transients in nine cities in a period of two years from January 1982 to December 1983, some reaching voltage and current peaks of nearly 2000 volts and 1500 amps respectively. This gives an average of 42 destructive transients per day per city. The time to peak voltage was around a few micro-seconds and to peak current was in the high tens of micro-seconds. The situation at some industrial sites can be much worse. At such sites, an extreme isolation transformer (EIT) is the first defense line against transients (as used in hospitals operating sensitive equipment).

High voltage spikes punch through semiconductor devices and destroy them. For a



TRANSIENT: Transients of an alternating-current wave.

Figure 30 AC line transients [30].

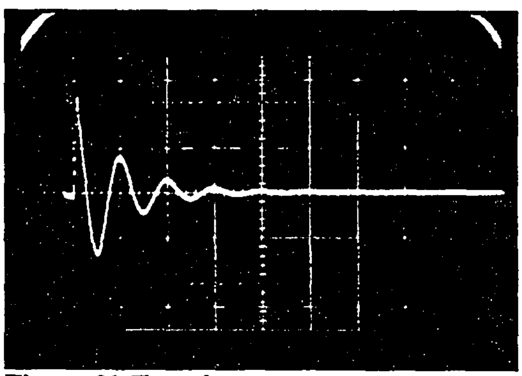


Figure 31 Transient current
Horizontal scale: 10 us/div
Vertical scale: 100A/div [30].

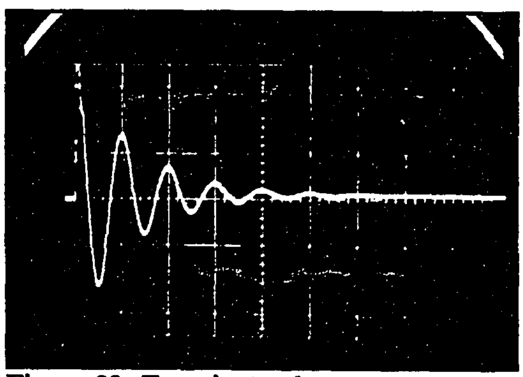


Figure 32 Transient voltage
Horizontal scale: 10us /div
Vertical scale: 2KV/div [30].

semiconductor device, only a trillionth of a second exposure to such transients is needed to bring immediate destruction. For current spikes, it may take a few milliseconds for the device to be destroyed. Figure 30 shows typical voltage transients on AC lines. Figures 31 and 32 show examples of severe voltage and current transients.

Obviously, the drive circuit must be protected against transients. Two commonly used over-voltage protection devices are silicon Transient Voltage Suppressor (TVS) and Metal Oxide Varistors (MOV) [10]. For over-current protection fusing offers a simpler solution.

A TVS is a Zener avalanche PN junction diode that shunts the voltage surge to ground when it exceeds the Zener's reverse bias voltage. When the surge is gone, the circuit is restored to its normal mode. Silicon TVS is an optimum transient suppressor due to its picosecond response time, low series resistance values, and high surge handling features. It is primarily used in DC circuits, although two devices back to back can be used in AC circuits.

The MOV is a variable resistor which behaves like two TVS's put back to back. It is a nonlinear resistor whose value decreases with increased applied voltage. It can provide clamping of both positive and negative AC swings. When the voltage exceeds the MOV's rating, it behaves like a short resistor with high current capability, thus absorbing the typically large currents associated with surges, without being destroyed. The only drawback of MOV's is that as the number of clamping cycles increase, especially after a few thousand times, they lose their effectiveness.

Fusing often provides some degree of over-current protection. Usually fuses have slow response time compared to high speed current transients, but nevertheless they provide a safe mechanism in most applications. For laser drive circuits, a fuse with a very fast response time (in the picosecond range) is recommended.

Finally, in the DC section of the drive circuit, supply rails must be filtered, and a slow start circuit is needed to absorb any transients with minimal feed-through. The slow start circuit also brings the current source smoothly to its operating point. In general, a good drive circuit has a transient feed through of equal to or less than 1 mA for a typical transient of 500-600 volts peak amplitude.

3.3.1.2 ESD

Electro-Static Discharge (ESD) is perhaps the most common cause of laser diode destruction. ESD can reach the laser diode from a human touch or from an ungrounded soldering iron tip. In either case, the failure mechanism is the same as any current transients induced in the active region. If the circuit is on, ESD can instantaneously cause a high peak laser light which overheats the facets and destroys them. In the absence of a DC field across the laser diode, ESD can punch through the active layer and destroy it.

Although laser diodes with wavelength longer than 1.3 microns or low threshold currents are more susceptible to ESD destruction, the general ESD isolation guideline given below should be followed regardless of the device used.

3.3.1.3 ESD Isolation

Simple precautions against ESD with bare laser diodes include: (a) wearing anti-ESD gear by anybody coming in contact with the laser diode, (b) using only a soldering iron with a grounded tip, and (c) transporting them in anti-static packages, with their leads shorted together.

With the laser diode inserted in the circuit, its case and heat sink must not make any ohmic contact with what may come in contact with the human touch especially while the system is on. Very few, if any, laser diodes can survive the ESD spikes. Although in many laboratories laser diode assemblies are handled by personnel wearing anti-static gears, designers should consider the worst case scenario and isolate both the case and the heat sink.

The drive circuit is usually enclosed. The enclosure should not have any ohmic contact with the drive circuit or its components, such as at ground points. Nor should external components of the circuit jeopardize the drive circuit ESD isolation. Although these concerns seem unusual, it is important and frequently overlooked. Some drive circuits provide the users with adjustments via external potentiometers mounted on the face plate or rear plate. If the potentiometer dial is metallic, or if its body is in ohmic contact with the enclosure, ESD from the operator may be large enough to affect the drive circuit and the laser diode.

3.4. Interference

Radio Frequency Interference (RFI) noise and Electro-Magnetic Interference (EMI) noise are two very serious and ever-present problems for sensitive equipment and circuits. Lightning, 60 hertz power line pick-up, noise from radio and TV transmitters, interference coming from nearby electrical equipment, motors and solenoids, TV sets, and switching power supplies/regulators also generate EMI and RFI noise.

The power spectrum and amplitude characteristics of RFI/EMI noise can vary significantly from one such noise source to another. For example, the 60 hertz pickup has a sharp, narrow spectrum with a relatively constant amplitude. On the other hand, the power spectrum of an impulsive noise source such as lighting is broad and the amplitude is spiky [15].

Interference in a circuit may be the result of (a) transients on power or signal input and output lines, (b) capacitive coupling between high and low frequency signals, (c) electromagnetic

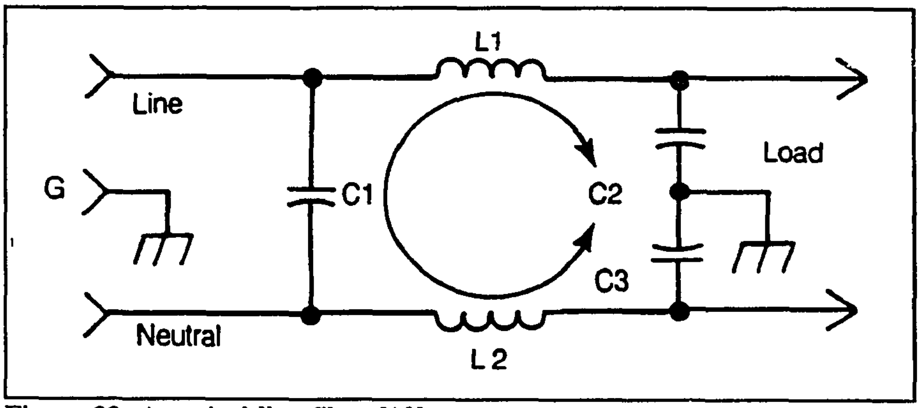


Figure 33 A typical line filter [10].

coupling to unshielded wires, (d) magnetic coupling to closed loops in the circuit, or (e) noisy signals from one part of the circuit coupling to another part through voltage drops on the ground or power supply lines [15]. Such interference can also seriously endanger a laser diode. Fortunately, good layout and construction, grounding, filtering, and shielding can reduce interference to insignificant levels, rendering them harmless to the laser diode [24].

Some interference sources can be quite conspicuous such as radiated noise form nearby high frequency (HF) sources like computers and instruments. For example, RFI can be coupled into capacitors that have high Effective Series Resistance (ESR), inductors, or the leads of the passive and active components in the printed circuit board, and create resonant pockets in various locations of the circuit. For capacitive coupling interference reduction, the best solution is a ground plane on the board. Inductors and wire-wound resistors are very susceptible to magnetic coupling, so it is best to avoid using them if possible.

To reduce RFI/EMI, line filters should be used. Basically, they are dual low pass filter networks as shown in Fig. 33. A line filter is put in series with AC line to attenuate the RFI noise (10 KHz to 30 MHz) to an acceptable level. At the same time, it permits the 50/60 HZ current to pass un-attenuated.

To reduce RFI coupling, long component leads should be avoided. If a cable is used to connect the laser diode to the drive circuit, twisted pair wires in a shielded cable provide the best interference immunity. To filter out high frequency interference noise, ferrite beads may be used, although the preferred method would be to use tantalum/ceramic pair bypassing capacitors. The pair acts as a self oscillatory tuned filter in the HF to VHF (tens to hundreds of megahertz) region.

CHAPTER FOUR

ELECTRICAL NOISE

Drive circuit noise comes from two main sources: *intrinsic* noise associated with the active and passive components in the circuit, and *interference* noise coupled into the circuit such as the 60 Hz hum which propagates through the system ground or comes from the power supply ripples.

Interference noise is in general far more insidious, albeit one can control it with intelligent preventive measures as discussed in Section 3.4. This chapter on electrical noise is focused on the sources of intrinsic noise and measures to reduce its various components.

Low amplitude electrical noise may not damage the laser diode, but it will degrade the performance. In applications where high accuracy and repeatability of a measurement is the prime concern, electrical noise must be reduced. In this chapter a brief discussion of physical sources of electrical noise will be presented and power spectral densities of noise generators in passive and active components including integrated circuits will be given. For a low noise laser diode driver circuit an understanding of these noise mechanisms is essential in selecting components with low noise behavior. Finally, the noise generated by the laser diode will be discussed.

4.1. Physical Sources of Electrical Noise

The term electrical noise means the unwanted signal that emanates from the intrinsic character of the electronic components used. Other external noise sources such as external interference is excluded from our discussion here.

Due to the quantum nature of electrical charge, electrical noise is the result of discrete random processes in electronic components. Electrical noise may be classified by its sources as *shot noise*, *thermal noise*, *flicker noise*, *burst noise*, and *avalanche* noise.

These noise sources are uncorrelated, and the total noise power is the sum of each one. For example, the total noise power of the flicker noise and the thermal noise for a given device is:

$$\overline{V_T}=\sqrt{<V_{th}^2>+<V_{1/f}^2>} \qquad (10)$$

where <.> indicates mean square or variance and the bar over V_T denotes root mean square (rms).

4.1.1 Shot Noise

Shot noise is the result of direct current flowing in p-n junction devices. The generation of charge carriers (electrons and holes) diffusing across the p-n junction under the influence of an electric field create random discrete current pulses with random amplitude and phase [31]. The random amplitude of the shot noise has a Gaussian probability distribution function. The mean square value of the shot noise component of the DC current across the p-n junction is given in A^2 by [11]

$$\sigma^2=\overline{i^2}=2qI_DB \qquad (11)$$

where q is the electric charge (1.6 X 10^{-19} C), I_D is the DC current in A, and B is the measurement bandwidth (hertz). This equation is valid up to many giga-hertz until 1/f becomes comparable to the carrier transit time through the depletion region. Thus the noise current spectral density, defined as

$$\frac{\overline{i^2}}{B}$$

is constant (white noise). From the Gaussian nature of the probability density function of the shot noise amplitude, one can deduce that 99.7% of the time the amplitude of the noise signal falls between ±3 sigma [11]. This amplitude can be represented as rms noise current per square root of the bandwidth. For example, the shot noise for a DC current of 100 mA through a p-n junction may be given as 179 nA per square root of hertz, written as

$$179\frac{nA}{\sqrt{Hz}}$$

Since 100 mA is a typical operating current for a laser diode, the shot noise contribution of the laser diode in CW mode is negligible.

4.1.2. Thermal Noise

Thermal or *Johnson* noise is a fundamental physical phenomenon in any linear passive resistor and results from the random thermal motion of electrons [11],[31], regardless of whether or not a current is present. The mean square value of the thermal voltage and current noise is given by [11],[31]

$$\overline{v^2}=4kTRB \qquad (12)$$

and

$$\overline{i^2} = 4kT\frac{1}{R}B \qquad (13)$$

respectively, where k is the Boltzmann's constant (1.380 X 10^{-23} J/K), T is the temperature in Kelvin, and B is the measurement bandwidth. Again, as seen from the above equations, the power spectral density of the thermal noise is independent of frequency (up to 10^{13} Hz), indicating that thermal noise is also white noise. For a 1 ohm resistor, the rms noise current per square root of hertz at 300 $°K$ is

$$129\frac{nA}{\sqrt{Hz}}$$

Like shot noise, thermal noise too has a Gaussian amplitude probability distribution function, its sum with shot noise is also Gaussian, making the two indistinguishable from each other in a circuit.

4.1.3 Flicker Noise (1/f Noise)

Flicker noise is a non-Gaussian low frequency type of noise generated by different mechanism in different devices when a direct current flows [11]. In semiconductor devices, the flicker noise is the result of structural defects and doping contaminations in the semiconductor crystal. These imperfections create traps inside the semiconductor which randomly capture and release charge carriers. The time constants associated with these processes are long. This means that the resulting current pulses have a low frequency power spectrum (hence the term 1/f noise) with a variance given by

$$\overline{i^2} = K_1 \frac{I^a}{f^b} \Delta f \qquad (14)$$

where I is a direct current, a is a constant in the range 0.5 to 2, b is a constant nearly equal to 1, and K_1 is a constant which results from the contamination and crystal defects. As such, K_1 can vary widely even on the same silicon wafer, because the aforementioned imperfections are randomly distributed. This implies that the mean square value of a flicker noise is not well defined, unlike that of the shot or thermal noise. However, a typical value for K_1 can be obtained empirically for a given process by measuring the power spectrum of flicker noise of an ensemble of devices fabricated by that process [11].

4.1.4. Burst Noise (Popcorn Noise)

Another type of non-Gaussian noise with a power spectrum at low frequencies (audio range) is burst noise. Burst noise is found on silicon integrated circuits and discrete bipolar transistors made with planar diffused process, and is shown to be high in devices with heavy-metal contamination [47],[11]. However, the exact source of burst noise is yet to be found. Since a "popping" noise is produced from a loudspeaker driven by burst noise, sometimes it is referred to as "popcorn" noise.

The power spectrum of burst noise overlaps that of the flicker (1/f) noise, although at higher frequencies it is proportional to $1/f^2$. Its power spectral density is of the form [11]

$$S_i(f)=K_2\frac{I^c}{1+(\frac{f}{f_c})^2}B \qquad (15)$$

where K_2 is a constant found empirically for a particular device, I is direct current, c is a constant between 0.5 and 2, f_c is a particular frequency for a given process, and B is the bandwidth of measurement.

4.1.5 Avalanche Noise

The process of avalanche breakdown in a p-n junction releases a great many electron-hole pairs randomly colliding with the silicon atoms and producing even more electron-hole pairs. The resulting current spikes form a random noise process with a generally non-Gaussian amplitude distribution but with an approximately flat spectral density [11].

A common source of avalanche noise in circuits is when Zener diodes are used to operate in their break-down region, for example as voltage references or in a clamping circuit. The magnitude of the mean square of avalanche noise is usually high enough to affect the performance of a low noise circuit. As an example, a typical value found for the avalanche noise of a Zener diode at a DC current of 0.5 mA was 10^{-14} V^2/Hz, which compares with thermal noise voltage of a 600 Kohm resistor [11]. Therefore, where low-noise operation is needed Zener diodes operating in their avalanche region should not be used.

4.2. Component Selection Criteria

Since, as we will see in chapter five, low noise operation is one of the specifications of the drive circuit, design components must be selected with low noise figures. This criterion applies to both passive and active components.

4.2.1. Passive Components

A. Capacitors

The characteristics of actual passive components such as capacitors and resistors deviate from their respective theoretical (ideal) models. The equivalent circuit of an actual capacitor is shown in Fig. 34 [32]. The parallel resistor R_2 is a function of the volume resistivity of the dielectric material and accounts for the parallel leakage. The series resistor R_1, known as *effective series resistance* (ESR) of the capacitor is a function of the dissipation factor of the capacitor. The inductance L is the result of the capacitor leads and structure [32]. Clearly, the RLC circuit equivalent of the capacitor indicates its behavior dependency on frequency. In fact, at some frequency, the capacitor becomes self-resonant. Therefore, for different frequency applications, different types of capacitors are needed. For each type, the lower frequency limit is set by the largest practical capacitance value that can be obtained, while the upper frequency limit is set to fall below the typical self-resonant frequency for each type.

There are many types of capacitors available today each suitable for use in a frequency range determined by its construction, and material properties. They can basically be categorized as either electrostatic or electrolytic capacitors. Electrostatic capacitors have solid material or air as dielectric. Plastic, paper, ceramic, glass, and MICA fall in this category. In electrolytic capacitors the oxide dielectric is formed by electrochemical reaction, and depending on the metal

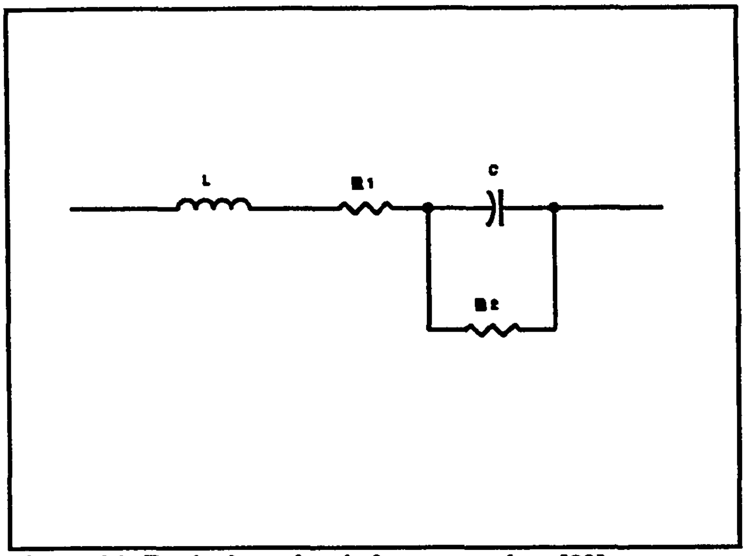


Figure 34 Equivalent circuit for a capacitor [32].

used they are sub-classified as aluminum or tantalum types [10]. A partial listing of capacitors and available values is provided in table 5.

Electrolytic capacitors have high capacitance-to-volume ratio with low ESR, and high inductance. Thus they are suited for low frequency filtering, bypassing, and coupling. Solid tantalum capacitors have a much lower ESR and inductance and are much more stable with respect to time, temperature and shock than the aluminum kind. They also perform better at voltages lower than their rated operating voltage.

Among the electrostatic category of capacitors, MICA, ceramic, and polystyrene types exhibit the lowest ESR and inductance. Polystyrene capacitor characteristics approach those of the ideal capacitor [32]. They are available in the sub-micro Farad range and are ideally suited for high frequency filtering and bypassing.

The only noise source in capacitors is the thermal noise which is generated by the their

Type	Capacitance Range	Maximum Voltage	Tolerance	Temperature Stability
Mica	1pF-0.01uF	100-600V	± 10%, ± 5%	Good
Ceramic	10pF-1uF	50-30,000V	± 20%, ± 10%	Poor
Polystyrene	10pF-2.7uF	100-600V	± 10%, ± 5%	Good
Polycarbonate	100pF-30uF	50-800V	± 20%, ±10%, ±5%, ±2.5%, ±1%	Excellent
Polypropylene	100pF-50uF	50-800V	± 5%, ±2%, ±1%	Good
Tantalum	0.047uF-470uF	6-100V	± 20%, ± 10%	Poor

Table 5. A partial list of capacitor types and properties [15], [32].

parasitic ESR. Therefore, high ESR capacitors such as electrolytic ones should be avoided. Also, the leads should be kept as short as possible. Wherever possible, chip capacitors should be used.

B. Resistors

As mentioned before, the thermal noise is one fundamental characteristic of resistors with voltage and current mean square values given in (12) and (13) respectively. As mentioned before, a resistor will always exhibit thermal noise whether a current is flowing through it or not. One can even consider the thermal noise as the open circuit noise of the resistor. Another fundamental noise process in resistors is a type of flicker noise which is generated when a DC current flows through the resistor. Since real resistors do not have a constant resistance along the DC current path, random voltage fluctuations along the resistor are inevitable. The power spectrum of these fluctuations exhibit a 1/f dependency. Thus the flicker noise of resistors depends on the their construction including the end caps and the resistive material. Carbon composition resistors have the worst rms flicker noise. By contrast metal film and wire wound exhibit practically no flicker noise [15],[31].

4.2.2 Active Components

A. Junction Diodes

Fig. 35 shows the noise model for a diode. V_s^2 represents the thermal noise generator resulting from the resistivity of the silicon and i^2 is the sum of shot noise and flicker noise. These noise variances are given in (16) and (17).

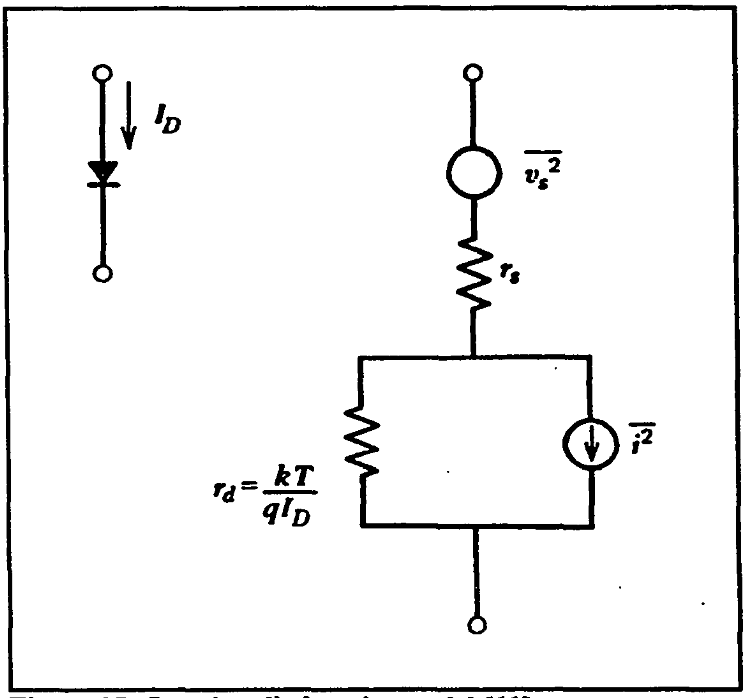


Figure 35 Junction diode noise model [11].

$$\overline{v_s^2} = 4kTr_s\Delta f \qquad (16)$$

$$\overline{i^2} = 2qI_D\Delta f + K\frac{I_D^a}{f}\Delta f \qquad (17)$$

B. Bipolar Transistors

In a bipolar transistor, whether *pnp* or *npn*, one should expect shot noise with the collector current I_C and base current I_B since both at the collector-base and base-emitter junctions the processes of carrier diffusion and drift are purely random. Furthermore, due to the base resistance of the bipolar transistor r_b there is the ever-present thermal noise. In addition, the base current shows flicker noise and burst noise components. Since all these noise sources are un-correlated, their mean square values add. Finally, there is the possibility of avalanche noise if the collector-emitter voltage V_{CE} gets within 5 volts of the BV_{CEO} (collector-emitter break-down voltage).

Manufacturers rarely give noise figures for bipolar transistors. However, the r_b figure is usually provided. Sometimes one may also find a noise plot in the data sheet. Before choosing a bipolar transistor for a low noise application, one should always obtain as much noise information as available and pick the transistor with the lowest noise power and r_b.

C. Field Effect Transistors (FET)

The most important source of noise in all FETs is the thermal noise due to the drain-source channel resistance. Drain-source current also exhibits flicker noise. In addition, there is shot noise generated by the gate leakage current.

D. Operational Amplifiers

The intrinsic noise of an operational amplifier has three sources which originate essentially from the operational amplifier's input stage [47]:

1. Thermal noise form the input transistor stages.
2. Flicker noise
3. Burst noise

For most available operational amplifiers today, only the first two sources are important.

The noise seen at the output is effectively the rms sum of all the aforementioned noise multiplied by the noise gain of the operational amplifier and can be significant when this output is driving a laser diode.

Two operational amplifier circuits are shown in Fig. 36 and 37 with i_n and e_n being the equivalent input noise current and voltage sources (rms per square root of hertz) respectively [15]. To select low noise operational amplifiers, one must look at i_n and e_n figures which are usually given. In some instances a plot of flicker noise is also provided in the data sheets.

The thermal noise of the feedback resistor should not be overlooked either. If we denote the total power spectral density of the input noise current and voltage by $<i^2_A>$ and $<e^2_A>$ respectively, and parallel equivalent resistance of R_1 and R_2 as $R_{//}$, we have for the non-inverting case (Fig. 36)

$$<i_A^2>=<i_n^2> \qquad (18)$$

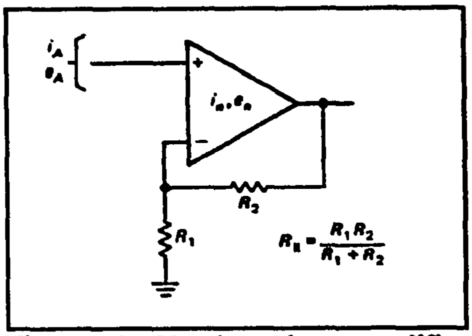


Figure 36 Non-inverting amplifier [15].

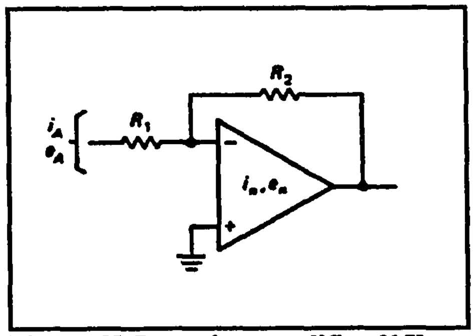


Figure 37 Inverting amplifier [15].

$$\langle e_A^2 \rangle = \langle e_n^2 \rangle + 4kTR_{\parallel} + \langle i_n^2 \rangle R_{\parallel}^2 \qquad (19)$$

and for the inverting case (Fig. 37)

$$\langle i_A^2 \rangle = \langle i_n^2 \rangle + \frac{4kT}{R_2} \qquad (20)$$

$$\langle e_A^2 \rangle = \langle e_n^2 \rangle + \langle i_A^2 \rangle R_1^2 \qquad (21)$$

As mentioned before, flicker noise is another source of noise in operational amplifiers. The point that the slope of the power spectral density of flicker noise starts to decrease is known as the 1/f corner frequency, as shown in Fig. 38. An operational amplifier used in a CW laser diode driver circuit must have very low 1/f noise. This is especially important when an operational amplifier is used in an Automatic Power Control (APC) circuit.

Traditionally, to reduce the 1/f noise, a designer has to implement filters with large time-constants. But this solution has a severe negative impact on the system's response time. Fortunately, there are many high speed precision operational amplifiers available now with low 1/f noise. One good choice is Linear Technology's LT1006 operational amplifier [19].

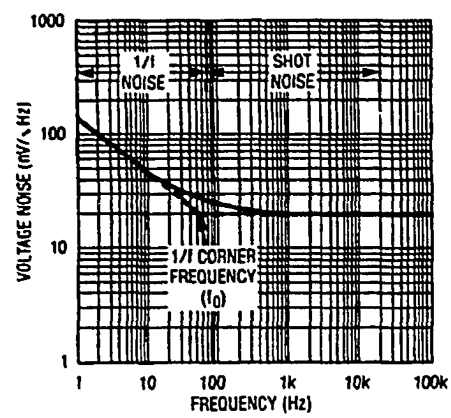


Figure 38 A Good operational amplifier 1/f noise figure.

Most manufacturers provide the 1/f noise figure for the frequency range from 0.1 Hz to 10 Hz. This is quite reasonable since the rms value of the 1/f noise amplitude at infinitesimal frequencies is only a few times bigger than the figure presented for the 0.1 to 10 hertz bandwidth. For example, by integrating (14) (page 64) from 0.1 to 10 hertz to get the noise variance $\langle I^2_{nA} \rangle$, and from 10^{-18} Hz (inverse of the age of the universe) to 10 Hz to get $\langle I^2_{nB} \rangle$, and then taking the ratio

$$\frac{\langle I_{nB} \rangle}{\langle I_{nA} \rangle} = \frac{\sqrt{\ln \frac{10}{10^{-18}}}}{\sqrt{\ln \frac{10}{10^{-1}}}} = \frac{\sqrt{\ln 10^{19}}}{\sqrt{\ln 10^{2}}} = 3.08 \qquad (22)$$

Another word, if you wait forever, the 1/f noise is only 3 times more [22].

A few more suggestions are provided to help choose an operational amplifier for the design and use it more optimally:

(1) Using a DC offset balancing resistor at the inverting or non-inverting input will increase the noise output and should be avoided.

(2) Increasing the input resistance causes the output noise power to increase.

(3) The current drift with time and temperature has to be examined. Only operational amplifiers with very low drift over time and temperature are suitable.

(4) Operational amplifiers with high common mode rejection ratios (CMRR) and power supply rejection ratios (PSRR) with both numbers over 120 dB are desirable.

(5) Finally, de-coupling capacitors should be used at the supply pins of the IC's. [35] provides a more detailed discussion of operational amplifier noise.

(6) In an APC, the operational amplifier output changes based on the feedback from the monitor diode, so the operational amplifier also needs to have a high slew rate and high bandwidth to quickly respond to the monitor diode changes versus laser diode's output intensity. This also provides a safeguard against runaway optical output power as a result of sudden temperature rises in the laser diode.

4.3. Laser Diode Noise

The noise behavior of a laser diode is related primarily to three sources: (a) quantum noise, (b), optical feedback noise, and (c) partition noise. A discussion of these sources of noise will now follow.

4.3.1 Quantum Noise

Another source of noise is the inherent noise generated by random spontaneous emissions inside the laser diode which cause intensity fluctuations. Due to quantum nature of light, this noise is termed quantum noise. Since below the threshold, spontaneous emission dominates, as the I_{th} increase, the quantum noise decreases rapidly. Quantum noise is more pronounced with multi-mode laser diodes than with single mode devices. It has a 1/f frequency spectrum. As manufacturers enhance the design and the fabrication process of the laser diodes, and bring down the I_{th}, this noise will become much lower in amplitude and may fall to the level of the shot noise (-133 dB).

4.3.2 Optical Feedback Noise

Optical feedback noise is generated when part of emitted laser beam is reflected back into the active layer by external lenses causing interference with the standing beams. The reflected beam oscillates in a pseudo cavity region formed by the laser diode end facet and the nearest surface of the external optics. The external cavity, which is mechanically unstable, produces a signal whose phase and amplitude is randomly varying. This noise is superimposed on the laser diode output beam, and results in an oscillating longitudinal mode (prolonged mode hopping), especially in single mode laser diodes.

Depending on the application, a few optical isolation methods exist to reduce the optical feedback noise. The only electronic method, uses a high frequency (HF) modulator in the laser diode current path (often in the same laser diode package), which can achieve a signal-to-noise ratio of 80 dB or better. Combining the HF modulator with one or two optical isolation methods can reduce the relative noise to -125 dB [41].

It should be noted that since glass windows of laser diodes have an anti-reflection coating to prevent back reflections into the laser facet, they should always be kept clean. Dirt or grease will allow back reflection to enter the active area exacerbating optical feedback problems.

4.3.3 Partition Noise

Partition noise is associated with multi-mode laser diodes with unstable longitudinal modes. The distribution of longitudinal modes is varied as the temperature changes. Thus the peak longitudinal mode may be at one wavelength for a given temperature, and at another wavelength when the temperature is changed.

CHAPTER FIVE

DRIVE CIRCUIT DESIGN

There are two operation modes of a drive circuit: pulse mode and continuous-wave (CW) mode. The die structure determines the way a laser diode should be driven. Pulsed laser diodes have smaller die sizes, with high yields and subsequently lower costs. Pulsed laser diodes also have more relaxed thermal contacts with the chip and the heat-sink, that is why they can only be driven by short duty cycle pulses; otherwise they'll be damaged by the heat built-up.

CW laser diodes on the other hand, have a larger die size which makes them more expensive per chip than their pulsed cousins. CW laser diodes incorporate a good thermal contact between the chip and the adjacent heat-sink; this enables them to be driven with a constant current. Obviously, one can drive a CW laser diode in a pulsed mode to achieve higher peak currents, but the reverse is not true for a pulsed laser diode and will result in its destruction [12]. In this thesis, we only consider drive circuits for CW operation.

5.1 General Specifications of a Drive Circuit

One might ask why not directly drive a laser diode from an off-the-shelf power supply or even an AC/DC adaptor. The answer lies in the fact that a drive circuit must protect the laser diode and at the same time provide it with a highly accurate, highly stable, very low noise, and bounded bias current. In addition, it must maintain a low voltage across the laser diode at the rated current (usually around 2 volts). None of these requirements are available off-the-shelf. For example, the best commercially available power supplies have an accuracy worse than 10 mA [16], and exhibit ripples and noise worse than tens of mA peak-to-peak. This is unacceptable for most laser diode applications.

5.1.1 Accuracy

The light output versus drive current (P-I) curve of laser diodes is a linear function of the form

$$P_o = K.(I - I_{th}) \qquad (23)$$

with P_o and I_{th} (and I) expressed in mW and mA respectively, and K the slope of the line (Watts/Amp). The fact that a given percentage change in the drive current results in the same percentage change in the output light intensity can be deceiving. As an example suppose we consider an ML4XX2A series laser diode by Mitsubishi [23]. For this device, I_{th} at 40 °C is 45 mA. Let's assume we are operating at a bias current of 50 mA which results in a light intensity of 3 mW. Using (23) we can write

$$\frac{P_2 - P_1}{P_1} = \frac{I_2 - I_1}{I_1 - I_{th}} \qquad (24)$$

Thus, if the current is increased by 1 mA, i.e., I_2 = 51 mA, P_2 will be 3.6 mW. Now if the application had required a light output of 3 mW $\pm$ 0.1 mW, we will be in trouble. In this case the bias current should be kept within $\pm$ 0.167 mA of the operating current, which requires an accuracy of 0.33%.

Therefore, to find the bias current accuracy needed for a given application, we start with the required light output, and its acceptable tolerance. Then using the data sheet given for the laser diode, we determine the I_{th} and the bias current needed for the required light output. Finally, we determine the acceptable tolerance of the bias current. In most CW applications, the drive circuit must be able to control the current output within a few hundreds of micro amps.

5.1.2 Stability

For the same reason given above, the current source must be very stable, with a stability tolerance of a few hundred micro amps. A bias current with ripples exceeding the maximum tolerance required for stable operation will de-stabilize laser output and shorten laser diode's life time.

5.1.3. Low Noise Operation

As discussed in Chapters 3 and 4, the impact of all sources of transients and noise should be reduced before they affect the drive current.

5.1.4 Bounded Operation

The maximum current that can be drawn from the current source under any condition including mishaps should be less than the absolute maximum drive rating of the laser diode. Drive current must be bounded. This means that protective measures must be taken in the design so that under no circumstance, whether accidental or by operator error, the drive current can exceed the absolute maximum rating of the laser diode. Practically, it is recommended to limit the maximum current source to a level safely below the absolute maximum current rating of the laser diode over the entire temperature range.

5.2 Modes Of Driving a Laser Diode

In CW operation, the laser diode can be driven in three different ways as required by the application: (a) constant output power, (b) constant frequency, and (c) constant current. In holography for example, a constant frequency is necessary. By maintaining a fixed current to the laser diode and stabilizing its temperature with thermo-electric cooling, the wavelength can be maintained within a few hundredth of nano-meter from the central wavelength, depending on the temperature sensitivity of the laser diode and the cooler circuit capability. For example, for an NEC NDL3200 laser diode, the temperature coefficient of peak wavelength is 0.200 nm/°C [29]. Since, with TEC one can control the case temperature to within 0.05 °C [21], the wavelength of this device can be stabilized to one hundredth of a nano-meter from the central wavelength.

Of course, not all applications may require optical output power or frequency stability. In such an application, the laser diode may just be driven with a reasonably stable current source without any feedback. Here we will discuss the most commonly used mode of laser diode operations, namely the constant optical output power mode. One application which uses such mode is in wavefront measurement of laser diodes for quality control. Here, a known laser diode is used as a reference source with a very stable output and its wavefront is compared with the laser diode under test.

The optical output of a laser diode driven by a constant current decreases as it ages and when temperature rises. For some applications, such as wave front measurements, as mentioned before, a constant optical output power is required regardless of the change in ambient temperature. A laser diode with integrated monitor diode allows the designer to monitor the optical output power in an APC (Automatic Power Control) circuit by reading the monitor diode's current in a feedback loop to maintain the power at the required level.

It should be noted that with a constant output power, as the ambient temperature increases, a higher operating current will be injected into the laser diode. To bound the bias current within the current rating, the driver circuit needs to make sure that during extended periods of the laser diode usage, ambient temperature rise will not cause APC to produce an over-current condition. It may be prudent to have a visual indication that current is near the absolute maximum rating. This can be accomplished by a comparator and an LED.

5.3 Components of a Driver Circuit

A basic drive circuit block diagram for a CW mode laser diode is shown in Fig. 39. It consists of a power supply, power supply filtering and regulation circuitry, an on/off and timing circuit, a slow start circuit, and a current source with an APC feedback circuit.

5.3.1 Power Supply Section

Not all applications may need the traditional AC/DC power supplies. When a low power laser diode with low threshold current is used and the application does not require a long time of operation, it is recommended to use batteries as power sources. The most important advantage is the elimination of all the noise and transients associated with power lines, transformers, rectifying circuits, etc. The best batteries are the low leakage ones such as alkaline and Ni-Cad rechargeable types.

The power supply should have good dynamic regulation to maintain steady output regardless of the line variations, transients, or load current variations. Many off-the-shelf power supplies offer very good specifications in these regards, but not good enough for supplying directly the voltage(s) to the current source of the drive circuit. For example, even a 1% line

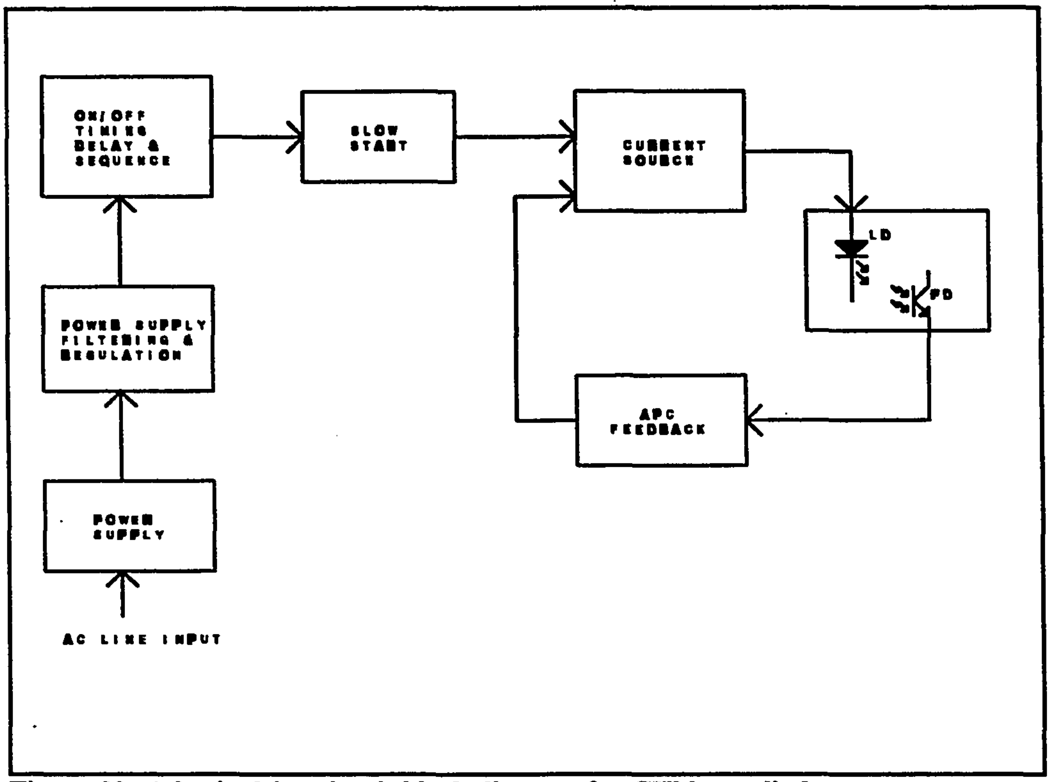


Figure 39 A basic drive circuit block diagram for CW laser diodes.

regulation of a 12 volt power supply means a 120 mV variation. Additional regulation with IC linear regulators is needed to reduce the variation of the voltage sources.

5.3.1.1 Switching versus Linear Power Supplies

A designer is often required to make cost/performance compromises. However, for all the reasons given before, power supply performance should outweigh cost considerations.

Because of this, a linear, well regulated power supply should always be chosen over a switching power supply with comparable power and regulation.

Switching power supplies are inherently noisy, although more efficient and usually smaller than linear power supplies of the same power ratings. Considering the high sensitivity of laser diodes to noise spikes, it is wise to avoid switchers. Linear power supplies, on the other hand are much quieter. However, even with a linear power supply one must implement filtering and additional regulation to achieve acceptable noise margins.

In more demanding applications, the designer may have to design the power supply. Usually it involves, among other things, a double shielded transformer at the front end to achieve better line transient isolation.

5.3.1.2 Dual Supply and Single Supply Drive Circuits

Drive circuits may be designed using a single voltage source (positive or negative) or a dual source. The choice may depend on the specific configuration of the LD-PD device, and/or the voltage requirement of the operational amplifier used as the current source. With the availability of many low noise, high performance operational amplifiers which may be powered from a single voltage source, it is possible to have single supply drive circuits for virtually all possible LD-PD configurations.

All operational amplifiers experience some DC voltage and current offset drifts as a result of the power supply potential drift which is inevitable with temperature variations and aging. The effect of the long term drift of the power supply voltage on the DC offset drifts of an operational amplifier are well indicated by the latter's *power supply rejection ratio* (PSRR) figure, usually expressed in dB in manufacturers' data sheets. The PSRR is defined as the ratio of the change in input offset voltage (in micro volts) to the change in power supply voltage (in volts) [R45]. Expressed in dB we have:

$$PSRR = 10\log(\frac{\Delta V_s}{\Delta V_{os}}) \qquad (25)$$

The PSRR is a function of frequency, and drops as frequency increases. The value provided by the manufacturers is usually the PSRR at DC, although some may provide its curve versus frequency. It is obvious that the higher the PSRR, the better. For example, in an operational amplifier with PSRR of 100 dB, a 1 volt drift in the power supply will cause a corresponding 10 nano-volt DC offset voltage at its input. Typically, a PSRR of 100 dB or more is desired.

It is known [47], that with operational amplifiers powered by a symmetrical dual supply source, magnitudes of the positive and negative rails must be matched closely (e.g., 1%), otherwise more DC offsets will be introduced into the operational amplifier. Thus, the symmetrical potentials must track each other with temperature and time to keep the undesirable DC offset drifts at bay. Even with high PSRR operational amplifiers, some user offset-adjustment may still be needed to calibrate the system.

The single supply solution is therefor the one to consider at first. It is inherently more elegant and stable, yet simpler. The magnitude matching and tracking stability required in dual supply designs are no longer necessary. The circuit has less components and occupies less space allowing miniaturization.

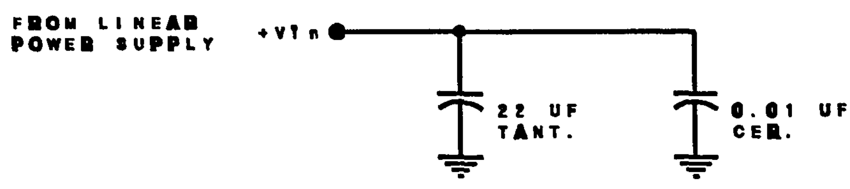


Figure 40 Typical power supply voltage filtering.

5.3.2 Power Supply Filtering and Regulation

For most single supply drive circuits a constant voltage source between 6 to 9 volts is sufficient. A power supply, typically 12 volts DC, is filtered by a pair of tantalum and ceramic capacitors in parallel (Fig. 40). The filtered voltage is stepped down with a regulator to give the constant voltage source 6-9 volts. The aim is to create a constant voltage source, with very low temperature coefficient, low drift and ripple, and line and load regulation figures better than 0.1%. Selecting the right IC regulator for the job is the first step [25].

Four basic regulator types are available: (1) low voltage variable output regulators (positive or negative 5 to 15 volts), where the output can be adjusted by some external components (usually a resistive network) within a given range; (2) fixed output regulators (positive or negative), where the output is fixed at a given voltage which is set internally; (3) tracking outputs regulators (dual supply), where the two outputs are symmetrical with reference to the ground, and track each other within some percentage, and (4) high voltage variable output regulators (also known as floating output regulators), where the desired output voltage can be any magnitude (usually over 40 volts), the limit of which is set by the capabilities of an external high power transistor [25].

The output of fixed regulators is not precise. So, for single supply operations a variable positive or negative regulator should be used due to their flexibility. This allows a design engineer to set the output voltage precisely.

The best variable output linear regulators utilize a band-gap reference and an error amplifier constructed with the "regulator within regulator approach" [25]. They have the lowest temperature induced drift, and the lowest output impedance to keep the voltage constant with load current variations.

For dual supply operation, the only available low voltage single IC tracking regulators have fixed outputs of $\pm$ 15 volts. For lower voltages there are two options available to a design engineer: (a) he/she can reduce the outputs of the tracking regulator IC with two variable regulators, one positive and one negative, whose outputs are equal in magnitude; or (b) design a dual tracking regulator from one voltage source. The latter approach can be very involved and usually requires a multitude of passive and active components in addition to the two variable regulators and their associated circuitry.

The absolute maximum forward current required for the majority of low power laser diodes in the 650 nm to 1.6 micron range falls below 150 mA for a given temperature range, with typical operating values less than 120 mA. The limits of bias current must also be observed. One of the best commercially available regulators capable of supplying up to 150 mA is the Motorola MC1723 which is second-sourced by many other manufacturers like SGS and Signetics. This regulator has a maximum of $0.2\%V_{out}$ line regulation and $0.6\%V_{out}$ load regulation (1.0 mA < I_L < 50 mA) from -55 °C to +125 °C, with typical numbers at 25 °C of $0.02\%V_{out}$ and $0.03\%V_{out}$ for line and load regulation respectively. It has an output ripple rejection of better than 74 dB, corresponding to a better than 1 mV p-p ripple on the output voltage for a 3 volts p-p ripple on the input voltage. It also allows for a current limiting feature set by an external resistor R_{SC} which puts the regulator in a shut-down mode when the limit is exceeded. This feature can be used to turn off the laser diode automatically when its maximum forward current is violated. Figure 41

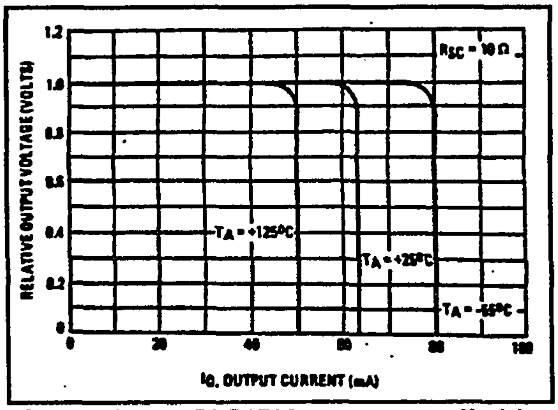


Figure 41 **MC1723 current limiting characteristics [25].**

is the current limit plot of MC1723 for an R_{SC} of 10 ohm [25]. It is obvious that the current limit is temperature sensitive. For a given R_{SC}, the shut down happens at lower currents as the temperature rises. In general, MC1723 should be adequately heat-sunk. In the driver circuit presented in this thesis, the R_{SC} value is 4.42 ohms; this causes the regulator to shut down when the current exceeds 149.3 mA at 25 °C.

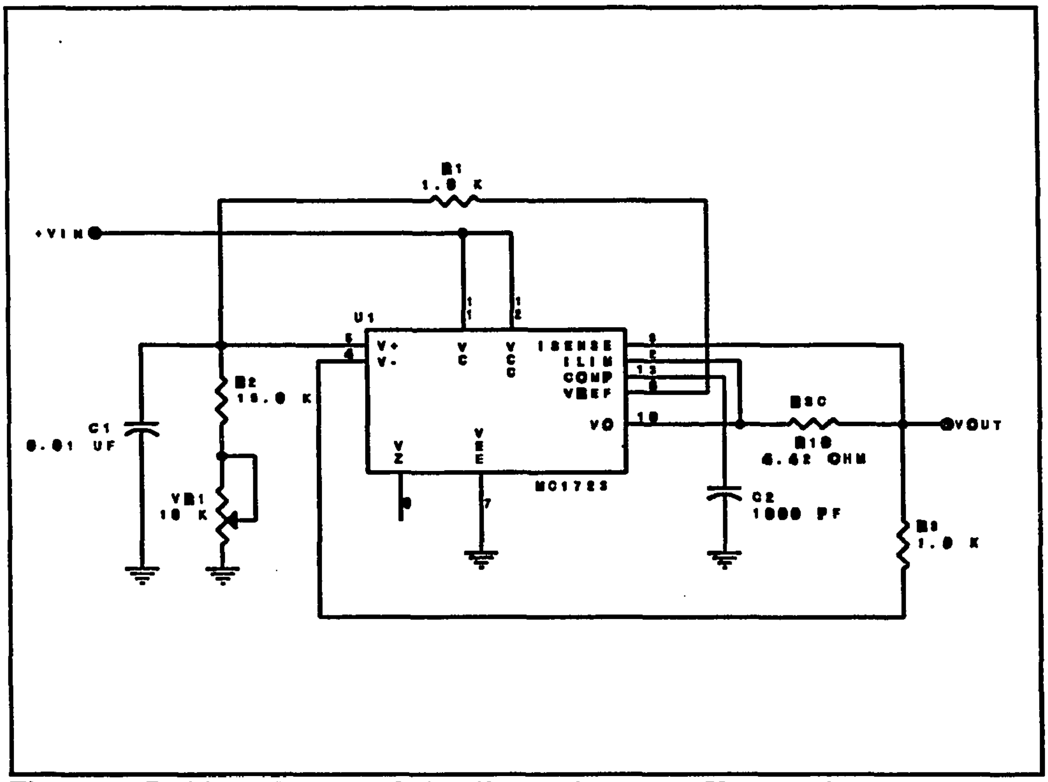


Figure 42 Positive voltage regulation (for V_{out} between 3 V and V_{ref}).

One suggested circuit using the MC1723 is the configuration shown in Fig. 42, which is the manufacturer's recommended circuit for output voltages less than or equal to the internal reference voltage V_{ref} and greater than or equal to 3 volts DC. V_{ref} is an internal voltage reference ranging from 6.65 volts to 7.35 volts from device to device. Resistors R_1 and R_2 basically form a divider network with the internal reference voltage V_{ref}, and the output voltage of the regulator V_{out} is given by [25]

$$V_{out} = V_{ref}\left(\frac{R_2}{R_1+R_2}\right) \qquad (26a)$$

Following design guidelines in [25], we limit the input V_{in} voltage such that $3 < (V_{in} - V_{out}) < 5$ volts. We now derive the values for R_1, R_2, R_3, and R_{SC} for our driver circuit.

For the purpose of calculation, in our design we set the upper limit on V_{out} to be 6.650 volts. I_{sc} maximum is set at 150 mA. With a typical V_{ref} of 7 Volts, using (26a) we get $R_2=19R_1$. From the off-the-shelf 1% metal film resistors (such as Dale PTF65 series) we can choose, R_1 = 1.00 K ohms, R_2 = 19.00 K ohms, and R_3 = 1.00 K ohms (R_3 is required to be equal to the equivalent parallel resistance of R_1 and R_2). Since, according to the MC1723 specifications, V_{ref} can vary from device to device by about 5%, we replace R_2 with a 15.0 K ohm resistor and a 25 turn, 10 K ohm Cermet potentiometer. Considering that the average temperature coefficient of output voltage is at worst case 0.015 %/°C, a 10 °C rise in the regulator's temperature corresponds to only 1.5 mV change in the output voltage. With sufficiently heat-sinking the IC, temperature rise can be controlled to be well below 10 °C, and V_{out} can be stabilized to within 1 mV of its desired value.

Most driver circuits may require more current due to added features and component supply current needs. The MC1723 regulator can be used with a current booster transistor to meet the higher current demands of such circuits. Figure 43 shows the regulator section of such a driver circuit. This design is also the one used in the driver circuit for this thesis.

The voltage output in this case is given by

$$V_{out} = V_{ref}\left(\frac{R_1+R_2}{R_2}\right) \qquad (26b)$$

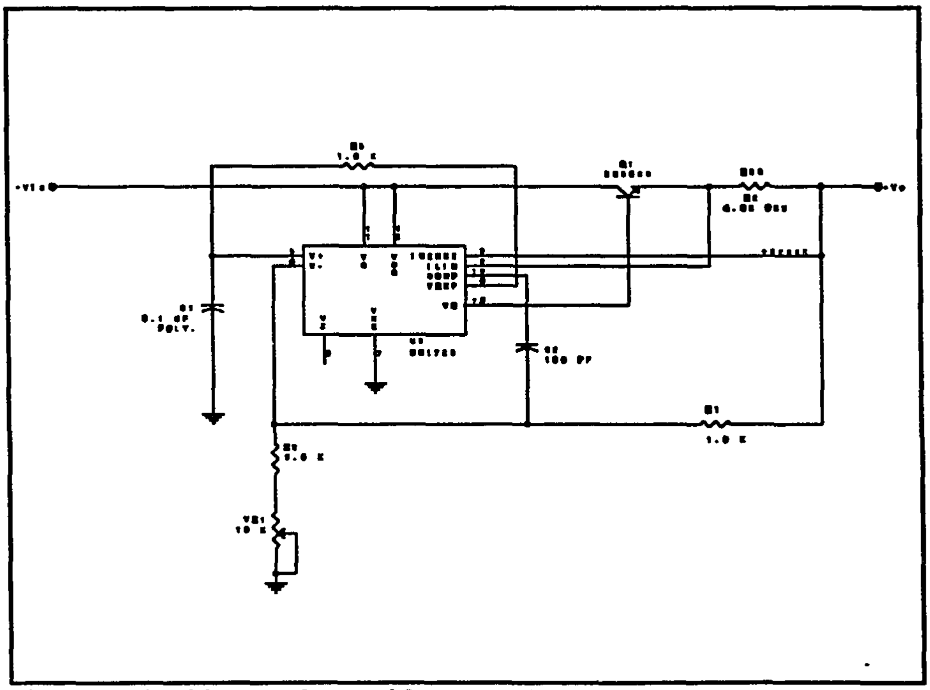


Figure 43 Positive regulator with current boost [25].

The absolute maximum current at which the regulator shuts down, is referred to as short circuit current, I_{SC} and at 25 °C is determined by (27) [25]

$$I_{SC} = \frac{0.66}{R_{SC}} \qquad (27)$$

For I_{SC} = 150 mA, we can choose R_{SC} = 4.42 ohms, 1/4 W, which is also a standard value. The resulting nominal I_{SC} is 149 mA.

5.3.3 On/Off Timing Delay

The Center for Devices and Radiological Health (CDRH), a federal government agency, requires that any laser device should be turned on at least four seconds later from the time that the power in other parts of the circuit is stabilized. The operator should be given a visual indication when the system power is on, to allow him/her to get out of the beam's way [9]. In the driver circuit we can easily implement the CDRH requirement for visual indication using a red LED in series with a current limiting resistor and powered from the regulated source.

The timing delay (or sequence) is easily achieved by an IC timer, such as the National Semiconductor's LM3905 [26], [27], and an RC network, such as the one shown in Fig. 44. Here, the delay time is the time constant of the RC network, after which the relay coil is energized. The regulated voltage is then allowed to power the slow start and subsequent circuits.

When using relays, the effect of relay coil inductance on the rest of the circuit and the relay bounce phenomenon need to be considered. By following proper circuit layout guidelines, usually provided in relay data books, the coil inductance problem can effectively be eliminated. It is also recommended to use relays with bifurcated linear contacts since they have significantly lower bounce tendency, than any other commercially available relays for low current, low voltage operation [38]. Among them, those with PGS (platinum, gold, silver) alloy contacts have the best corrosion resistance. A good bifurcated relay with PGS alloy is the Aromat R-C series smart relay, which has a bounce time of about 0.5 ms and a contact resistance of about 0.06 ohm [1]. Additionally, at the coil, negligible heat is generated (low thermal electromotive force), and no counter electromotive force occurs. For added bounce suppression a parallel RC network, as provided in the circuit in Fig. 44 (R_2 and C_3), may also be used.

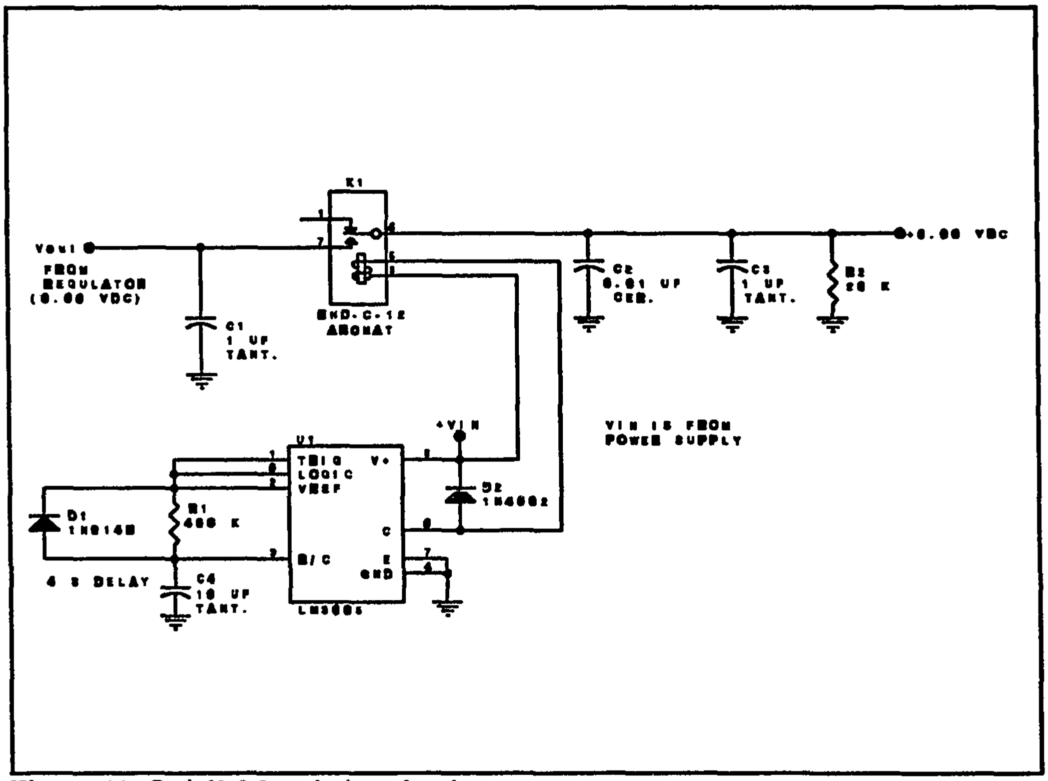


Figure 44 On/off delay timing circuit.

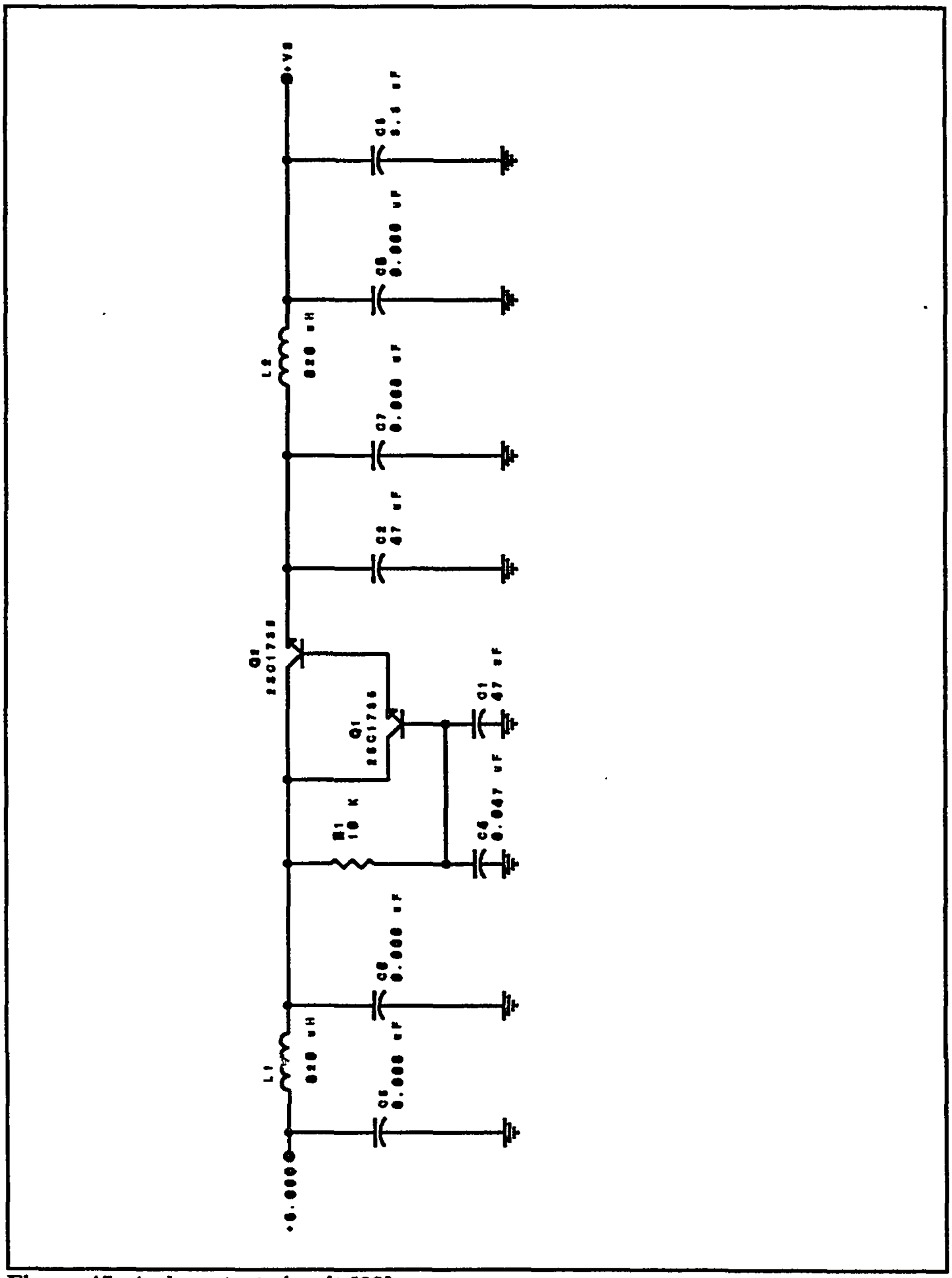


Figure 45 A slow start circuit [23].

5.3.4 Slow Start Section

As mentioned before, the reason for a slow starter circuit is to eliminate power-on transients. Most transients last only several tens of milli seconds. A slow start circuit with a period of 100 milliseconds is more than adequate. The slow start circuit in Fig. 45, proposed by Mitsubishi Electric Corporation [23], suppresses transients on a positive voltage rail. Its transient response, captured by a digital oscilloscope, is shown in Fig. 46. Note that the horizontal scale is 1 second per division.

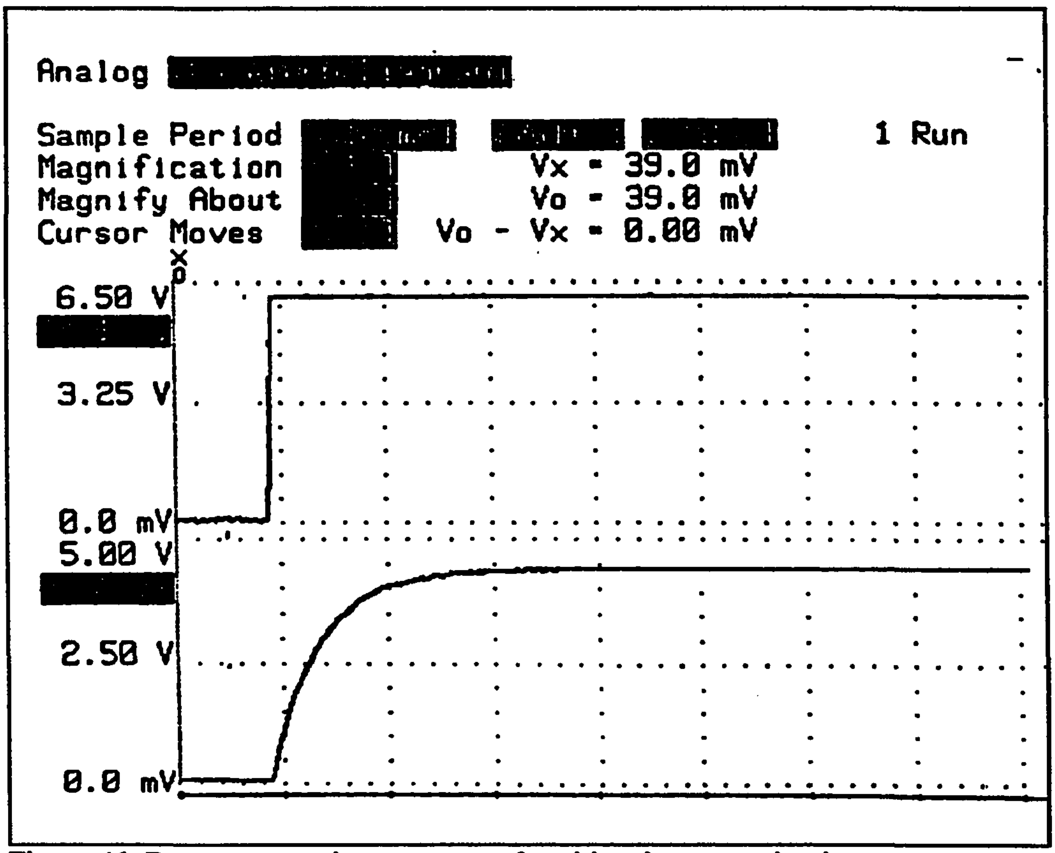


Figure 46 Power-on transient response of positive slow start circuit.

As shown in Fig. 39, the output of the positive regulator is input to the slow start section. Thus the value for $+V_s$ is $(V_{out} - 2\ V_{BE})$, where V_{BE} is the typical Base-Emitter voltage of Q1 and Q2 in Fig. 44. $+V_s$ is determined by the APC circuit and the laser diode. In our design, the operational amplifier in the APC circuit requires a 5 to 15 volts supply voltage. Thus, we set $+V_s$ to be 5.000 volts and work backward to find the proper V_{out} accordingly.

5.3.5 Current Source with APC for Constant Optical Output Power

An adjustable current source for a laser diode in a type R package is shown in Fig. 47. This circuit is an enhanced version of a circuit proposed by Sharp [40]. As mentioned before, $+V_s$ is the output of the slow start circuit for the positive source case. In the operating region of the laser diode, Q_1 transistor, whose collector supplies the laser diode current, is in the forward active region. Applying *KVL* to the loop consisting of R_1, Q_1, R_3, and the laser diode, we get

$$+V_s = I_c R_1 + V_{CE} + I_E R_3 + V_{LD} \tag{28}$$

where V_{LD} is the forward voltage of the laser diode. Assuming $I_C = I_E = I_{LD}$, and for the given resistor values in Fig. 46, we get

$$I_{LD} = \frac{V_s - (V_{CE} + V_{LD})}{21} \tag{29}$$

The typical forward voltage for laser diodes is 2 volts. Given $V_S = 5.000$ volts, the laser diode current depends entirely on V_{CE} as given by

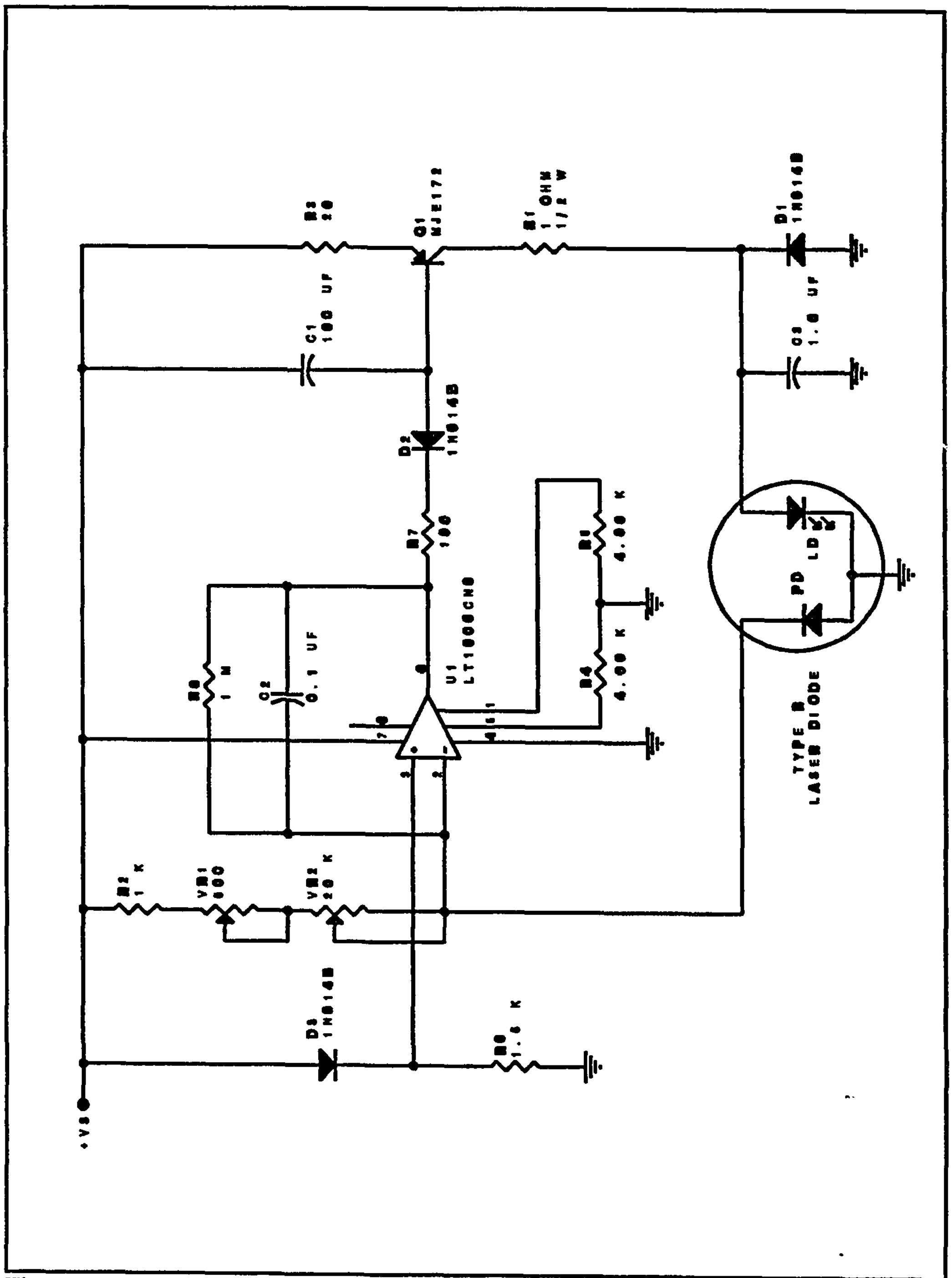


Figure 47 Adjustable current source with APC for type R laser diode.

$$I_{LD}=0.1429-\frac{V_{CE}}{21} \qquad (30)$$

V_{CE} in turn depends on the output voltage of operational amplifier U_1. This output voltage has a range of 0 volts to nearly $+V_s$, corresponding to Q_1 being fully saturated to being off. A saturated Q_1 has a typical V_{CE} of 0.4 volts. Therefore, the maximum laser diode current is about 123.8 mA which should meet the operating forward current requirement for many low power laser diodes as mentioned in Section 5.3.2. As shown above, R_3 has acted to limit the laser diode current. This is a second current limit feature provided in the circuit of Fig. 47. The first current limit protection was built in the voltage regulator section (R_{SC} in Fig. 42 and 43).

For any given laser diode operating light output, the laser diode current is adjusted by two potentiometers VR_1 and VR_2. Potentiometer VR_2 brings up the laser diode to the vicinity of its operating point (coarse adjustment), after which potentiometer VR_1 sets the forward current at the precise level required in the application (fine adjustment), taking into consideration the monitor diode's current. Unless a new light output setting is required, there is no need to re-adjust VR_1 and VR_2.

During operation, the current from monitor diode follows the variations of the laser diode output power (see Fig. 17). For example, when output power is reduced so is the monitor diode current. This reduction acts to reduce the output voltage of U_1. The U_1 output voltage accordingly drives the base of Q_1 harder, thus reducing its V_{CE}, which results in an increase of the laser diode current. This current increase brings up the light output power. If the light output exceeds the pre-set constant value, the reverse operation takes place. The response of the APC loop consisting of the monitor diode and the current source is very fast given the quick response time of the monitor diode (sub-micro-second) and the high slew rate of the operational amplifier (0.4 volts per micro-second). The APC is therefore fast enough to maintain a constant laser diode output power.

For reverse voltage protection of the laser diode, diode D_1 is included in the circuit. The absolute reverse voltage specified for most CW laser diodes is 2 to 5 volts. D_1 is chosen to switch on at a forward voltage of 0.4 volts (at 25 °C), in less than 4 ns. Therefore, before the reverse voltage on the laser diode has a chance to exceed its breakdown level, D1 shorts across it.

Another feature of this circuit is the insertion of a precision 1 ohm resistor (R_1) in laser diode's current path. Thus the voltage developed across this resistor is equal in magnitude to the current through it. An instrumentation amplifier followed by an analog-to-digital converter (ADC) can provide dynamic readout of the laser diode current without disturbing the circuit. It should be noted that an ammeter must never be used to monitor the laser diode's current. Similarly, it is not recommended to connect a voltmeter across R_1. However, if one absolutely insists on using a voltmeter, it should never be connected to or disconnected from R_1 while the power to the drive circuit is on. When the voltmeter is being used, it should not be turned off or switched to other modes.

As described above, the current source shown in Fig. 47 is capable of driving all type R laser diodes with operating forward currents less than or equal to 120 mA. The APC adjusts the current to compensate for aging and temperature drifts while maintaining a constant optical output from the laser diode.

Figure 48 shows a drive circuit for a type N LD-PD configuration. This circuit is a

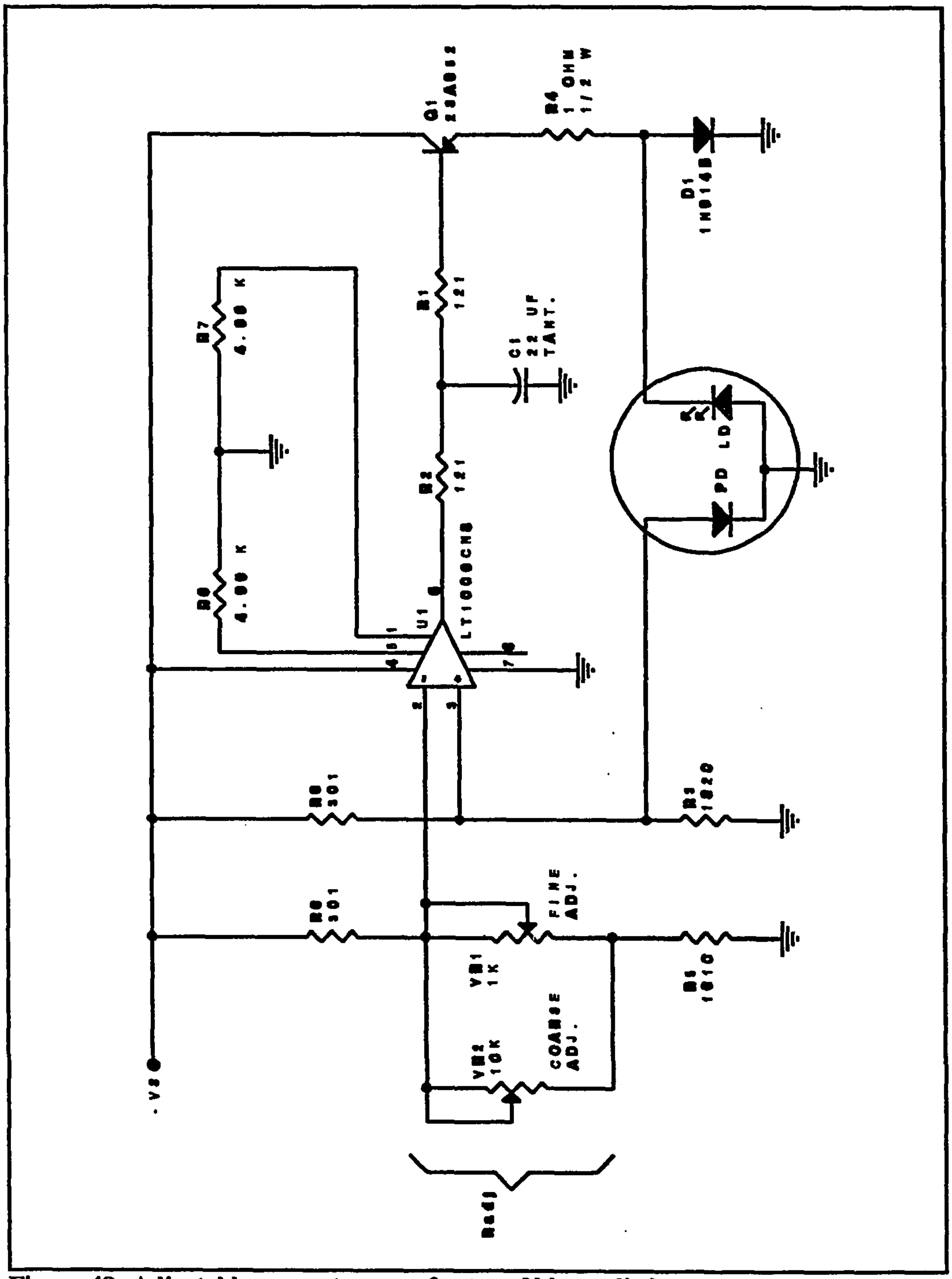


Figure 48 Adjustable current source for type N laser diode.

modified and enhanced version of the one proposed by Philips Amperex for device part number CQL70A [35]. Its operation is very similar to the one described above for type R configuration.

5.4 Connection to the Laser Diode

A laser diode should never be connected to or disconnected from the drive circuit while the latter is on. If the supply is on and the laser diode is connected, the pin voltage rises suddenly and a surge current follows which destroys the laser diode facets as mentioned previously. When powering off, adequate off time (a few seconds would do for most cases) should be allowed for all the capacitors in the circuit to fully discharge.

Also, one must always make sure that the laser diode is connected correctly. Laser diodes have low reverse voltage breakdowns in the 2-5 volts range. Accidental mis-connections resulting in polarity reversals will not damage the laser diode unless the reverse breakdown voltage is exceeded. Large reverse current will damage the laser diode.

5.4.1 Proper Connection Type

When the laser diode assembly is connected to the drive circuit via a cable, only high reliability connectors such as shielded circular DIN connectors (Fig. 49), or D-Subminiature connector DB9 (Fig. 50) with EMI/RFI shells should be used. It is also important to allocate two pins of the connector for each pin of the laser diode to add protection in case one pin was connected loosely.

A loose connection may break the contact by vibration. In this case, the APC may see an infinite impedance, and try to pump more current into the laser diode. Although we assume current limiting precautions are already taken, nevertheless, the sudden current surge will degrade

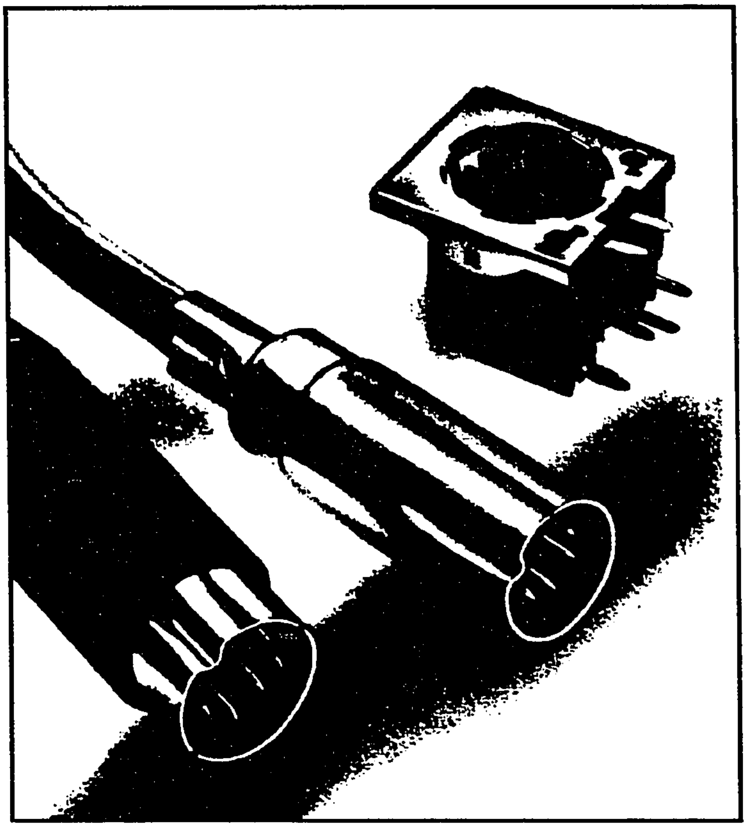


Figure 49 Shielded circular DIN connectors.

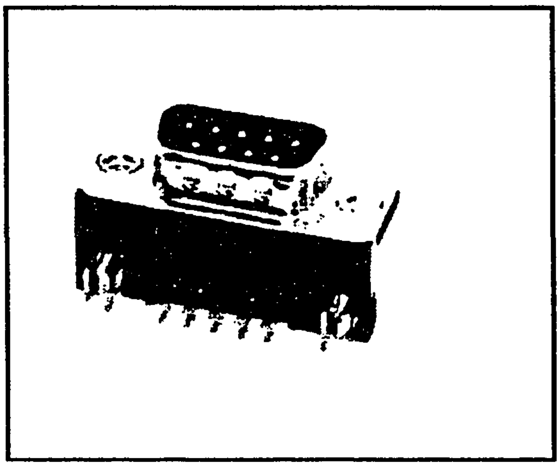


Figure 50 A DB9 connector.

the laser diode before the power is shut off by the over current sensing mechanism of the regulator.

5.4.2 Shielding

In applications where the laser diode is attached to the current source via a cable, a shielded cable to protect against EMI/RFI must be used. Although twisted pairs provide a good deal of noise-immunity from the surrounding sources, a cable with coaxial shield is a much better choice. The shield should not carry any signal current, since this may defeat the purpose of using it. The shield should be grounded only at the current source side to prevent current loops. On the cable side, the shield wire should be connected to the metal body of the connector. The mating connector on the current source should also have a metallic body. The point at which the shield is grounded depends on the system design and in many instances it is best to find it experimentally. The rule of thumb is to find the point on the chassis which exhibits the lowest resistance to the AC ground. A screw terminal with a star washer at that point can then be used and the shield brought to it. See [24] for an in-depth treatment of shielding.

5.5 Drive Circuit Layout Considerations

All the protective and noise reduction measures we have discussed thus far will be defeated by a poor layout. Signal ground, signal routing, and component orientations are some of the key considerations in layout. [5] gives an excellent overview of general parameters that need to be considered in these areas.

The best layout strategy involves a ground plane at its center. Because the equivalent circuit of a ground wire is a series R L network [32], the potential seen as ground by components at different parts of the printed circuit board can vary due to conduction induced offsets emanating from the flow of ground currents. This situation can drastically degrade circuit performance. A ground plane inherently has the lowest impedance. It provides the most stable ground level (equi-potential) seen by all components throughout the board. Minimizing ground currents is also important in this regard. This can be easily accomplished by using a wider copper path (0.050 inch or wider [13]) for signals carrying large currents and utilization of low current components.

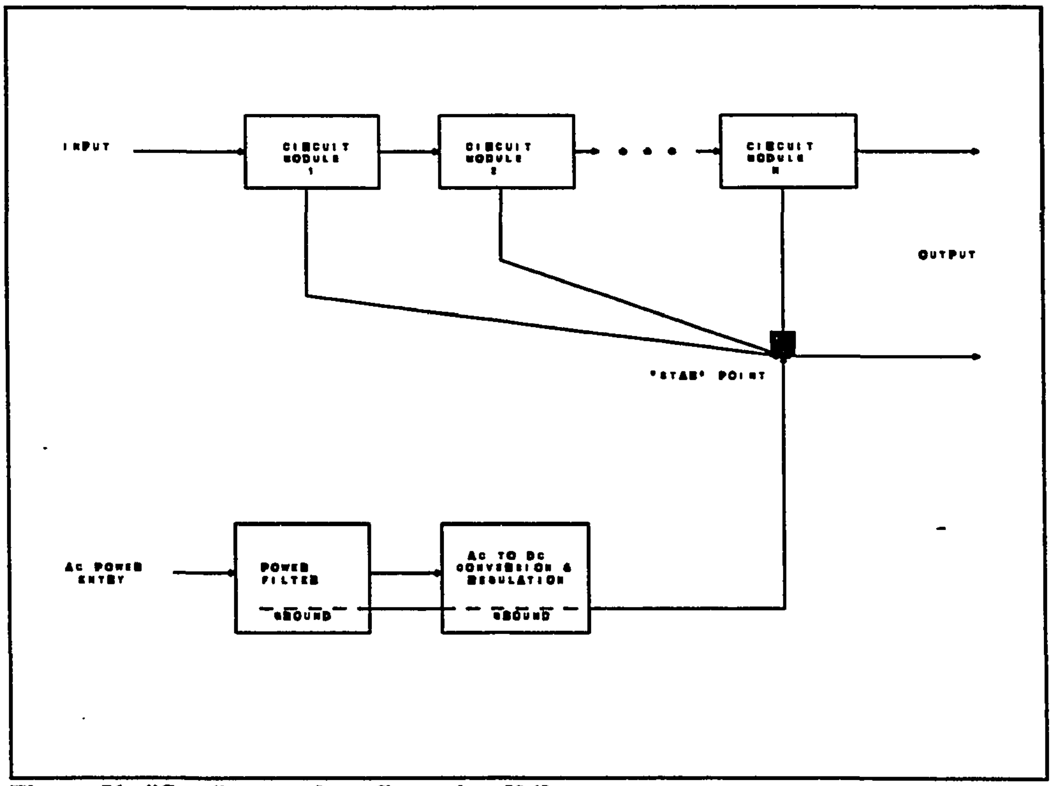


Figure 51 "Star" ground configuration [24].

Noise from one component can induce ground potential differences in other devices via the ground path. By using a ground separation technique known as "star" [24], one can achieve isolation between noisy devices and the rest of the circuit in low frequency applications. A typical "star" grounding scheme is shown in Fig. 51. In the laser diode driver circuit, for example, the on-off relay ground should be isolated from the ground plane of the rest of the circuit. These two grounds meet only at one place (the "star" point) where power and ground is brought into the board from the power supply.

As for the power busses, they need to be wide. In a large circuit with one power source for all ICs, a power plane is the best choice. However, in our design it is not necessary, adding only to the cost. If more than six op-amps are being used in the circuit, separate power busses should be used to feed them instead of one long "party line". Also, component orientation should be such that it facilitate current flow between the IC power feed pins and the printed circuit board power feed entry.

Signal routing is very important too. There should be a logical flow of signals in a drive circuit. Thus, components should be arranged as to minimize the length of signal paths. When signals on different layers of the printed circuit board cross each other, they should be at a 90 degree angle to each other to minimize capacitive coupling.

The printed circuit board material, its layer separation, and copper weight (thickness) should not be overlooked either in the overall scheme of noise reduction. [13] provides a brief overview of issued involved.

5.6 A Complete Driver Circuit for a Type R Laser Diode

Following the methodology presented in this thesis a prototype board was built to drive

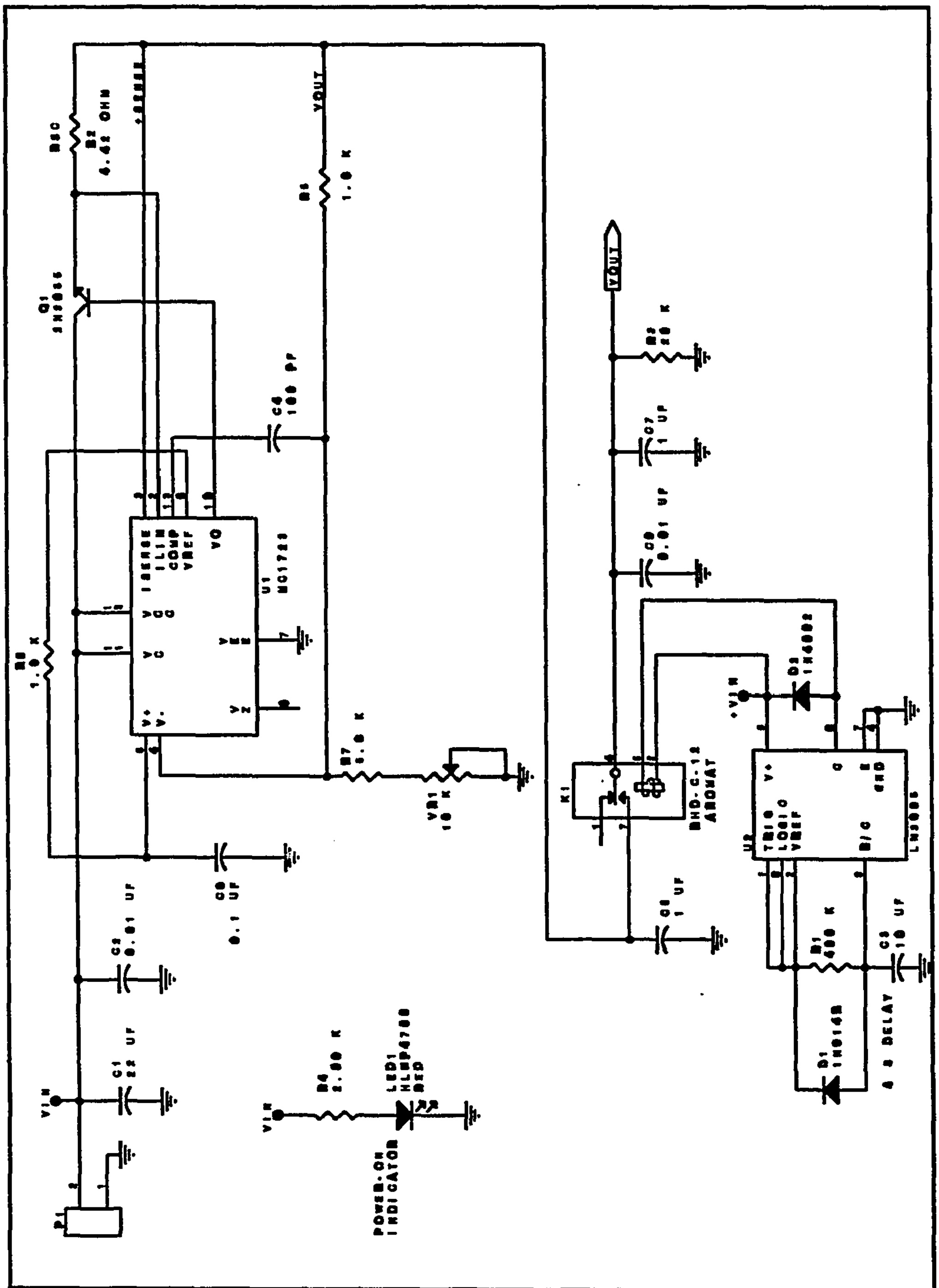


Figure 52 Schematics of type R drive circuit (sheet 1).

a type R laser diode. The laser diode chosen was a Mitsubishi ML40115R [23], data sheets of which are reproduced in appendix B. Figures 52, 53, and 54 show the complete circuit and Table 6 is the parts list for it. Figure 55 shows the cable assembly drawing for connecting the laser diode to the driver circuit.

A series of tests were conducted on the prototype board to check its performance against the criteria established in Section 5.1. The following is a list of the tests that were performed on the prototype board and results were captured by a Hewlett Packard digital oscilloscope, model HP-54502A. A summary of the results for each test along with the captured data will follow this list. All tests were conducted at an ambient temperature of 75 °F $\pm$ 2 °F, unless noted otherwise.

1. Transient Response Tests:
   A. Power-on Transient
   B. Line-Induced Transient
2. Noise on Input Voltage V_{IN} and Current Source Voltage $+V_s$
3. Optical Output Variations versus Temperature
4. Forward Current Variations versus Temperature

5.6.1 Transient Response Tests

A. Power-on Transient Response

Figure 56 shows the power-on transient response of the prototype board. The upper screen is Channel 1 showing the board's input voltage, V_{IN}. The vertical scale is 4.00 Volts/Division (V/div), and the horizontal scale is 1 second/division (s/div). The lower screen is channel 2 showing the $+V_s$ voltage. The vertical scale is 2.00 V/div, and the horizontal scale is the same as in channel 1.

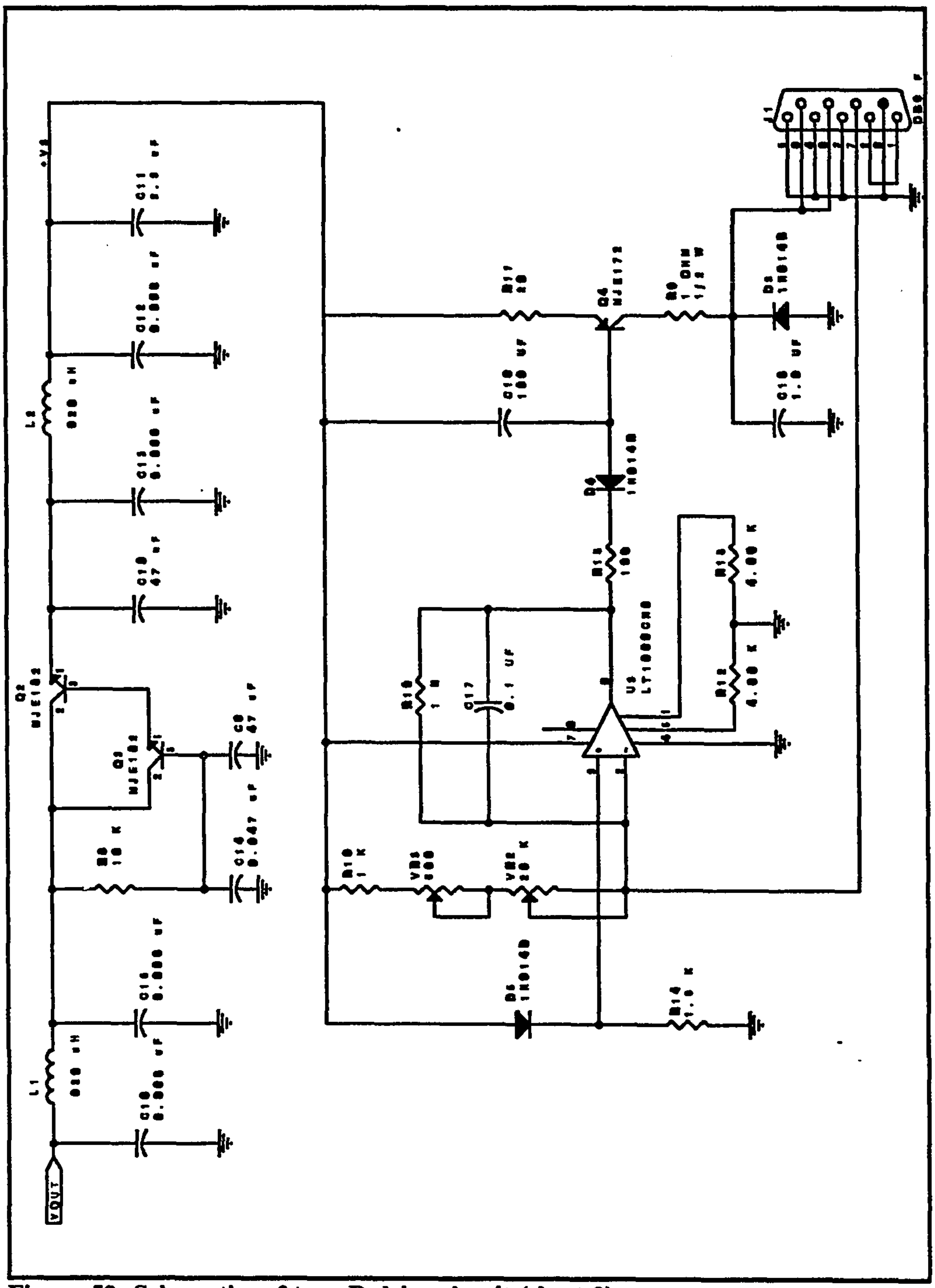


Figure 53 Schematics of type R drive circuit (sheet 2).

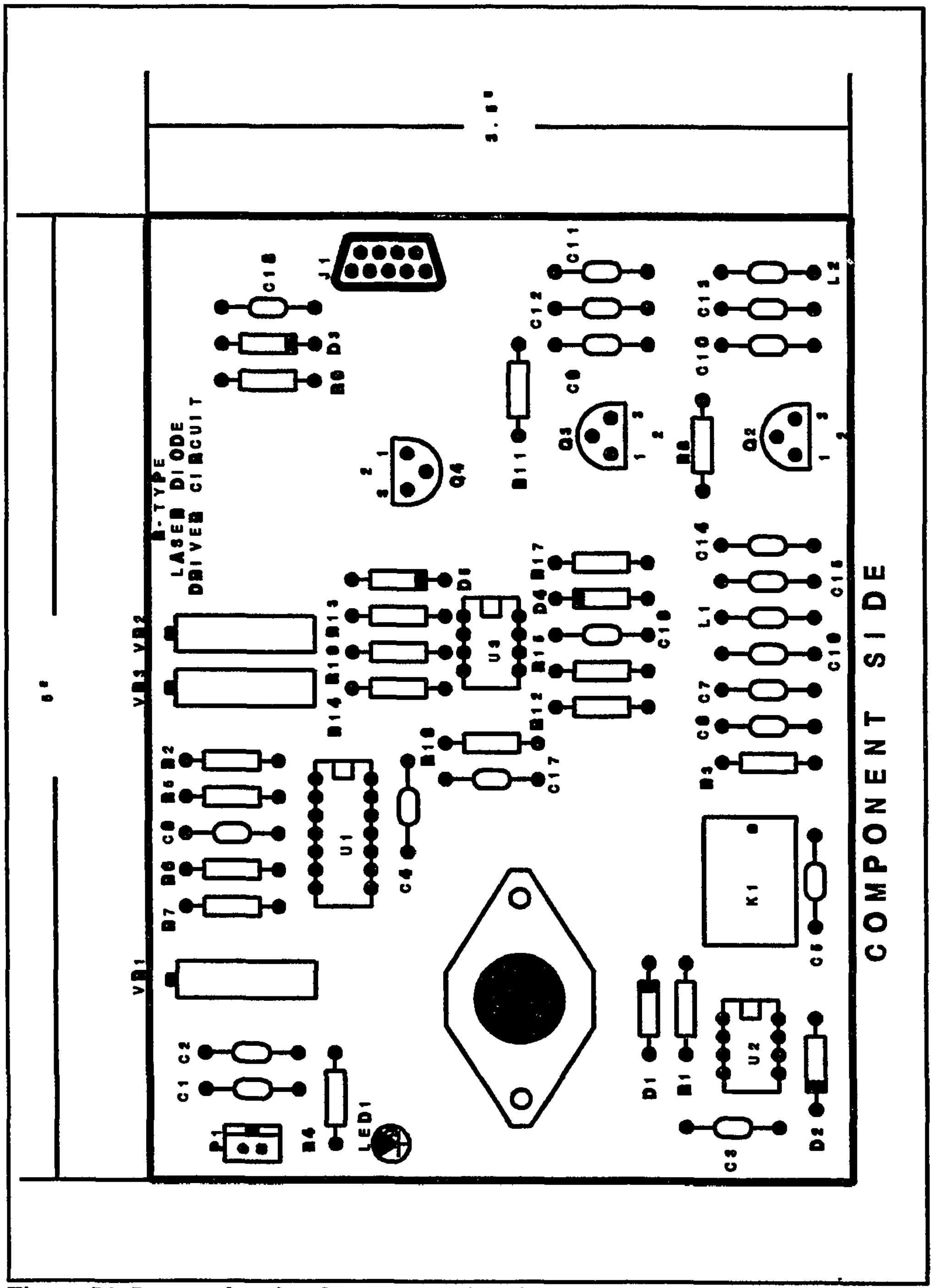


Figure 54 Layout drawing for type R drive circuit (sheet 3).

Item	Quantity	Reference	Part
1	1	C1	22 UF, CAPACITOR, TANT.
2	2	C2,C6	0.01 UF, CAPACITOR, POLY.
3	1	C3	10 UF, CAPACITOR, POLY.
4	1	C4	100 PF, CAPACITOR, POLY.
5	3	C5,C7,C18	1 UF, CAPACITOR, POLY.
6	2	C9,C10	47 UF, CAPACITOR, TANT.
7	1	C11	3.3 UF, CAPACITOR, POLY.
8	4	C12,C13,C15,C16	0.068 UF, CAPACITOR, POLY.
9	1	C14	0.047 UF, CAPACITOR, POLY.
10	2	C8,C17	0.1 UF, CAPACITOR, POLY.
11	1	C19	100 UF, CAPACITOR, TANT.
12	4	D1,D3,D4,D5	1N914B, DIODE
13	1	D2	1N4002, DIODE
14	1	J1	DB9 SOCKET CONNECTOR, PCB, AMP
15	1	K1	RHD-C-12, RELAY, AROMAT
16	1	LED1	HLMP4700, RED LED, HP
17	2	L1,L2	820 UH, INDUCTOR
18	1	P1	2 PIN MALE CONNECTOR, MOLEX
19	1	Q1	2N3055, NPN TRANSISTOR, MOTOROLA
20	2	Q2,Q3	MJE182, NPN TRANSISTOR, MOTOROLA
21	1	Q4	MJE172, PNP TRANSISTOR, MOTOROLA
22	1	R1	400 K, RESISTOR, 1%, 1/4 W, METAL
23	1	R2	4.42 OHM, RESISTOR, 1%, 1/2 W, METAL
24	1	R3	20 K, RESISTOR, 1%, 1/4 W, METAL
25	1	R4	2.00 K, RESISTOR, 1%, 1/4 W, METAL
26	3	R5,R6,R10	1.0 K, RESISTOR, 1%, 1/4 W, METAL
27	1	R7	5.0 K, RESISTOR, 1%, 1/4 W, METAL
28	1	R8	10 K, RESISTOR, 1%, 1/4 W, METAL
29	1	R9	1 OHM, RESISTOR, 1%, 1/4 W, METAL
30	1	R11	20, RESISTOR, 1%, 1/4 W, METAL
31	2	R12,R13	4.99 K, RESISTOR, 1%, 1/4 W, METAL
32	1	R14	1.5 K, RESISTOR, 1%, 1/4 W, METAL
33	1	R15	100, RESISTOR, 1%, 1/4 W, METAL
34	1	R16	1 M, RESISTOR, 1%, 1/8 W, METAL
35	1	U1	MC1723, REGULATOR IC, MOTOROLA
36	1	U2	LM3905, TIMER IC, NATIONAL
37	1	U3	LT1006CN8, OPERATIONAL AMPLIFIER, LINEAR TECHNOLOGY
38	1	VR1	10 K, POTENTIOMETER, 20 TURN, CERMET, DALE
39	1	VR2	20 K, POTENTIOMETER, 20 TURN, CERMET, DALE
40	1	VR3	500, POTENTIOMETER, 20 TURN, CERMET, DALE

Table 6. Parts List for the Type R Driver Circuit

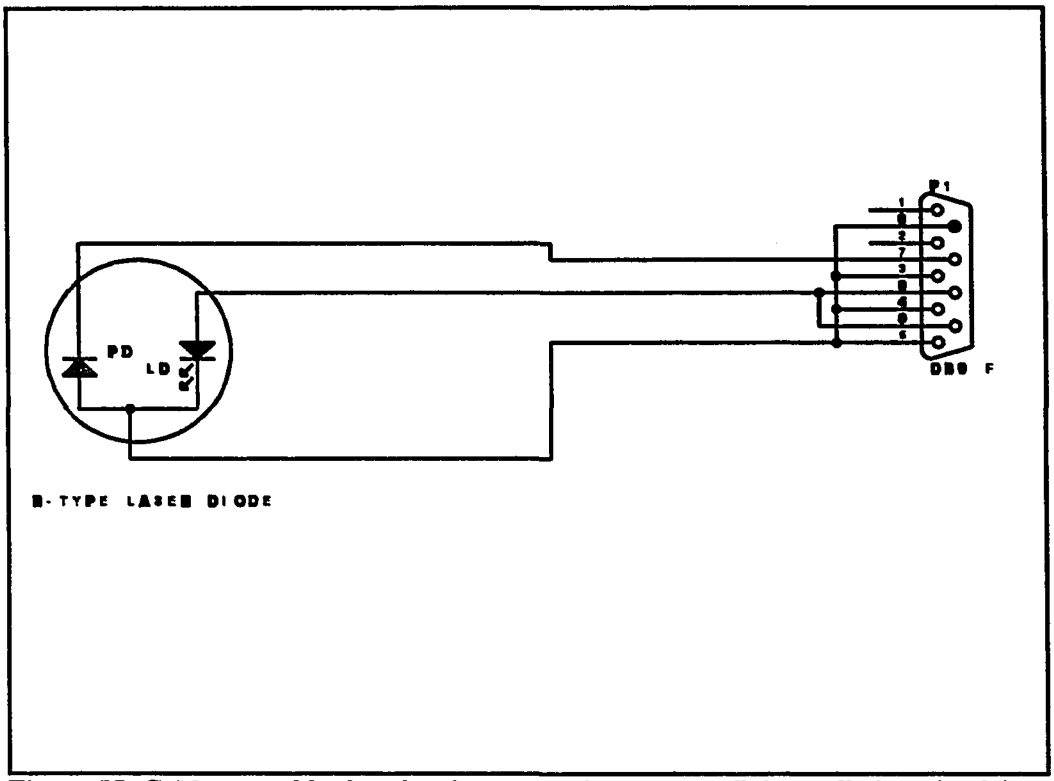


Figure 55 Cable assembly drawing for connecting the type R laser diode to its driver circuit.

Figure 56 clearly shows a delay of approximately 4.4 second from the time V_{IN} turns on and the time $+V_s$ begins to turn on. So the CDRH requirement discussed in Section 5.3.3 is met. Furthermore, on power-on, V_{IN} is a step signal with a rise time of less than or equal to 19.96 milliseconds, whereas $+V_s$ is a slowly rising signal with a rise time of nearly 698.60 milliseconds. Thus, in accordance with Section 5.3.4 the slow start circuit has suppressed the power-on transient successfully.

As can also be seen from Fig. 56, V_{IN} slightly drops when $+V_s$ is settling. The drop is due

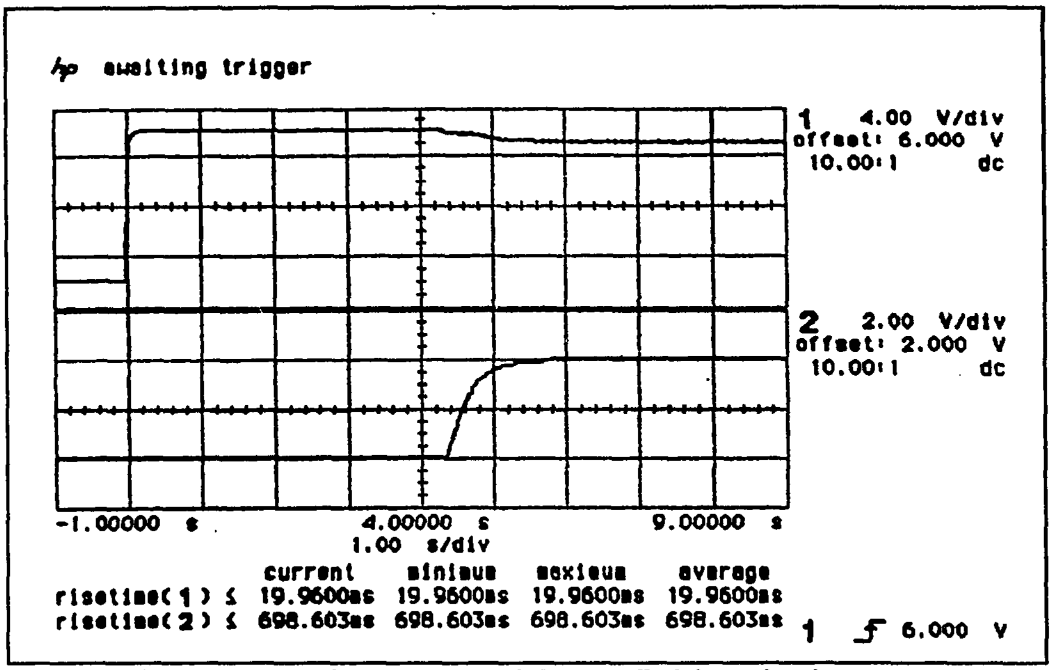


Figure 56 Power-on transient response of the type R driver circuit.

to the fact that the no-load voltage of the power supply is higher than its loaded voltage.

B. Line-Induced Transient Response

Figure 57 shows the result of introducing transient spikes on the input voltage, V_{IN}, and its effects on $+V_s$. As can be seen on channel 1 of the digital oscilloscope's display, a transient of almost 5 volts amplitude and 100 milliseconds duration with a 13.97 millisecond rise time was coupled to the board's input voltage supply V_{IN}. The behavior of the current source supply voltage $+V_s$ was monitored on channel 2. The laser diode was on and drawing 62.7 mA. No noticeable

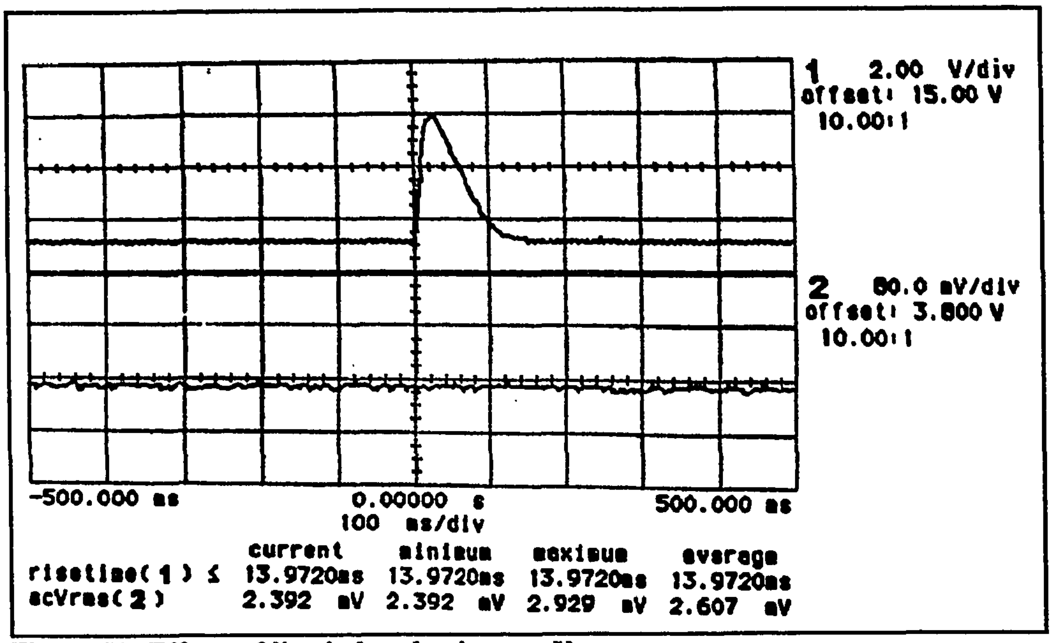


Figure 57 Effects of line-induced noise on $+V_r$.

change was observed on $+V_r$.

5.6.2 Noise Measurements

Figure 58 shows the voltage ripple noise on the board's input voltage, V_{IN}, and the corresponding noise on $+V_r$. The operating current of the laser diode was 54.6 mA. In this test, channel 1 scale is 200 mV/div and channel 2 scale is 40 mV/div. The horizontal scale is 5 ms/div for both channels. Channel 2 shows a remarkably low noise on $+V_r$, with and RMS noise of about 2 mV. Considering that the displayed noise is the rms sum of the oscilloscope's probe noise and the actual noise on the APC supply line, $+V_r$, one can appreciate the driver circuit's noise performance. One can expect an even lower noise performance from the same circuit on

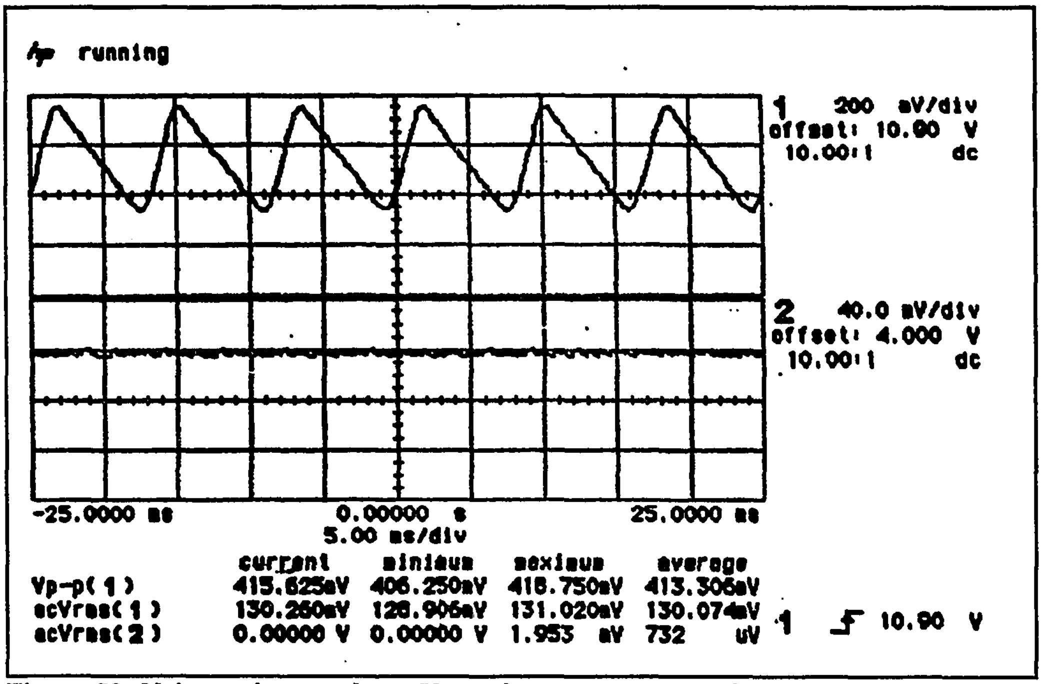


Figure 58 Noise on input voltage V_{IN} and current source voltage $+V_s$.

a printed circuit board with a ground plane.

5.6.3 Optical Output Variation versus Temperature

For the temperature tests a Fluke Thermocouple Module, model 80TK was used. According the its specifications, the 80TK model has a 0.5% of reading ± 3.6 °F accuracy in a temperature range of -4 to +662 °F. It was calibrated to have a 1 mV output per 1 °F. The thermocouple module was plugged into a Fluke 87 Digital Multimeter (DMM). The 0-300 mV setting of the DMM was selected. The thermocouple tip was placed firmly on the case of the laser diode at the heatsink.

For measuring the optical output power, a Newport Model 835 Optical Power Meter was used. The wavelength of the laser diode under test was 785 nanometer as specified by the manufacturer, however the center wavelength on the detector was set at 790 nanometer since it could only change in decade increments.

The test was conducted with the thermocouple probe at 85 °F. A heat-gun was used to blow hot air on the surface of the board and the laser diode increasing the temperature gradually to 120 °F. The total measurement time was about one hour, the result of which is shown in Fig. 59. As can be seen, the APC maintained a constant optical output power.

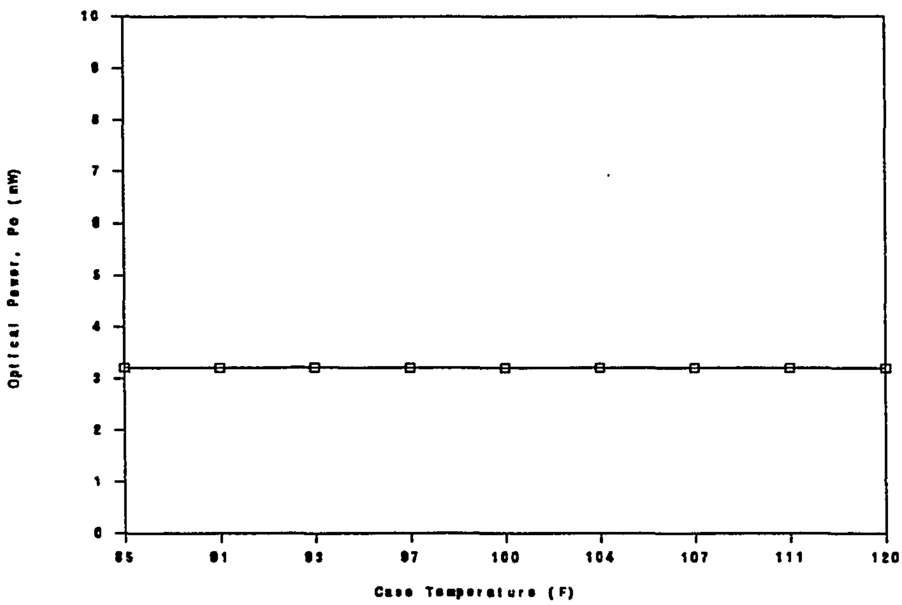


Figure 59 Optical output power versus case temperature with APC.

5.6.4 Forward Current Variations versus Temperature

This test was conducted simultaneously with the test in Section 5.6.3. The probes of a Fluke 77 DMM were placed across R9, and the 0-300 mV setting was selected. Since R9 was a precision 1 ohm resistor, the voltage across it was numerically identical to the current through it, which was the laser diode current. Figure 60 shows the result of this test. As can be seen, the current kept increasing with temperature, but the laser diode optical output power (Fig. 59) stayed constant due to the APC. This is because, as mentioned in Section 3.2.1, the laser diode threshold

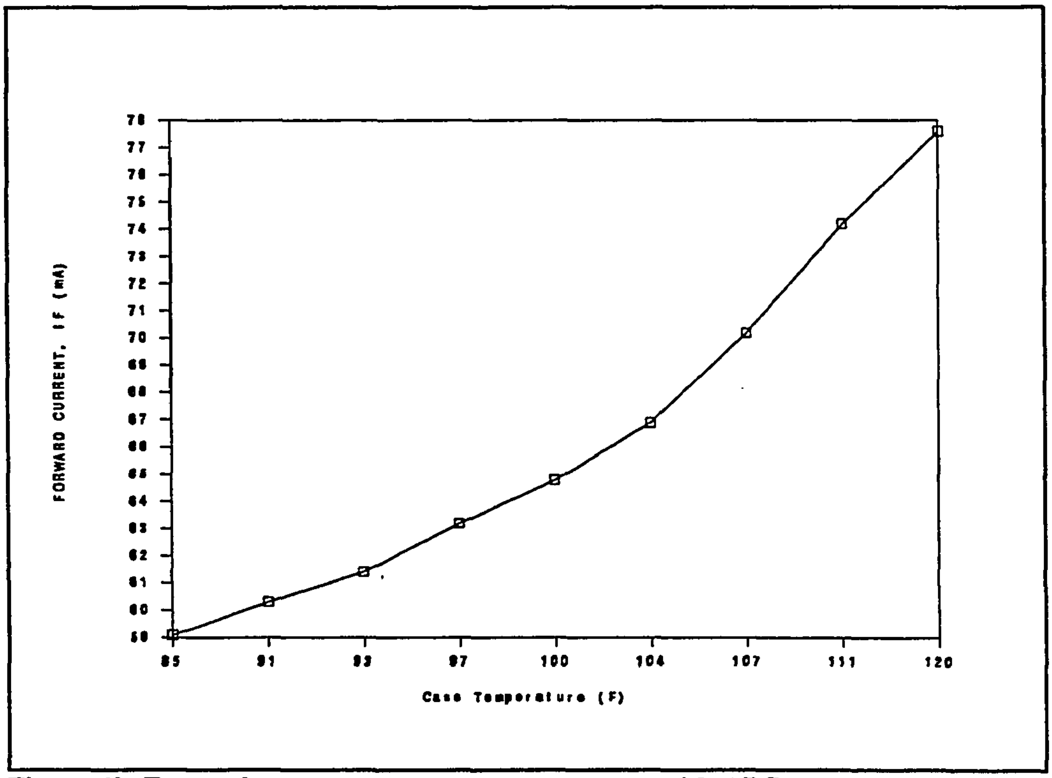


Figure 60 Forward current versus case temperature with APC.

current, I_{th}, increases with temperature. Therefore, it takes a higher forward current to achieve the same optical output power at a higher temperature than at a lower one. The results of the tests in Sections 5.6.3 and 5.6.4 are tabulated in Table 7. The optical output power had a mean of 3.197 mW and a standard deviation of 0.038 mW.

Case Temperature (°F)	Forward Current (mA)	Optical Output (mW)
85	59.1	3.125
91	60.3	3.216
93	61.4	3.220
97	63.2	3.218
100	64.8	3.214
104	66.9	3.216
107	70.2	3.218
111	74.2	3.217
120	77.6	3.219

Table 7. The temperature test results.

5.7 Conclusions

This thesis discussed the characteristics of CW laser diodes, focusing on their susceptibility to electrical noise, transients, and thermal stress. The noise contributions of components typically found in CW laser driver circuits were presented to aid in choosing low noise devices for a design. Transients and measures to prevent them from reaching the laser diode were reviewed. Thermal relief options of heatsinking the laser diode and/or thermoelectric cooling it were presented. Performance criteria for a low noise CW driver circuit was set and designs for the successive blocks of an optimum driver circuit were offered. Finally the performance of a complete circuit based on the methodology presented in the thesis was evaluated. It was shown that the circuit met all the criteria despite being built on a prototype board. It suppressed transients, delivered a low noise (1 mv RMS) and stable supply to the laser diode, and maintained the laser diode's output power via a feedback circuit called APC. The high quality of parts used in the circuit was instrumental in the good performance of the circuit. A printed circuit version of the proposed design with uniform grounding such as a ground plane is expected to perform even better. Although the methodology in this thesis was applied to the design of a driver circuit for CW laser diodes with constant optical power, it can be used in other applications such as a low noise constant current source.

APPENDIX A

MANUFACTURERS DATA SHEETS

In the following pages data sheets of some of the components used in the complete design are reproduced for reference.

LINEAR TECHNOLOGY

LT1006

Precision, Single Supply Op Amp

FEATURES

- Single Supply Operation
  - Input Voltage Range Extends to Ground
  - Output Swings to Ground while Sinking Current
- *Guaranteed* Offset Voltage 50μV Max.
- *Guaranteed* Low Drift 1.3μV/°C Max.
- *Guaranteed* Offset Current 0.5nA Max.
- *Guaranteed* High Gain
  - 5mA Load Current 1.5 Million Min.
  - 17mA Load Current 0.8 Million Min.
- *Guaranteed* Low Supply Current 520μA Max.
- Supply Current can be Reduced by a Factor of 4
- Low Voltage Noise, 0.1Hz to 10Hz 0.55μVp-p
  - Low Current Noise—Better than OP-07 0.07pA/$\sqrt{Hz}$ at 10Hz
- High Input Impedance 250MΩ Min.
- *Guaranteed* Minimum Supply Voltage 2.7V Min.

APPLICATIONS

- Low Power Sample and Hold Circuits
- Battery Powered Precision Instrumentation
  - Strain Gauge Signal Conditioners
  - Thermocouple Amplifiers
- 4mA-20mA Current Loop Transmitters
- Active Filters

DESCRIPTION

The LT1006 is the first precision single supply operational amplifier. Its design has been optimized for single supply operation with a full set of specifications at 5V. Specifications at ±15V are also provided.

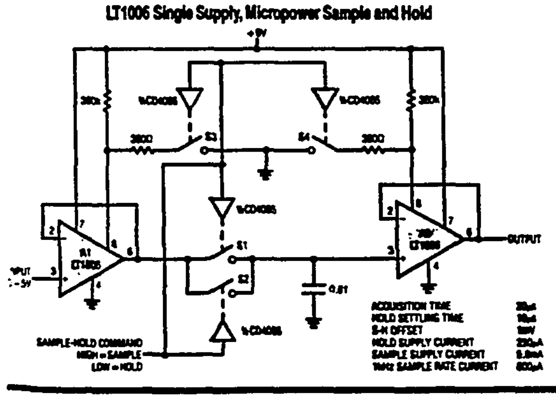
The LT1006 has low offset voltage of 20μV, drift of 0.2μV/°C, offset current of 120pA, gain of 2.5 million, common-mode rejection of 114dB, and power supply rejection of 126dB.

Although supply current is only 340μA, a novel output stage can source or sink in excess of 20mA while retaining high voltage gain. Common-mode input range includes ground to accommodate low ground-referenced inputs from strain gauges or thermocouples, and output can swing to within a few millivolts of ground. If higher slew rate (in excess of 1V/μs) or micropower operation (supply current down to 90μA) is required, the operating currents can be modified by connecting an external optional resistor to Pin 8.

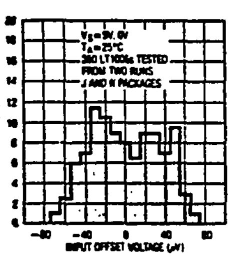
For similar single supply precision dual and quad op amps, please see the LT1013/LT1014 data sheet. For micropower dual and quad op amps, please see the LT1078/LT1079 data sheet.

2

LT1006 Single Supply, Micropower Sample and Hold



Distribution of Input Offset Voltage

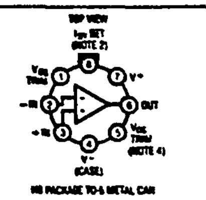


LT1006

ABSOLUTE MAXIMUM RATINGS

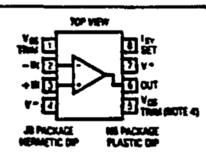
Supply Voltage .... ±22V
Input Voltage .... Equal to Positive Supply Voltage
.........5V Below Negative Supply Voltage
Differential Input Voltage............................30V
Output Short Circuit Duration.................. Indefinite
Operating Temperature Range
LT1006AM, M .... −55°C to 125°C
LT1006AC, C ....0°C to 70°C
Storage Temperature Range
All Devices .... −65°C to 150°C
Lead Temperature (Soldering, 10 sec) ....300°C

PACKAGE/ORDER INFORMATION



ORDER PART NUMBER

LT1006AMH
LT1006MH
LT1006ACH
LT1006CH



LT1006AMJ8
LT1006MJ8
LT1006ACJ8
LT1006CJ8
LT1006CN8

ELECTRICAL CHARACTERISTICS $V_S = 5V$, $V_{CM} = 0V$, $V_{OUT} = 1.4V$, $T_A = 25°C$, unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	LT1006AM/AC MIN	LT1006AM/AC TYP	LT1006AM/AC MAX	LT1006M/C MIN	LT1006M/C TYP	LT1006M/C MAX	UNITS
V_{OS}	Input Offset Voltage			20	50		30	80	µV
$\frac{\Delta V_{OS}}{\Delta Time}$	Long Term Input Offset Voltage Stability			0.4			0.5		µV/Mo
I_{OS}	Input Offset Current			0.12	0.5		0.15	0.9	nA
I_B	Input Bias Current			9	15		10	25	nA
e_n	Input Noise Voltage	0.1Hz to 10Hz		0.55			0.55		µVp-p
	Input Noise Voltage Density	$f_o = 10Hz$ (Note 3) $f_o = 1000Hz$ (Note 3)		23 22	32 25		23 22	32 25	nV/√Hz nV/√Hz
i_n	Input Noise Current Density	$f_o = 10Hz$		0.07			0.08		pA/√Hz
	Input Resistance Differential Mode Common-Mode	(Note 1)	 180	 400 5		 100	 300 4		 MΩ GΩ
	Input Voltage Range		3.5 0	3.8 −0.3		3.5 0	3.8 −0.3		V V
CMRR	Common-Mode Rejection Ratio	$V_{CM} = 0V$ to 3.5V	100	114		97	112		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	106	126		103	124		dB
A_{VOL}	Large Signal Voltage Gain	$V_O = 0.03V$ to 4V, $R_L = 10k$ $V_O = 0.03V$ to 3.5V, $R_L = 2k$	1.0 0.5	2.5 2.0		0.7 0.3	2.0 1.8		V/µV V/µV
	Maximum Output Voltage Swing	Output Low, No Load Output Low, 600Ω to GND Output Low, $I_{SINK} = 1mA$ Output High, No Load Output High, 600Ω to GND	 4.0 3.4	15 5 220 4.4 4.0	25 10 350	 4.0 3.4	15 5 220 4.4 4.0	25 10 350	mV mV mV V V
SR	Slew Rate		0.25	0.4		0.25	0.4		V/µs
I_S	Supply Current	$R_{SET} = \infty$ $R_{SET} = 180k$ Pin 8 to Pin 7 (Note 2)		340 90	520		350 90	570	µA µA
	Minimum Supply Voltage		2.7			2.7			V

ELECTRICAL CHARACTERISTICS

$V_S = 5V, 0V, V_{CM} = 0.1V, V_O = 1.4V, -55°C \le T_A \le 125°C$, unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS		LT1006AM MIN	LT1006AM TYP	LT1006AM MAX	LT1006M MIN	LT1006M TYP	LT1006M MAX	UNITS
V_{OS}	Input Offset Voltage		●		40	180		80	250	μV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Input Offset Voltage Drift		●		0.2	1.3		0.3	1.8	μV/°C
I_{OS}	Input Offset Current		●		0.4	2.0		0.5	4.0	nA
I_B	Input Bias Current		●		13	25		16	40	nA
A_{VOL}	Large Signal Voltage Gain	$V_O = 0.05V$ to $3.5V$, $R_L = 2k$	●	0.25	0.8		0.15	0.7		V/μV
CMRR	Common-Mode Rejection Ratio	$V_{CM} = 0.1V$ to $3.2V$	●	90	103		87	102		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	●	100	117		97	116		dB
	Maximum Output Voltage Swing	Output Low, 600Ω to GND	●		6	15		6	18	mV
		Output High, 600Ω to GND	●	3.2	3.8		3.1	3.8		V
I_S	Supply Current		●		380	630		400	650	μA

ELECTRICAL CHARACTERISTICS

$V_S = 5V, 0V, V_{CM} = 0V, V_O = 1.4V, 0°C \le T_A \le 70°C$, unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS		LT1006AC MIN	LT1006AC TYP	LT1006AC MAX	LT1006C MIN	LT1006C TYP	LT1006C MAX	UNITS
V_{OS}	Input Offset Voltage		●		30	110		45	160	μV
		LT1006N8	●					50	190	μV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Input Offset Voltage Drift		●		0.2	1.3		0.3	1.8	μV/°C
		LT1006N8	●					0.5	2.5	μV/°C
I_{OS}	Input Offset Current		●		0.25	1.2		0.3	2.5	nA
I_B	Input Bias Current		●		11	20		12	30	nA
A_{VOL}	Large Signal Voltage Gain	$V_O = 0.04V$ to $3.5V$, $R_L = 2k$	●	0.35	1.3		0.25	1.2		V/μV
CMRR	Common-Mode Rejection Ratio	$V_{CM} = 0V$ to $3.4V$	●	98	109		92	108		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	●	101	120		97	118		dB
	Maximum Output Voltage Swing	Output Low, 600Ω to GND	●		6	13		6	13	mV
		Output High, 600Ω to GND	●	3.3	3.9		3.2	3.9		V
I_S	Supply Current		●		350	570		380	620	μA

The ● denotes the specifications which apply over the full operating temperature range.

Note 1: This parameter is guaranteed by design and is not tested.

Note 2: Regular operation does not require an external resistor. In order to program the supply current for low power or high speed operation, connect an external resistor from Pin 8 to Pin 7 or from Pin 8 to Pin 4, respectively. Supply current specifications (for $R_{SET} = 180k$) do not include current in R_{SET}.

Note 3: This parameter is tested on a sample basis only. All noise parameters are tested with $V_S = \pm 2.5V$, $V_O = 0V$.

Note 4: Optional offset nulling is accomplished with a potentiometer connected between the trim terminals and the wiper to V^-. A 10k pot (providing a null range of ±6mV) is recommended for minimum drift of nulled offset voltage with temperature. For increased trim resolution and accuracy, two fixed resistors can be used in conjunction with a smaller potentiometer. For example: two 4.7k resistors tied to pins 1 and 5, with a 500Ω pot in the middle, will have a null range of ±150μV.

ELECTRICAL CHARACTERISTICS $V_S = \pm 15V$, $T_A = 25°C$, unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS	LT1006AM/AC MIN	LT1006AM/AC TYP	LT1006AM/AC MAX	LT1006M/C MIN	LT1006M/C TYP	LT1006M/C MAX	UNITS
V_{OS}	Input Offset Voltage			30	100		80	180	μV
I_{OS}	Input Offset Current			0.1	0.5		0.15	0.9	nA
I_B	Input Bias Current			7.5	12.0		8.0	20.0	nA
	Input Voltage Range		13.5 −15.0	13.8 −15.3		13.5 −15.0	13.8 −15.3		V V
CMRR	Common-Mode Rejection Ratio	$V_{CM} = +13.5V, -15V$	100	117		97	116		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	106	126		103	124		dB
A_{VOL}	Large Signal Voltage Gain	$V_O = \pm 10V$, $R_L = 2k$ $V_O = \pm 10V$, $R_L = 600\Omega$	1.5 0.8	5.0 1.5		1.2 0.5	4.0 1.0		V/μV V/μV
V_{OUT}	Maximum Output Voltage Swing	$R_L = 2k$	±13	±14		±12.5	±14		V
SR	Slew Rate	$R_{SET} = \infty$ $R_{SET} = 390\Omega$ Pin 8 to Pin 4	0.25 1.0	0.4 1.2		0.25 1.0	0.4 1.2		V/μs V/μs
I_S	Supply Current			380	540		380	600	μA

ELECTRICAL CHARACTERISTICS $V_S = \pm 15V$, $-55°C \le T_A \le 125°C$, unless otherwise noted.

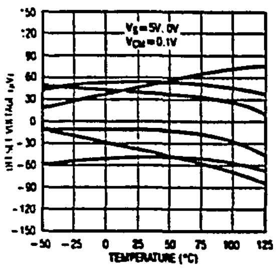
SYMBOL	PARAMETER	CONDITIONS		LT1006AM MIN	LT1006AM TYP	LT1006AM MAX	LT1006M MIN	LT1006M TYP	LT1006M MAX	UNITS
V_{OS}	Input Offset Voltage		●		80	320		110	460	μV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Input Offset Voltage Drift		●		0.5	2.2		0.6	2.8	μV/°C
I_{OS}	Input Offset Current		●		0.2	2.0		0.3	3.0	nA
I_B	Input Bias Current		●		9	18		11	27	nA
A_{VOL}	Large Signal Voltage Gain	$V_O = \pm 10V$, $R_L = 2k$	●	0.5	1.5		0.25	1.0		V/μV
CMRR	Common-Mode Rejection Ratio	$V_{CM} = +13V, -14.9V$	●	97	114		94	113		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	●	100	117		97	116		dB
	Maximum Output Voltage Swing	$R_L = 2k$	●	±12	±13.8		±11.5	±13.8		V
I_S	Supply Current		●		400	650		400	750	μA

ELECTRICAL CHARACTERISTICS $V_S = \pm 15V$, $0°C \le T_A \le 70°C$, unless otherwise noted.

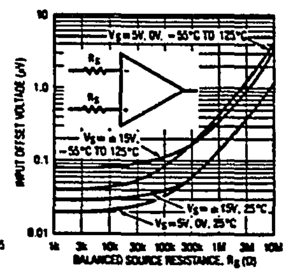
SYMBOL	PARAMETER	CONDITIONS		LT1006AC MIN	LT1006AC TYP	LT1006AC MAX	LT1006C MIN	LT1006C TYP	LT1006C MAX	UNITS
V_{OS}	Input Offset Voltage	 LT1006N8	●		50	200		75 80	300 330	μV μV
$\frac{\Delta V_{OS}}{\Delta Temp}$	Input Offset Voltage Drift	 LT1006N8	● ●		0.5	2.2		0.6 0.7	2.8 3.5	μV/°C μV/°C
I_{OS}	Input Offset Current		●		0.15	1.0		0.25	2.0	nA
I_B	Input Bias Current		●		8.0	15		10	23	nA
A_{VOL}	Large Signal Voltage Gain	$V_O = \pm 10V$, $R_L = 2k$	●	1.0	3.0		0.7	2.5		V/μV
CMRR	Common-Mode Rejection Ratio	$V_{CM} = 13V, -15V$	●	98	116		94	114		dB
PSRR	Power Supply Rejection Ratio	$V_S = \pm 2V$ to $\pm 18V$, $V_O = 0V$	●	101	120		97	118		dB
	Maximum Output Voltage Swing	$R_L = 2k$	●	±12.5	±13.9		±11.5	±13.8		V
I_S	Supply Current		●		370	600		380	680	μA

TYPICAL PERFORMANCE CHARACTERISTICS

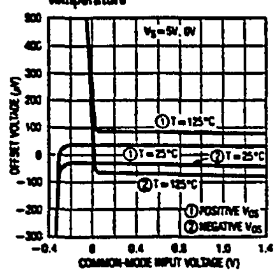
Offset Voltage Drift with Temperature of Representative Units



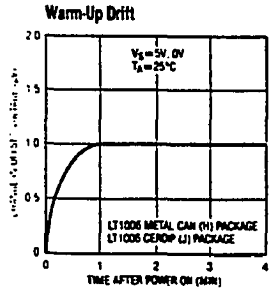
Offset Voltage vs Balanced Source Resistor



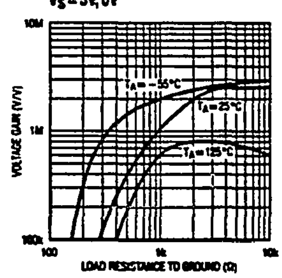
V_{OS} vs Common-Mode Voltage vs Temperature



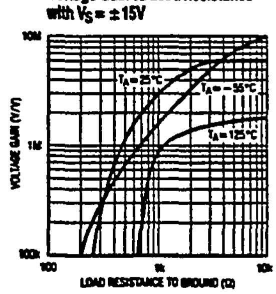
Warm-Up Drift



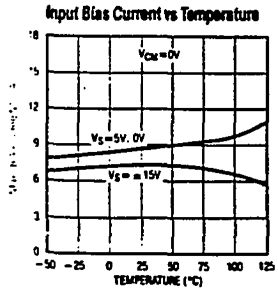
Voltage Gain vs Load Resistance, $V_S = 5V, 0V$



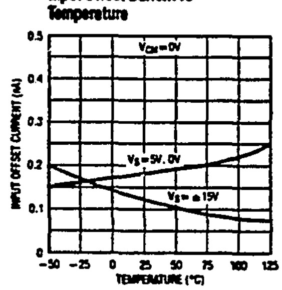
Voltage Gain vs Load Resistance with $V_S = \pm15V$



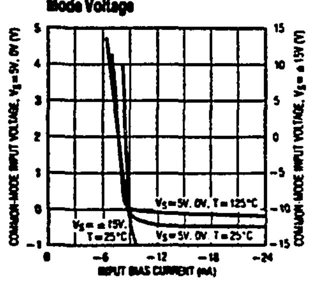
Input Bias Current vs Temperature



Input Offset Current vs Temperature

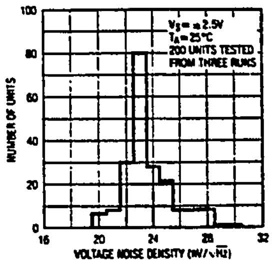


Input Bias Current vs Common-Mode Voltage

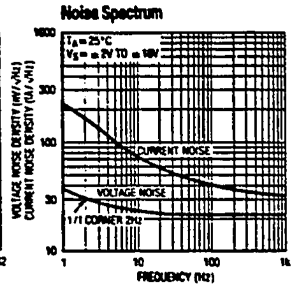


TYPICAL PERFORMANCE CHARACTERISTICS

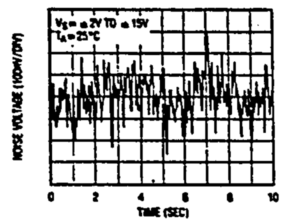
10Hz Voltage Noise Distribution



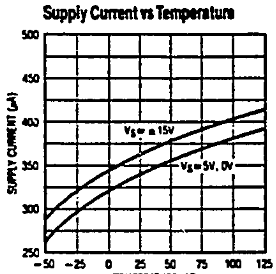
Noise Spectrum



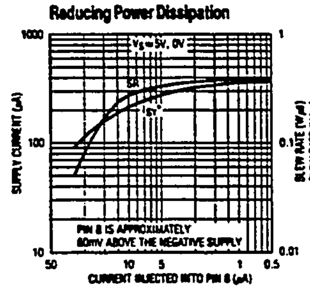
0.1Hz to 10Hz Noise



Supply Current vs Temperature

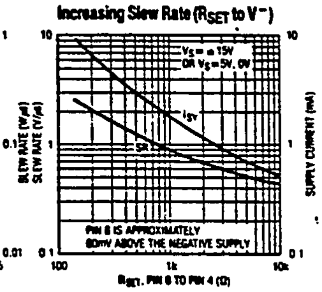


Reducing Power Dissipation

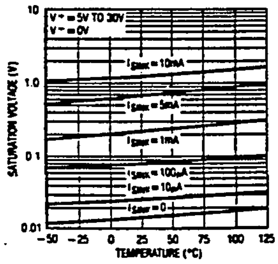


*I_{SY} DOES NOT INCLUDE CURRENT THROUGH R_{SET}

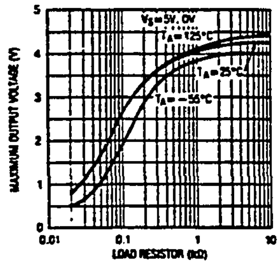
Increasing Slew Rate (R_{SET} to V^-)



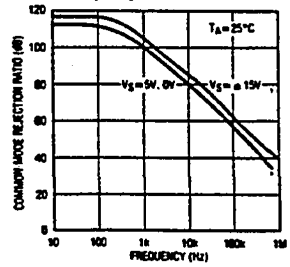
Output Saturation vs Sink Current vs Temperature



Maximum Output Swing vs Load Resistor

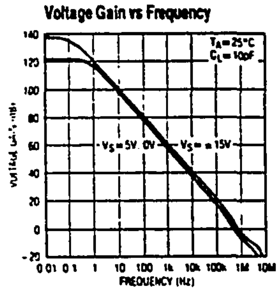


Common-Mode Rejection Ratio vs Frequency

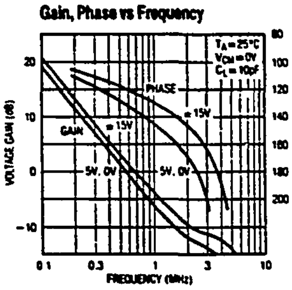


TYPICAL PERFORMANCE CHARACTERISTICS

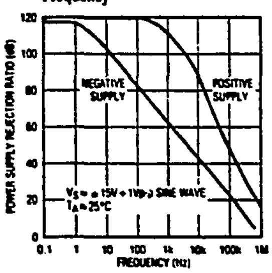
Voltage Gain vs Frequency



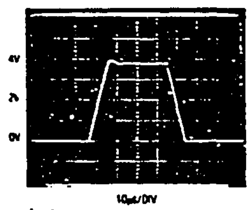
Gain, Phase vs Frequency



Power Supply Rejection Ratio vs Frequency

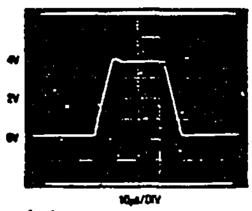


Large Transient Response, $V_S = 5V, 0V$



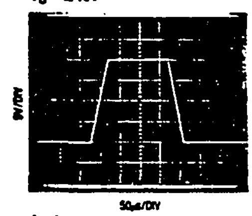
$A_V = 1$
$R_L = 4.7k$ TO 5V
INPUT = 0V TO 3.8V

Large Signal Transient Response, $V_S = 5V, 0V$



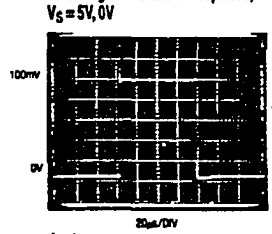
$A_V = 1$
$R_L = 4.7k$ TO GROUND
INPUT = 0V TO 3.8V

Large Signal Transient Response, $V_S = \pm 15V$



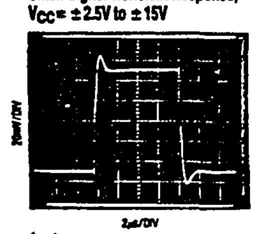
$A_V = 1$

Small Signal Transient Response, $V_S = 5V, 0V$



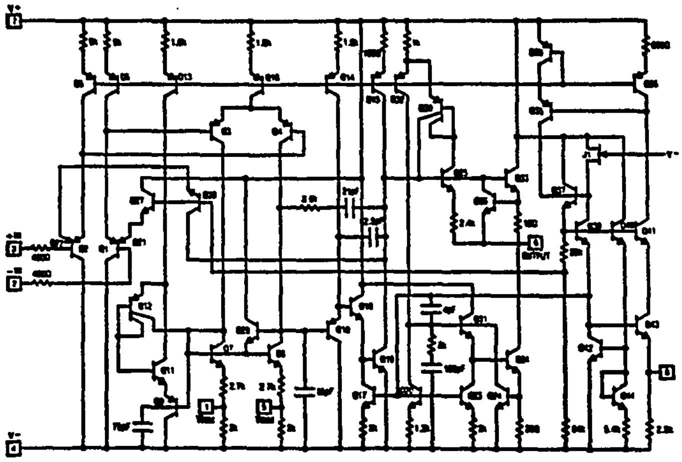
$A_V = 1$
$C_L = 10pF$
$R_L = 600\Omega$ TO GND
INPUT = 0V TO 100mV PULSE

Small Signal Transient Response, $V_{CC} = \pm 2.5V$ to $\pm 15V$



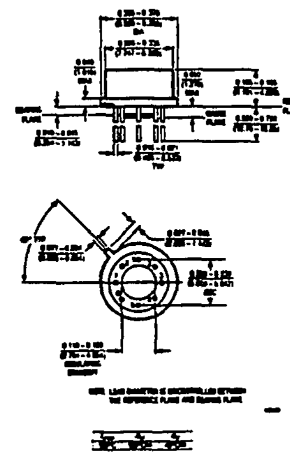
$A_V = 1$
$C_L = 10pF$

LT1006 SCHEMATIC DIAGRAM

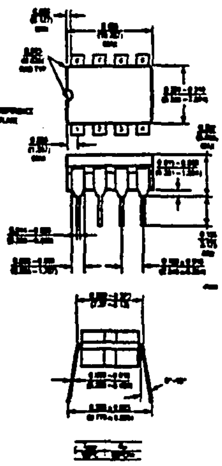


PACKAGE DESCRIPTION Dimensions in inches (millimeters) unless otherwise noted.

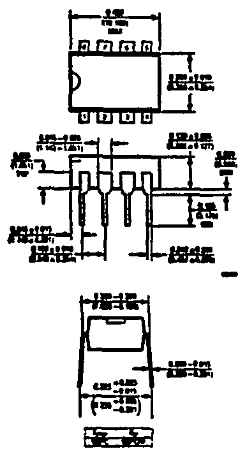
H8 Package
TO-5 Metal Can



J8 Package
Hermetic DIP



N8 Package
Plastic DIP



New product

ML4XX15 SERIES

FOR OPTICAL INFORMATION SYSTEMS

TYPE NAME **ML40115N, ML40115C, ML40115R**

DESCRIPTION

Mitsubishi ML4XX15 are AlGaAs laser diodes emitting light beams around 780nm wavelength. They lase by applying forward current exceeding threshold values, and emit light power of about 3mW/facet at an operating current of around 13mA in excess of the threshold current. They operate, under CW or pulse conditions according to input current, at case temperatures up to 60℃.

ML4XX15 are hermetically sealed devices having a Si photodiode for monitoring the light output. Output current of the photodiode can be used for automatic control of the operating currents or case temperatures of the lasers. They are well suited for optical information systems and other optical systems.

FEATURES

- Si photodiode is installed in the laser package
- High reliability, long operation life
- Low optical noise (High S/N)
- Multi-mode oscillation

APPLICATION

Audio compact disc players

ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Conditions	Ratings	Unit
P_O	Light output	CW	5	mW
		Pulse (Note 1)	6	
V_{RL}	Reverse voltage (Laser diode)	—	2	V
V_{RD}	Reverse voltage (Photodiode)	—	15	V
I_{FD}	Forward current (Photodiode)	—	10	mA
T_C	Case temperature	—	−40～+60	℃
T_{stg}	Storage temperature	—	−55～+100	℃

Note 1 : Duty less than 50%, pulse width less than 1μs.

ELECTRICAL/OPTICAL CHARACTERISTICS (T_C=25℃)

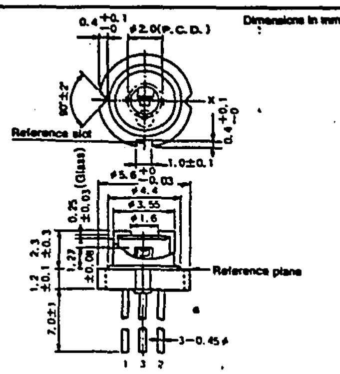
Symbol	Parameter	Test conditions	Limits			Unit
			Min	Typ.	Max.	
I_{th}	Threshold current	CW	—	45	60	mA
I_{OP}	Operating current	CW, P_O=3mW	—	58	70	mA
V_{OP}	Operating voltage (Laser diode)	CW, P_O=3mW	—	1.8	2.5	V
P_O	Light output	CW, $I_F=I_{th}$+13mA	—	3	—	mW
λ_P	Lasing wavelength	CW, P_O=3mW	765	780	795	nm
$\theta_{//}$	Full angle at half maximum	CW, P_O=3mW	9	11	16	deg.
$\theta_{\perp}$			30	38	48	deg.
I_m	Monitoring output current	CW, P_O=3mW V_{RD}=1V R_L=10Ω (Note 2)	0.15	0.35	0.7	mA
I_D	Dark current (Photodiode)	V_{RD}=10V	—	—	0.5	μA
C_t	Capacitance (Photodiode)	V_R=0V, f=1MHz	—	7	—	pF

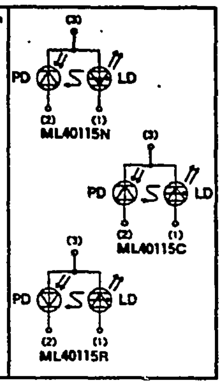
Note 2 : R_L is load resistance of the photodiode.

MITSUBISHI ELECTRIC

OUTLINE DRAWINGS

ML40115N/ ML40115C/ ML40115R

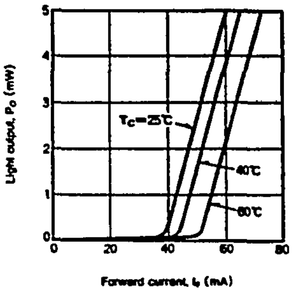




1 Light output vs. forward current

Typical light output vs. forward current characteristics are shown in Fig. 1. The threshold current for lasing is typically 45mA at room temperature. Above the threshold, the light output increases linearly with current, and no kinks are observed in the curves. As can be seen in Fig. 1, the threshold current and slope efficiency (dP_O/dI_F) depends on case temperature of the lasers. This suggests that automatic control of temperature or current is necessary to keep the light output constant since temperature variation is inevitable in practical systems. The automatic controls should be such that the maximum ratings for the light output and the case temperature are not exceeded. "OPERATING CONSIDERATIONS." gives an example of an automatic light output control circuit.

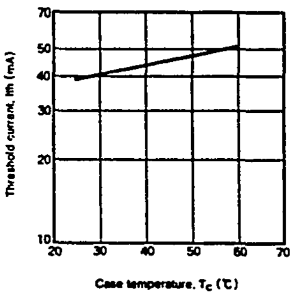
Fig. 1 Light output vs. forward current



2 Temperature dependence of threshold current (I_{th})

A typical temperature dependence of the threshold current is shown in Fig. 2. The characteristic temperature T_O of the threshold current is typically 130K in $T_C \leq 60$℃, where the definition of T_O is $I_{th} \propto \exp(T_C/T_O)$

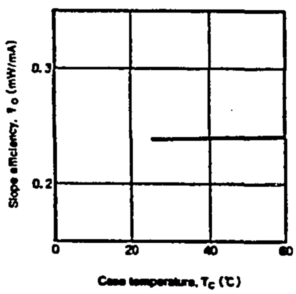
Fig. 2 Temperature dependence of threshold current



3 Temperature dependence of slope efficiency

A typical temperature dependence of the slope efficiency η_O is shown in Fig. 3. The gradient is about 0mW/mA/℃.

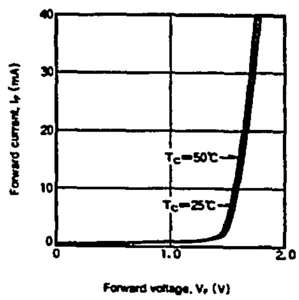
Fig. 3 Temperature dependence of slope efficiency



4 Forward current vs. voltage

Typical forward current vs. voltage characteristics are shown in Fig. 4. In general, as the case temperature rises, the forward voltage V_F decreases slightly against the constant current I_F. V_F varies typically at a rate of -1.5mV/℃ at $I_F = 1$mA.

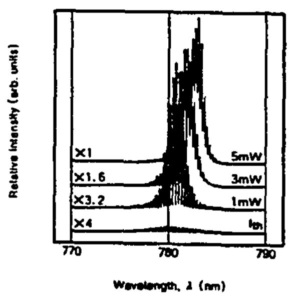
Fig. 4 Forward current vs. voltage characteristics



5 Emission spectra

Typical emission spectra under CW operation are shown in Fig. 5. In general, at an output of 3mW, multi mode is observed. The peak wavelength depends on the operating case temperature and forward current (output level).

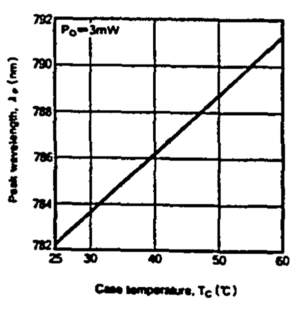
Fig. 5 Emission spectra under CW operation



6 Temperature dependence of peak wavelength

A typical temperature dependence of the peak wavelength at an output of 3mW is shown in Fig.6.
The peak wavelength of the beam shifts to adjacent longitudinal mode by variation of operating temperature.
Averaged temperature coefficient is about 0.26nm/℃.

Fig. 6 Temperature dependence of peak wavelength



7 Far-field radiation pattern

The ML4XX15 laser diodes lase in fundamental transverse (TE_{00}) mode and the mode does not change with the current. They have a typical emitting area (size of near-field pattern) of $1.5 \times 0.5 \mu m^2$. Fig. 7 and Fig. 8 show typical far-field radiation patterns in "parallel" and "perpendicular" planes.

The full angles at half maximum points (FAHM) are typically 11° and 38°.

Fig. 7 Far-field patterns in plane parallel to heterojunction

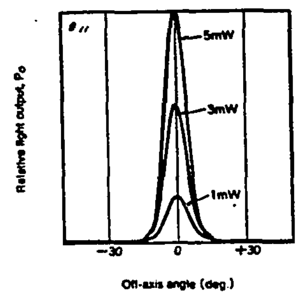
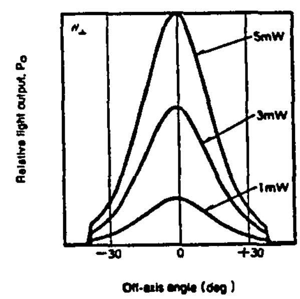


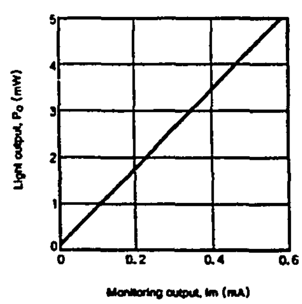
Fig. 8 Far-field patterns in plane perpendicular to heterojunction



8 Monitoring output

The laser diodes emit beams from both of their mirror surfaces, front and rear surfaces (see the outline drawing). The rear beam can be used for monitoring power of front beam since the rear beam is proportional to the front one. In the case of ML4XX15 lasers, the rear beam powers are changed into photocurrent by the monitoring photodiodes. *Fig. 9 shows an example of light output vs. monitoring photocurrent characteristics.* Above the threshold current, the monitored photocurrent linearly increases with the light output.

Fig. 9 Light output vs. monitoring output current



9 S/N vs. optical feedback ratio

S/N vs. optical feedback ratio, where frequency is 20kHz and the bandwidth is 300Hz is shown in Fig. 10.
And that where the frequency is 10MHz and the bandwidth is 300kHz is shown in Fig. 11.

10 Astigmatic focal distance

There seems to be a difference in luminous point in the parallel and perpendicular direction with the laser beam. This distance between the two points is the astigmatic focal distance. Therefore, when the laser beam is focused, there is a difference in focal point in the two directions.
The typical astigmatic focal distance at NA = 0.7 of ML4XX15 is shown in Fig. 12.

Fig. 10 S/N vs. optical feedback ratio
$f=20kHz, BW=300Hz, T_C=25-50°C$

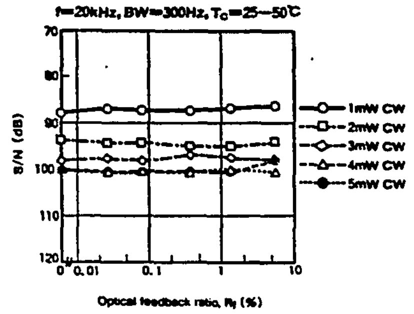


Fig. 11 S/N vs. optical feedback ratio
$f=10MHz, BW=300kHz, T_C=25-50°C$

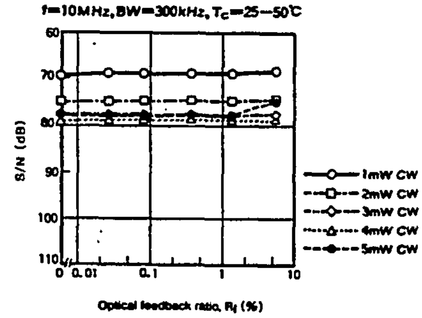
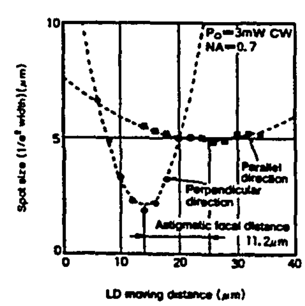


Fig. 12 Astigmatic focal distance



ORDERING INFORMATION

Device	Alternate	Temperature Range	Package
MC1723CD		0°C to +70°C	SO-14
MC1723CG	LM723CH, μA723HC	0°C to +70°C	Metal Can
MC1723CL	LM723CD, μA723DC	0°C to +70°C	Ceramic DIP
MC1723CP	LM723CN, μA723PC	0°C to +70°C	Plastic DIP
MC1723G		−55°C to +125°C	Metal Can
MC1723L		−55°C to +125°C	Ceramic DIP

MC1723
MC1723C

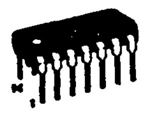
VOLTAGE REGULATOR

The MC1723 is a positive or negative voltage regulator designed to deliver load current to 150 mAdc. Output current capability can be increased to several amperes through use of one or more external pass transistors. MC1723 is specified for operation over the military temperature range (-55°C to +125°C) and the MC1723C over the commercial temperature range (0 to +70°C)

- Output Voltage Adjustable from 2 Vdc to 37 Vdc
- Output Current to 150 mAdc Without External Pass Transistors
- 0.01% Line and 0.03% Load Regulation
- Adjustable Short-Circuit Protection

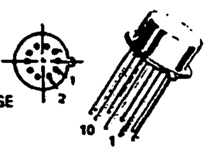
VOLTAGE REGULATOR

SILICON MONOLITHIC INTEGRATED CIRCUIT

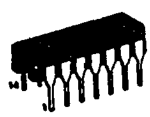


P SUFFIX
PLASTIC PACKAGE
CASE 646-06

(Bottom View)



G SUFFIX
METAL PACKAGE
CASE 603-04



L SUFFIX
CERAMIC PACKAGE
CASE 632-02

D SUFFIX
PLASTIC PACKAGE
CASE 751A-02
SO-14

FIGURE 1 – CIRCUIT SCHEMATIC

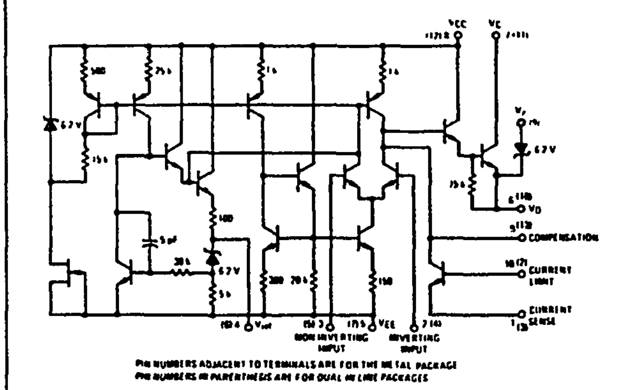


FIGURE 2 – TYPICAL CIRCUIT CONNECTION

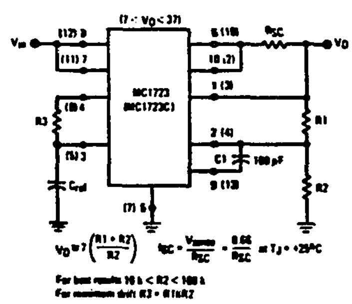
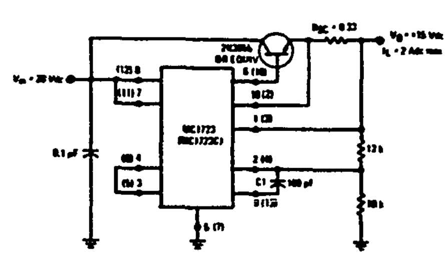


FIGURE 3 – TYPICAL NPN CURRENT BOOST CONNECTION



MC1723, MC1723C

MAXIMUM RATINGS (T_A = +25°C unless otherwise noted.)

Rating	Symbol	Value	Unit
Pulse Voltage from V_{CC} to V_{EE} (50 ms)	$V_{in(p)}$	50	V_{peak}
Continuous Voltage from V_{CC} to V_{EE}	V_{in}	40	Vdc
Input-Output Voltage Differential	$V_{in} - V_O$	40	Vdc
Maximum Output Current	I_L	150	mAdc
Current from V_{ref}	I_{ref}	15	mAdc
Current from V_z	I_z	25	mA
Voltage Between Non-Inverting Input and V_{EE}	V_{ie}	8.0	Vdc
Differential Input Voltage	V_{id}	±5.0	Vdc
Power Dissipation and Thermal Characteristics			
Plastic Package			
T_A = +25°C	P_D	1.25	W
Derate above T_A = +25°C	$1/\theta_{JA}$	10	mW/°C
Thermal Resistance, Junction to Air	θ_{JA}	100	°C/W
Metal Package			
T_A = +25°C	P_D	1.0	Watt
Derate above T_A = +25°C	$1/\theta_{JA}$	6.6	mW/°C
Thermal Resistance, Junction to Air	θ_{JA}	150	°C/W
T_C = +25°C	P_D	2.1	Watts
Derate above T_A = +25°C	$1/\theta_{JA}$	14	mW/°C
Thermal Resistance, Junction to Case	θ_{JC}	35	°C/W
Dual In-Line Ceramic Package	P_D	1.5	Watt
Derate above T_A = +25°C	$1/\theta_{JA}$	10	mW/°C
Thermal Resistance, Junction to Air	θ_{JA}	100	°C/W
Operating and Storage Junction Temperature Range	T_J, T_{stg}		°C
Metal Package		-65 to +150	
Dual In-Line Ceramic		-65 to +175	
Operating Ambient Temperature Range	T_A		°C
MC1723C		0 to +70	
MC1723		-55 to +125	

ELECTRICAL CHARACTERISTICS (Unless otherwise noted: T_A = +25°C, V_{in} 12 Vdc, V_O = 5.0 Vdc, I_L = 1.0 mAdc, R_{SC} = 0, C1 = 100 pF, C_{ref} = 0 and divider impedance as seen by the error amplifier ≤ 10 kΩ connected as shown in Figure 2)

Characteristic	Symbol	MC1723			MC1723C			Unit
		Min	Typ	Max	Min	Typ	Max	
Input Voltage Range	V_{in}	9.5	–	40	9.5	–	40	Vdc
Output Voltage Range	V_O	2.0	–	37	2.0	–	37	Vdc
Input-Output Voltage Differential	$V_{in}-V_O$	3.0	–	38	3.0	–	38	Vdc
Reference Voltage	V_{ref}	6.95	7.15	7.35	6.80	7.15	7.50	Vdc
Standby Current Drain (I_L = 0, V_{in} = 30 V)	I_{IB}	–	2.3	3.5	–	2.3	4.0	mAdc
Output Noise Voltage (f = 100 Hz to 10 kHz)	V_n							µV(RMS)
C_{ref} = 0		–	20	–	–	20	–	
C_{ref} = 5.0 µF		–	2.5	–	–	2.5	–	
Average Temperature Coefficient of Output Voltage (T_{low} ① < T_A < T_{high} ②)	TCV_O	–	0.002	0.015	–	0.003	0.015	%/°C
Line Regulation	Reg_{line}							$\%V_O$
(T_A = +25°C) 12 V < V_{in} < 15 V		–	0.01	0.1	–	0.01	0.1	
(T_A = +25°C) 12 V ≤ V_{in} < 40 V		–	0.02	0.2	–	0.1	0.5	
(T_{low} ① < T_A < T_{high} ②) 12 V < V_{in} < 15 V		–	–	0.3	–	–	0.3	
Load Regulation (1.0 mA < I_L < 50 mA)	Reg_{load}							$\%V_O$
T_A = +25°C		–	0.03	0.15	–	0.03	0.2	
T_{low} ① < T_A < T_{high} ②		–	–	0.6	–	–	0.6	
Ripple Rejection (f = 50 Hz to 10 kHz)	RR							dB
C_{ref} = 0		–	74	–	–	74	–	
C_{ref} = 5.0 µF		–	86	–	–	86	–	
Short Circuit Current Limit (R_{SC} = 10 Ω, V_O = 0)	I_{sc}	–	65	–	–	65	–	mAdc
Long Term Stability	$\Delta V_O/\Delta t$	–	0.1	–	–	0.1	–	%/1000 Hr

① T_{low} = 0°C for MC1723C
= -55°C for MC1723

② T_{high} = +70°C for MC1723C
= +125°C for MC1723

MC1723, MC1723C

TYPICAL CHARACTERISTICS

(V_{in} = 12 Vdc, V_O = 5.0 Vdc, I_L = 1.0 mAdc, R_{SC} = 0, T_A = +25°C unless otherwise noted.)

FIGURE 4 – MAXIMUM LOAD CURRENT AS A FUNCTION OF INPUT-OUTPUT VOLTAGE DIFFERENTIAL

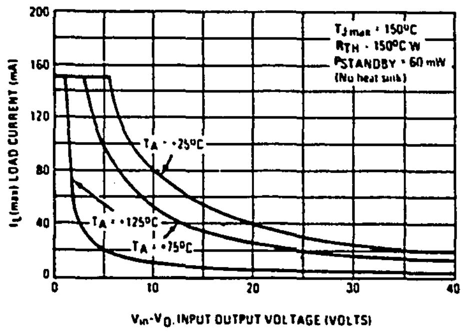


FIGURE 5 – LOAD REGULATION CHARACTERISTICS WITHOUT CURRENT LIMITING

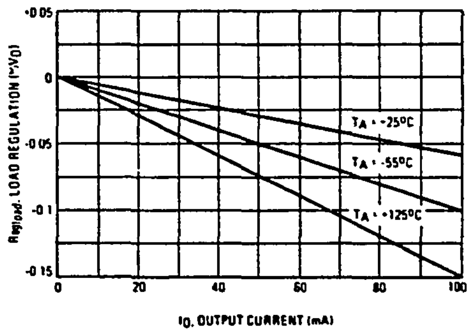


FIGURE 6 – LOAD REGULATION CHARACTERISTICS WITH CURRENT LIMITING

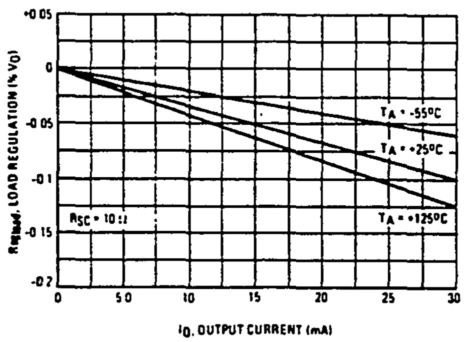


FIGURE 7 – LOAD REGULATION CHARACTERISTICS WITH CURRENT LIMITING

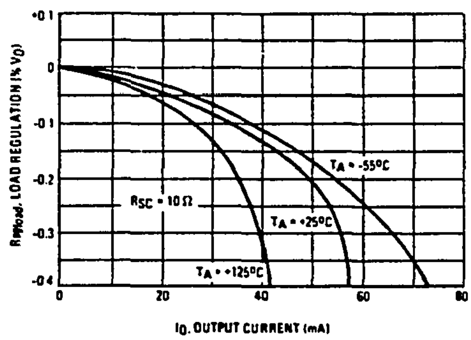


FIGURE 8 – CURRENT LIMITING CHARACTERISTICS

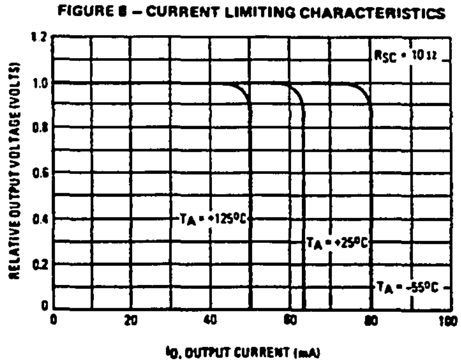
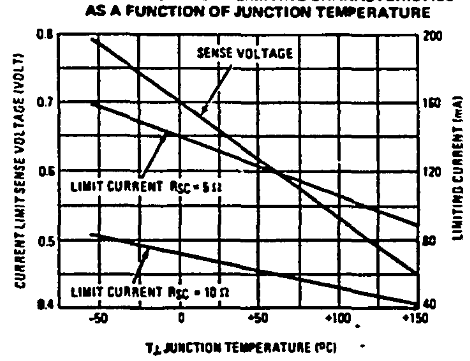


FIGURE 9 – CURRENT LIMITING CHARACTERISTICS AS A FUNCTION OF JUNCTION TEMPERATURE



MC1723, MC1723C

TYPICAL CHARACTERISTICS (continued)

FIGURE 10 – LINE REGULATION AS A FUNCTION OF INPUT-OUTPUT VOLTAGE DIFFERENTIAL

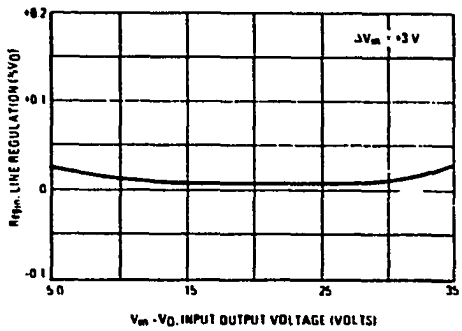


FIGURE 11 – LOAD REGULATION AS A FUNCTION OF INPUT-OUTPUT VOLTAGE DIFFERENTIAL

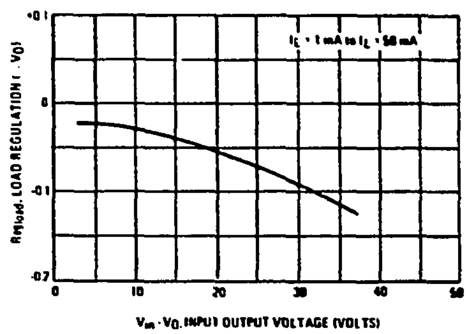


FIGURE 12 – STANDBY CURRENT DRAIN AS A FUNCTION OF INPUT VOLTAGE

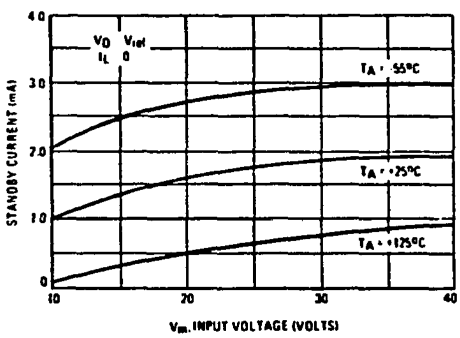


FIGURE 13 – LINE TRANSIENT RESPONSE

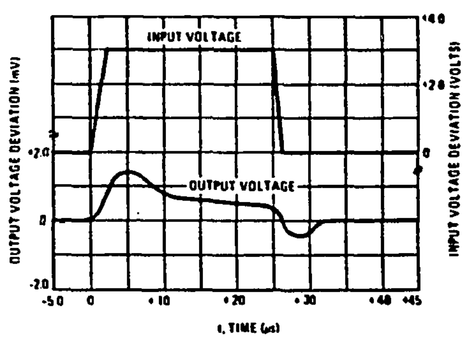


FIGURE 14 – LOAD TRANSIENT RESPONSE

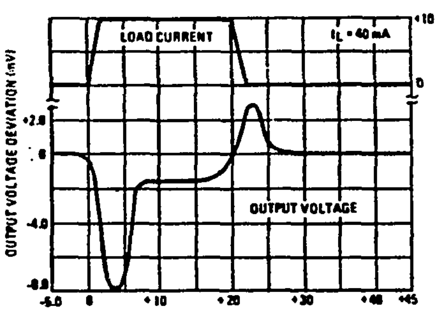
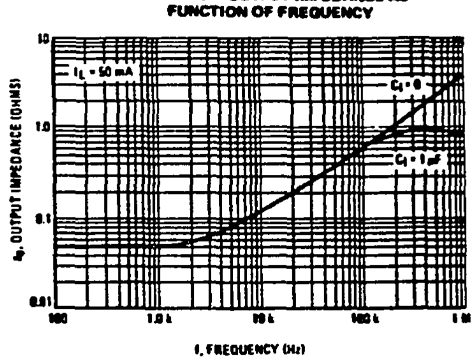


FIGURE 15 – OUTPUT IMPEDANCE AS FUNCTION OF FREQUENCY



MOTOROLA
SEMICONDUCTOR
TECHNICAL DATA

NPN
2N3055
PNP
MJ2955

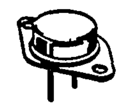
COMPLEMENTARY SILICON POWER TRANSISTORS

. . . designed for general-purpose switching and amplifier applications.

- DC Current Gain — h_{FE} = 20–70 @ I_C = 4 Adc
- Collector-Emitter Saturation Voltage — $V_{CE(sat)}$ = 1.1 Vdc (Max) @ I_C = 4 Adc
- Excellent Safe Operating Area

15 AMPERE
POWER TRANSISTORS
COMPLEMENTARY SILICON

60 VOLTS
115 WATTS



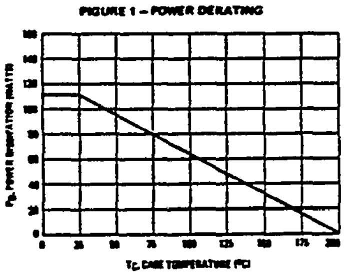
MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector-Emitter Voltage	V_{CEO}	60	Vdc
Collector-Emitter Voltage	V_{CER}	70	Vdc
Collector-Base Voltage	V_{CB}	100	Vdc
Emitter-Base Voltage	V_{EB}	7	Vdc
Collector Current — Continuous	I_C	15	Adc
Base Current	I_B	7	Adc
Total Power Dissipation @ T_C = 25°C Derate above 25°C	P_D	115 0.657	Watts W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−65 to +200	°C

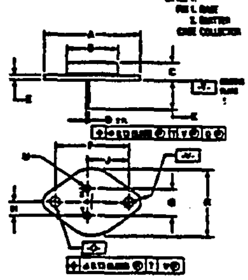
THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1.52	°C/W

FIGURE 1 — POWER DERATING



STYLE 1:
PIN 1. BASE
2. EMITTER
CASE: COLLECTOR



DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	—	39.37	—	1.550
B	—	21.08	—	0.830
C	6.35	8.25	0.250	0.325
D	0.97	1.09	0.038	0.043
E	1.40	1.77	0.055	0.070
F	30.15 BSC		1.187 BSC	
G	10.92 BSC		0.430 BSC	
H	5.46 BSC		0.215 BSC	
J	16.89 BSC		0.665 BSC	
K	11.18	12.19	0.440	0.480
Q	3.84	4.19	0.151	0.165
R	—	26.67	—	1.050
U	4.83	5.33	0.190	0.210
V	3.84	4.19	0.151	0.165

NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. ALL RULES AND NOTES ASSOCIATED WITH REFERENCED TO-204AA OUTLINE SHALL APPLY.

CASE 1-06
TO-204AA
(TO-3)

2N3055 NPN/MJ2955 PNP

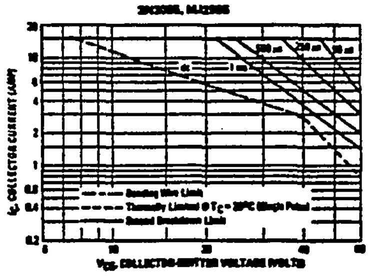
ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
***OFF CHARACTERISTICS**				
Collector-Emitter Sustaining Voltage (1) (I_C = 200 mAdc, I_B = 0)	$V_{CEO(sus)}$	60	–	Vdc
Collector-Emitter Sustaining Voltage (1) (I_C = 200 mAdc, R_{BE} = 100 Ohms)	$V_{CER(sus)}$	70	–	Vdc
Collector Cutoff Current (V_{CE} = 30 Vdc, I_B = 0)	I_{CEO}	–	0.7	mAdc
Collector Cutoff Current (V_{CE} = 100 Vdc, $V_{BE(off)}$ = 1.5 Vdc) (V_{CE} = 100 Vdc, $V_{BE(off)}$ = 1.5 Vdc, T_C = 150°C)	I_{CEX}	– –	1.0 5.0	mAdc
Emitter Cutoff Current (V_{BE} = 7.0 Vdc, I_C = 0)	I_{EBO}	–	5.0	mAdc
***ON CHARACTERISTICS (1)**				
DC Current Gain (I_C = 4.0 Adc, V_{CE} = 4.0 Vdc) (I_C = 10 Adc, V_{CE} = 4.0 Vdc)	h_{FE}	20 5.0	70 –	–
Collector-Emitter Saturation Voltage (I_C = 4.0 Adc, I_B = 400 mAdc) (I_C = 10 Adc, I_B = 3.3 Adc)	$V_{CE(sat)}$	–	1.1 3.0	Vdc
Base-Emitter On Voltage (I_C = 4.0 Adc, V_{CE} = 4.0 Vdc)	$V_{BE(on)}$	–	1.5	Vdc
SECOND BREAKDOWN				
Second Breakdown Collector Current with Base Forward Biased (V_{CE} = 40 Vdc, t = 1.0 s; Nonrepetitive)	$I_{s/b}$	2.87	–	Adc
DYNAMIC CHARACTERISTICS				
Current Gain — Bandwidth Product (I_C = 0.5 Adc, V_{CE} = 10 Vdc, f = 1.0 MHz)	f_T	2.5	–	MHz
*Small-Signal Current Gain (I_C = 1.0 Adc, V_{CE} = 4.0 Vdc, f = 1.0 kHz)	h_{fe}	15	120	–
*Small-Signal Current Gain Cutoff Frequency (V_{CE} = 4.0 Vdc, I_C = 1.0 Adc, f = 1.0 kHz)	f_{hfe}	10	–	kHz

* Indicates Within JEDEC Registration. (2N3055)
(1) Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

FIGURE 2 – ACTIVE REGION SAFE OPERATING AREA

2N3055, MJ2955



There are two limitations on the power handling ability of a transistor: average junction temperature and second breakdown. Safe operating area curves indicate I_C-V_{CE} limits of the transistor that must be observed for reliable operation; i.e., the transistor must not be subjected to greater dissipation than the curves indicate.

The data of Figure 2 is based on T_C = 25°C; $T_{J(pk)}$ is variable depending on power level. Second breakdown pulse limits are valid for duty cycles to 10% but must be derated for temperature according to Figure 1.

2N3055 NPN/MJ2955 PNP

NPN
2N3055

PNP
MJ2955

FIGURE 3 — DC CURRENT GAIN

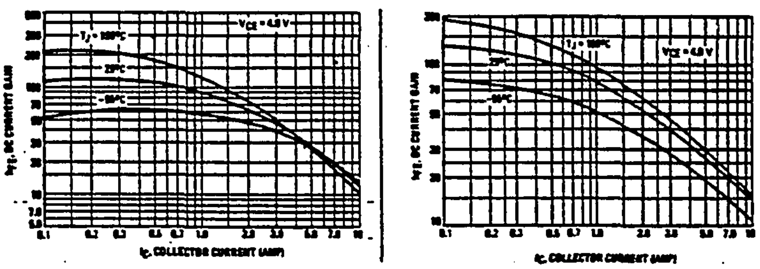


FIGURE 4 — COLLECTOR SATURATION REGION

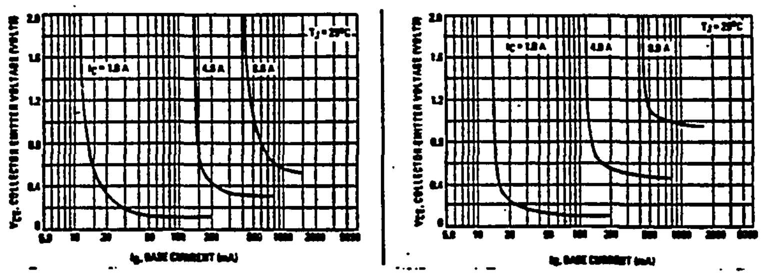
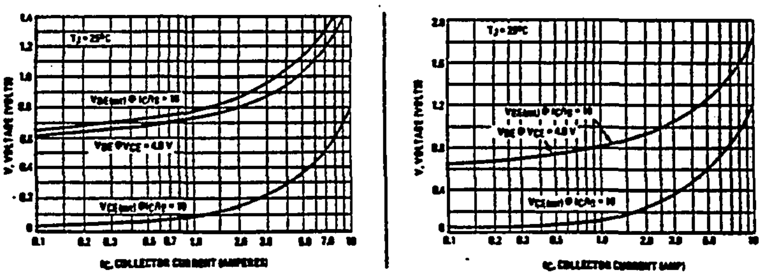


FIGURE 5 — "ON" VOLTAGES



MOTOROLA
SEMICONDUCTOR
TECHNICAL DATA

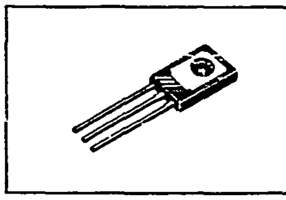
PNP
MJE170 thru MJE172
NPN
MJE180 thru MJE182

COMPLEMENTARY PLASTIC SILICON POWER TRANSISTORS

. . . designed for low power audio amplifier and low current, high speed switching applications.

- Collector-Emitter Sustaining Voltage —
  $V_{CEO(sus)}$ = 40 Vdc — MJE170, MJE180
  = 60 Vdc — MJE171, MJE181
  = 80 Vdc — MJE172, MJE182
- DC Current Gain —
  h_{FE} = 30 (Min) @ I_C = 0.5 Adc
  = 12 (Min) @ I_C = 1.5 Adc
- Current Gain — Bandwidth Product —
  f_T = 50 MHz (Min) @ I_C = 100 mAdc
- Annular Construction for Low Leakages —
  I_{CBO} = 100 nA (Max) @ Rated V_{CB}

3 AMPERE
POWER TRANSISTORS
COMPLEMENTARY SILICON
40-60-80 VOLTS
12.5 WATTS



MAXIMUM RATINGS

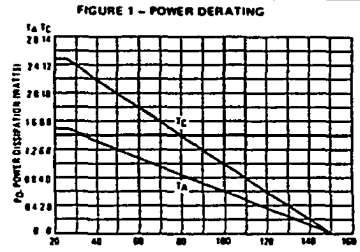
Rating	Symbol	MJE170 MJE180	MJE171 MJE181	MJE172 MJE182	Unit
Collector Base Voltage	V_{CB}	60	80	100	Vdc
Collector Emitter Voltage	V_{CEO}	40	60	80	Vdc
Emitter-Base Voltage	V_{EB}		7.0		Vdc
Collector Current Continuous Peak	I_C		3.0 6.0		Adc
Base Current	I_B		1.0		Adc
Total Power Dissipation @ T_A = 25°C Derate above 25°C	P_D		1.5 0.012		Watts W/°C
Total Power Dissipation @ T_C = 25°C Derate above 25°C	P_D		12.5 0.1		Watts W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}		-65 to +150		°C

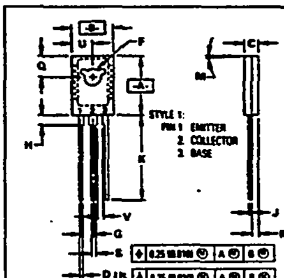
THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	θ_{JC}	10	°C/W
Thermal Resistance, Junction to Ambient	θ_{JA}	83.4	°C/W

3

FIGURE 1 — POWER DERATING





NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.

DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	10.80	11.04	0.425	0.435
B	7.50	7.74	0.295	0.305
C	2.42	2.66	0.095	0.105
D	0.51	0.66	0.020	0.026
F	2.93	3.17	0.115	0.125
G	2.29 BSC		0.090 BSC	
H	1.27	2.41	0.050	0.095
J	0.39	0.63	0.015	0.025
K	14.61	16.63	0.575	0.655
M	5° TYP		5° TYP	
Q	3.76	4.01	0.148	0.158
R	1.15	1.39	0.045	0.055
S	0.64	0.88	0.025	0.035
U	3.69	3.93	0.145	0.155
V	1.02	—	0.040	—

CASE 77-06
TO-225AA TYPE

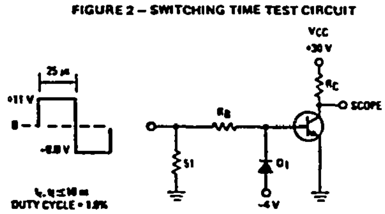
MJE170, MJ3171, MJE172, PNP, MJE180, MJE181, MJE182, NPN

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Max	Unit
OFF CHARACTERISTICS					
Collector-Emitter Sustaining Voltage		$V_{CEO(sus)}$			Vdc
(I_C = 10 mAdc, I_B = 0)	MJE170, MJE180		40	–	
	MJE171, MJE181		60	–	
	MJE172, MJE182		80	–	
Collector Cutoff Current		I_{CBO}			µAdc
(V_{CB} = 60 Vdc, I_E = 0)	MJE170, MJE180		–	0.1	
(V_{CB} = 80 Vdc, I_E = 0)	MJE171, MJE181		–	0.1	
(V_{CB} = 100 Vdc, I_E = 0)	MJE172, MJE182		-	0.1	
(V_{CB} = 60 Vdc, I_E = 0, T_C = 150°C)	MJE170, MJE180		–	0.1	mAdc
(V_{CB} = 80 Vdc, I_E = 0, T_C = 150°C)	MJE171, MJE181		–	0.1	
(V_{CB} = 100 Vdc, I_E = 0, T_C = 150°C)	MJE172, MJE182		–	0.1	
Emitter Cutoff Current (V_{BE} = 7.0 Vdc, I_C = 0)		I_{EBO}	–	0.1	µAdc
ON CHARACTERISTICS					
DC Current Gain		h_{FE}			–
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc)			50	250	
(I_C = 500 mAdc, V_{CE} = 1.0 Vdc)			30	–	
(I_C = 1.5 Adc, V_{CE} = 1.0 Vdc)			12	–	
Collector-Emitter Saturation Voltage		$V_{CE(sat)}$			Vdc
(I_C = 500 mAdc, I_B = 50 mAdc)			–	0.3	
(I_C = 1.5 Adc, I_B = 150 mAdc)			–	0.9	
(I_C = 3.0 Adc, I_B = 600 mAdc)			–	1.7	
Base-Emitter Saturation Voltage		$V_{BE(sat)}$			Vdc
(I_C = 1.5 Adc, I_B = 150 mAdc)			–	1.5	
(I_C = 3.0 Adc, I_B = 600 mAdc)			–	2.0	
Base-Emitter On Voltage (I_C = 500 mAdc, V_{CE} = 1.0 Vdc)		$V_{BE(on)}$	–	1.2	Vdc
DYNAMIC CHARACTERISTICS					
Current-Gain — Bandwidth Product (1) (I_C = 100 mAdc, V_{CE} = 10 Vdc, f_{test} = 10 MHz)		f_T	50	–	MHz
Output Capacitance		C_{ob}			pF
(V_{CB} = 10 Vdc, I_E = 0, f = 0.1 MHz)	MJE170/MJE172		–	60	
	MJE180/MJE182		–	40	

(1) $f_T = |h_{fe}| \cdot f_{test}$

FIGURE 2 – SWITCHING TIME TEST CIRCUIT

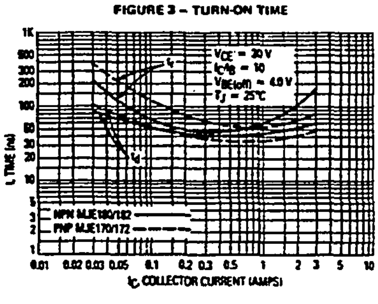


R_B and R_C VARIED TO OBTAIN DESIRED CURRENT LEVELS

D_1 MUST BE FAST RECOVERY TYPE, eg:
MBD5300 USED ABOVE I_B ≈ 100 mA
MSD6100 USED BELOW I_B ≈ 100 mA

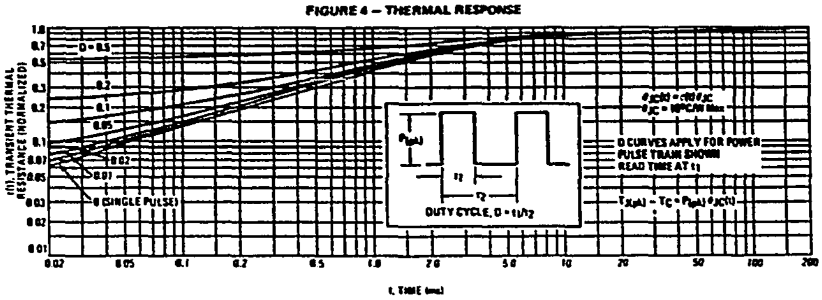
For PNP test circuit, reverse all polarities.

FIGURE 3 – TURN-ON TIME



MJE170, MJ3171, MJE172, PNP, MJE180, MJE181, MJE182, NPN

FIGURE 4 – THERMAL RESPONSE



ACTIVE-REGION SAFE OPERATING AREA

FIGURE 5 – MJE170, MJE171, MJE172

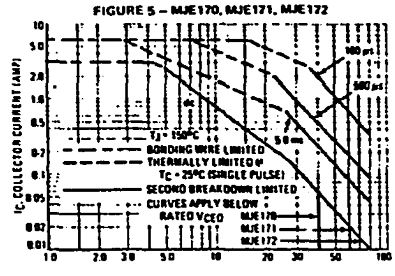
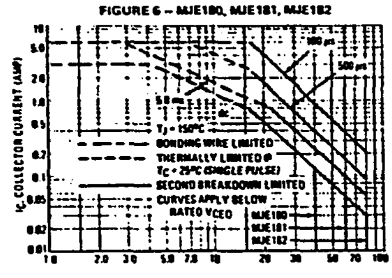


FIGURE 6 – MJE180, MJE181, MJE182



3

There are two limitations on the power handling ability of a transistor – average junction temperature and second breakdown. *Safe operating area curves indicate I_C – V_{CE} limits of the transistor* that must be observed for reliable operation; i.e., the transistor *must not be subjected to greater dissipation than the curves indicate.*

The data of Figures 5 and 6 is based on $T_{J(pk)} = 150^{\circ}C$; T_C is variable depending on conditions. Second breakdown pulse limits are valid for duty cycles to 10% provided $T_{J(pk)} \leq 150^{\circ}C$. *$T_{J(pk)}$ may be calculated from the data in Figure 4. At high case temperature*, thermal limitations will reduce the power that can be handled to values less than the limitations imposed by second breakdown.

FIGURE 7 – TURN-OFF TIME

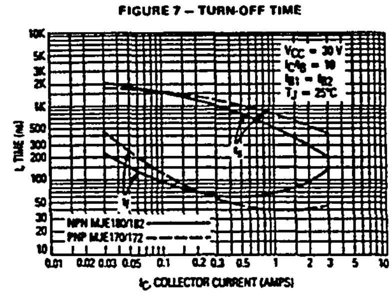
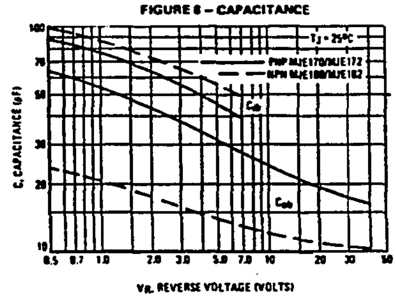


FIGURE 8 – CAPACITANCE

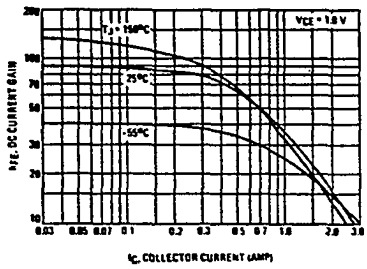


MJE170, MJ3171, MJE172, PNP, MJE180, MJE181, MJE182, NPN

PNP
MJE170, MJE171, MJE172

NPN
MJE180, MJE181, MJE182

FIGURE 9 – DC CURRENT GAIN



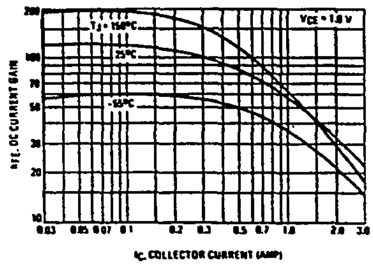
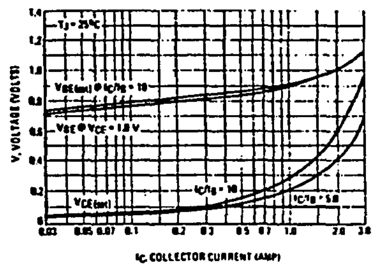


FIGURE 10 – "ON" VOLTAGES



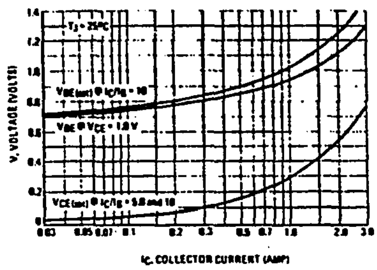
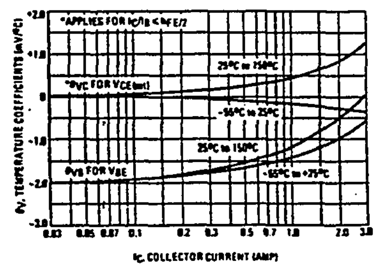
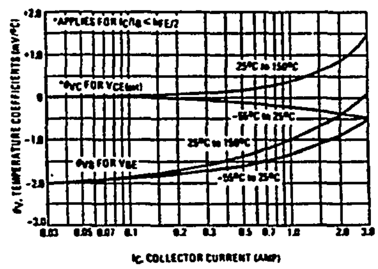


FIGURE 11 – TEMPERATURE COEFFICIENTS





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