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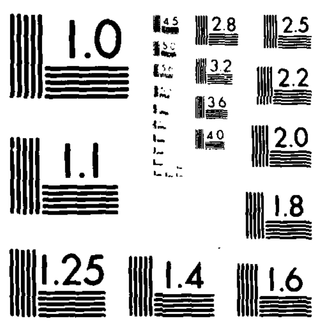

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November 1980

ELECTRONIC CIRCUITS AND OPTICAL SOURCES FOR FIBER OPTIC SYSTEMS

MITRE Corporation

G. L. Tenuta

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This document is one in a series of technical reports on the subject of fiber optic systems design. This report covers the electronic circuits and optical components needed to design high-performance laser and LED (light, emitting diode) transmitters for optical communications. Subsequent reports in this series will cover the design of low-noise, high-sensitivity preamplifiers, including related hardware such as AGC (automatic gain control) and FM receivers. Applications involving a

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bidirectional link and video transmitter and receiver are also described, as well as architectures and concepts for development of complete systems.

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SECTION 1

INTRODUCTION

Fiber optics is a relatively new but fast-growing technology that is based on the transmission of light through relatively low-cost, lightweight optical glass fibers. At the present time fiber optics technology has progressed to the point where extremely pure, high-quality glass fibers with optical bandwidths exceeding 1 GHz and having nominal attenuations of between 3 to 5 dB/km have been produced by several manufacturers. Optical sources and detectors needed for launching and detecting light, primarily at wavelengths between 0.8 to 0.9 μm, have also been developed. Presently, work is actively going on to develop components for operations around 1.3 and 1.5 μm where the dispersion and optical attenuation of fibers approach theoretical limits. Such components will enable development of future optical systems that will provide operation between fixed plant development systems now at 50 km. Because these systems will operate at optical frequencies, the potential for extremely high bandwidth systems, considerably higher than microwave, will be possible for optical communications.

Concern now in tactical (mobile) situations centers on power limitations imposed by connector technology and the darkening effect resulting from nuclear radiation. To cope with these problems as much power as possible should be coupled to the fiber--particularly the small 50-micron core communication fibers. Because of the wide variety of environmental extremes (temperature), currently available fibers with periodic connectors limit the deployment range to about 4 or 5 km at 850 nm.

With the increasing interest in fiber optics, many system designers are asking basic questions concerning how one goes about designing a fiber optic system. The design, to those who have already looked into the subject, is clearly different from that of a microwave or conventional communications system. This document attempts to answer those questions by focusing on fundamental concepts essential to the design of a fiber optic system. The present document places primary emphasis on the design of fiber optics transmitters, both lasers and LED's (light emitting diodes). Other documents in this series will cover remaining subjects that range from designing a receiver preamplifier to designing a long-haul, point-to-point fiber optic system. A description of the components, how they are used, and how to select the right one for a particular application will also be discussed, as well as specific case studies and applications essential to a firm understanding of the material.

SECTION 2

FIBER OPTICS TRANSMITTER DESIGN

A high-performance fiber optic transmitter can be implemented with either a semiconductor injection laser or LED. A laser provides considerably more output power along with better coupling efficiency between the source and fiber, but is significantly more temperature sensitive than an LED. As a result, a well-designed laser transmitter should include some form of optical feedback or thermoelectric cooling or both to achieve adequate temperature stability and output power control.

Thermoelectric cooling can also significantly extend the lifetime of a laser by removing excess heat that develops at the laser's junction, the primary failure mechanism. LED's, on the other hand, while not as spectrally pure (i.e., spectral bandwidths are considerably broader, typically 40 nm versus the approximately 3 nm for a laser) are considerably less temperature sensitive and less expensive. Coupling efficiency between source and fiber is also poorer, typically 13 dB for a standard LED. However, new lensing techniques combined with integral fiber pigtails, attached directly to the LED's emitting surface, can appreciably reduce excess coupling loss to within acceptable limits. When coupling to small core fibers is of primary concern, particularly for high-bandwidth systems operating above 20 Mb/s, an edge-emitting LED can offer greater coupling efficiency and increased bandwidth over standard surface emitters.

Unless higher output power or speed is needed for a particular application, an LED should always be given first preference over a laser, particularly for short links. For military tactical systems, however, the requirements are somewhat more demanding. Link length, for example, may not be known beforehand. In such cases, it may be better to have a higher power budget than that dictated by a careful link analysis. For instance, additional margin should be allowed for field splices, dirty connectors, and the relatively unknown quantitative effects of nuclear radiation. Furthermore, the concept of photobleaching to recover irradiated fibers shows considerable promise and thus dictates that the highest power sources available be used.

2.1 DESIGN FUNDAMENTALS

A few simple design procedures should be kept in mind when designing with a laser or LED. First and foremost is that a laser or LED is essentially current dependent and, therefore, should be driven, modulated, by a current varying device, such as a transistor. A voltage driver which varies the voltage across a laser or LED is not considered suitable and will result in suboptimal or degraded performance.

A second point to keep in mind is that a laser is extremely susceptible to damage that results from circuit noise or power line transients. A good design practice is to keep a minimum of 10 ohms resistance in the laser's biasing circuit, as this will limit the magnitude of currents that can flow through the laser.

A final point to remember, particular for lasers, is the possibility of thermal burnout or current runaway conditions that result from a failed component, particularly in the optical feedback circuitry. A similar condition to guard against is current surges developed during startup or after powering down. More lasers are distroyed in this way than through any other means including normal failure.

The best protection against the occurrence of any of these problems is simply knowledge and taking the few necessary preventive steps to ensure that they do not occur, generally by adding some form of current and/or voltage limiting device.

Unfortunately, the addition of extra electronic devices inevitably leads to reduced performance, greater complexity, and increased cost. However, through careful design such devices can easily be accommodated with only slight penalty, providing that they are incorporated earlier during the design process and not afterwards when the design is finalized.

2.2 LASER TRANSMITTER DESIGN

A fiber optics transmitter, optimized for digital operation, is shown in figure 2-1. The circuit shown has been breadboarded and tested and found to be capable of operating at speeds of 200 Mb/s (plus) without detectable overshoot or undershoot and with faithful reproduction of pulse rise times to 400 Mb/s. The circuit was also found to be suitable for analog application, but the frequency range of linear operation was limited to about 100 MHz.

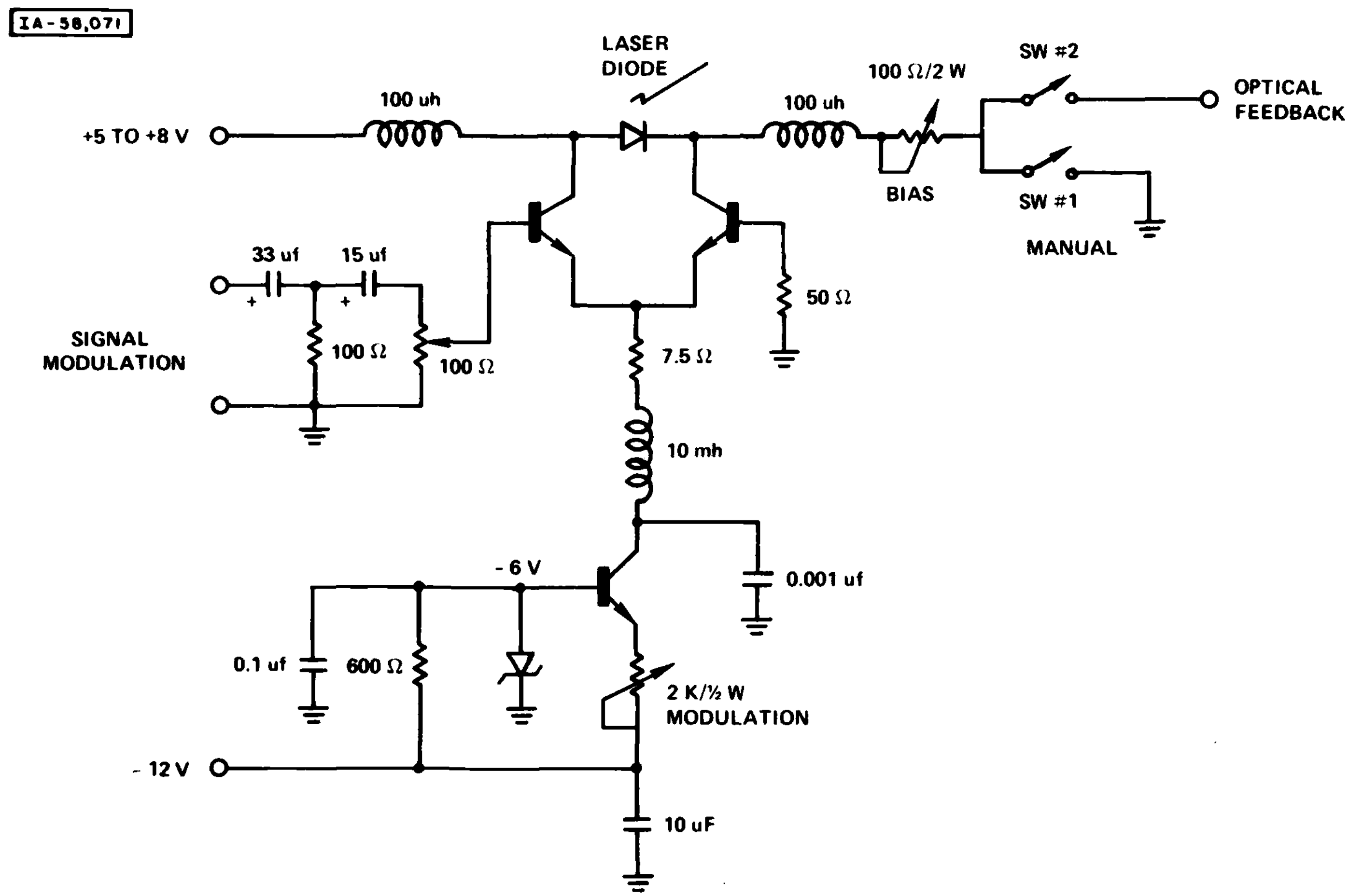

Figure 2-1 High-Speed Laser Transmitter Design

As seen from the circuit diagram, the laser is RF coupled to the collectors of a differential pair, a popular structure, particularly for high-speed digital applications. Biasing of the laser is provided via a standard potentiometer, located in a path separate from the modulation electronics. The latter was done to minimize the loading on the laser driver, thus enhancing the speed and linearity capability of the circuit.

The laser is biased in accordance with the modulation required, below threshold for digital and midway within the laser's linear region for analog operation. The alignment process is facilitated by switch #1, which is also used for manual operation. Switch #2 is used for optical feedback (discussed in the next subparagraph).

The modulation index is set by a standard current source which simultaneously serves as the biasing circuit for the differential pair. Normally, the current source is adjusted to provide 50 to 100 percent modulation of the laser. Since the quantum efficiency of a laser is relatively high, only a small amount of current is required, typically 5 to 20 mA in comparison to the tens to hundreds of milliamperes required to bias the laser.

A two-stage, 40-dB/decade, high-pass filter is used as the input stage to the transmitter. The primary purpose of the filter is to help remove the d.c. and low-frequency signal components from the modulation signal components, thereby preventing these signals from appearing at the optical output of the laser. Removal of these signals is extremely important for proper optical feedback operation since the photodetector is d.c.-coupled and responds to the average d.c. value of the laser bias current, e.g., output power.

An alternate transmitter design, praticularly suited for analog system applications, is shown in figure 2-2. This particular circuit design employs a high power, high-speed VMOS (vertical metal oxide semiconductor) transistor to provide extremely linear operation into the HF and VHF bands.

The design differs from the preceding digital design in that a single transistor is used for both modulation and optical feedback control. Another key difference is that voltage instead of current feedback is employed to control the laser's output power. Although considerably more electrical power is used over the previous design, approximately 7 to 10 W, fewer components are needed to develop the circuit.

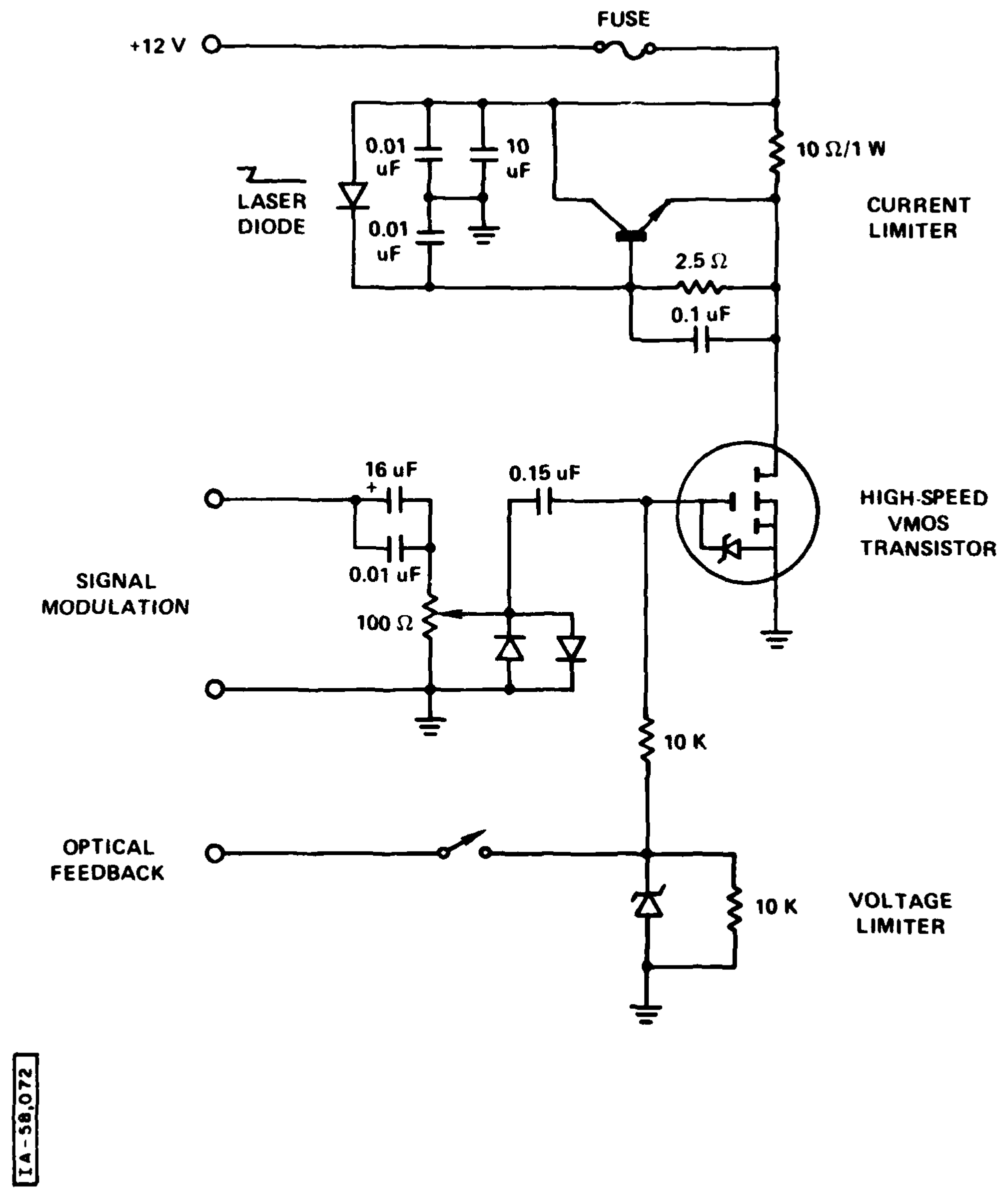

Figure 2-2. Laser Transmitter Design for Analog System Applications

2.2.1 Optical Feedback

Optical feedback is a technique employed to stabilize the output power of a laser over time and temperature. A block diagram illustrating how this is accomplished is shown in figure 2-3. A detailed circuit schematic of an optical feedback control circuit used in conjunction with the laser transmitter described in the preceding paragraph is shown in figure 2-4. Measurements have indicated that the circuit shown was capable of correcting as much as 100 mA of laser power output variation with less than 1 percent error. However, very seldom is this amount and degree of control needed for a practical system application.

Before contemplating the design of a similar circuit, the designer must first determine how to establish the optical linkage with the laser. Several techniques are available, the simplest and easiest involves purchasing a laser assembly with an integrated detector. An alternative is to couple an additional fiber to the laser pellet. For maximum light collection, the fiber should be positioned either directly above or below the plane parallel to the laser's junction. The remaining technique, and the one considered herein, involves the use of a directional coupler. The latter is acceptable if a coupler is required for the application; otherwise, either of the two approaches discussed previously should be considered.

Optical feedback, as illustrated in figure 2-3 or 2-4, is implemented by sensing the output power of the laser, coupling the power through a low-pass filter used to detect the average output power of the laser (e.g., bias), and comparing this power against a temperature stabilized reference to arrive at an error signal. The error signal, which is proportional to the difference between the laser's output power and reference (e.g., the desired power output), is then highly amplified and applied to a driver circuit used to offset the laser bias in such a direction as to reduce the error signal. In general, the higher the feedback gain, the smaller the error signal; hence, the better the actual output power of the laser will correlate with the desired output (e.g., reference). However, care must be exercised that the gain is not increased beyond a point where the system becomes unstable.

In the present design, the system is conditionally stable for all values of gain, providing that the laser's power/current characteristics, including optical linkages, remain linear. The latter is extremely important when considering the use of a coupler, which, if not designed properly, exhibits a nonlinear power versus current relationship that can degrade the performance of the laser optical feedback control circuit.

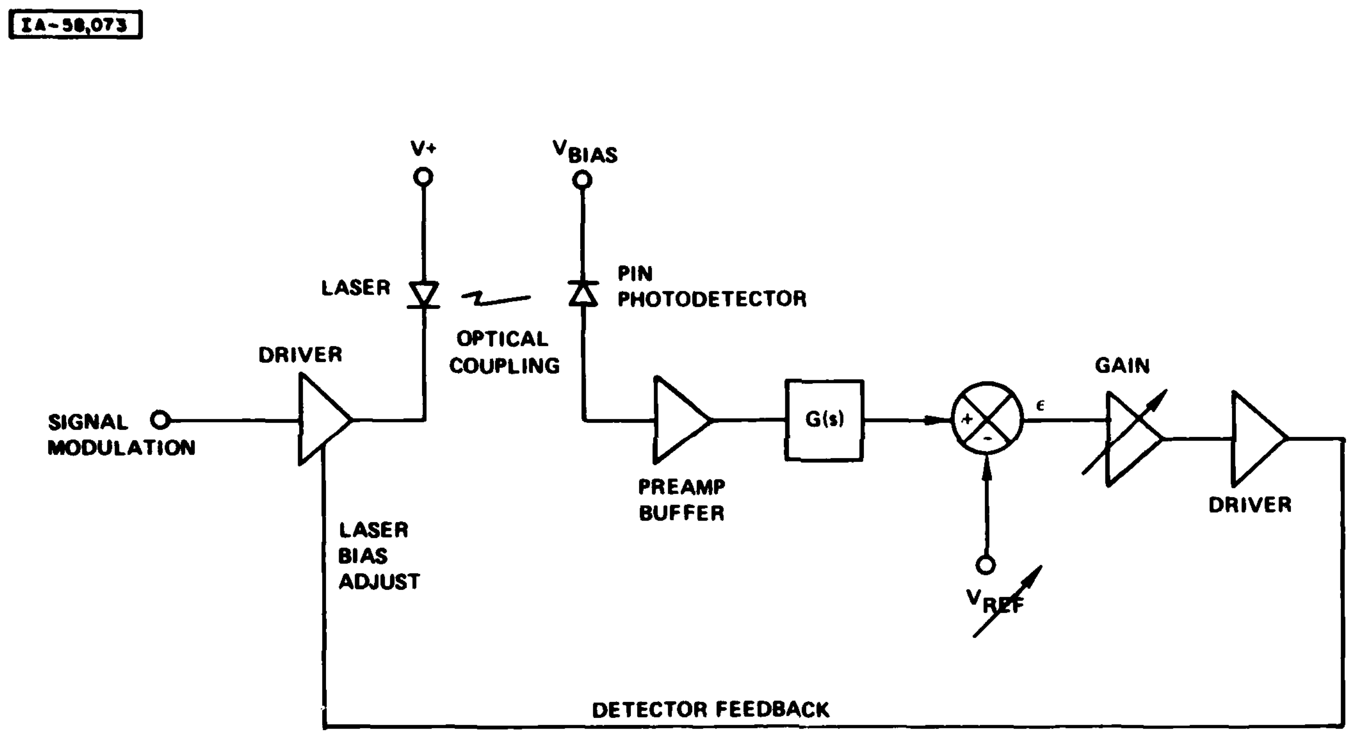

Figure 2-3. Block Diagram of Optical Feedback Circuit

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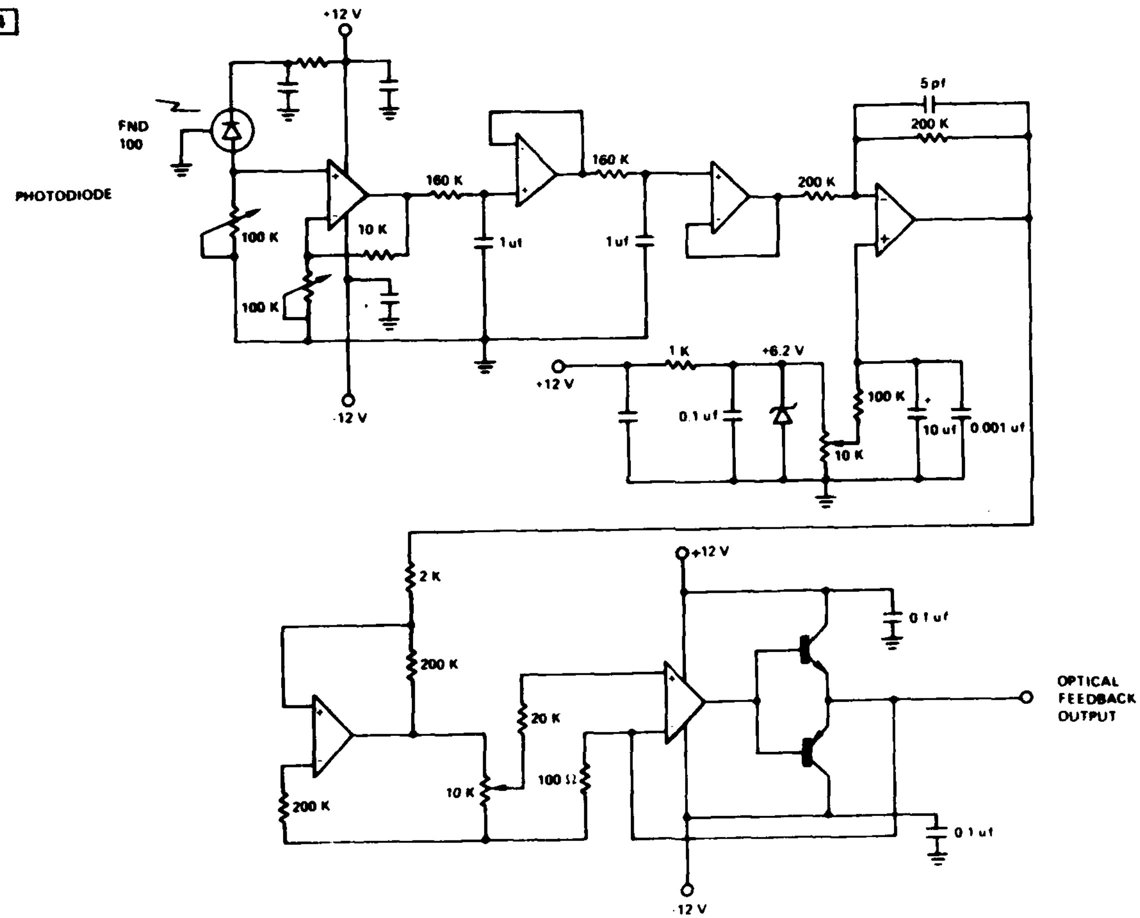

Figure 2-4. Detailed Schematic of Optical Feedback Circuit

Stability, however, can always be achieved by ensuring that the poles of the open loop transfer function are real and no greater than two. This assumes no zeros in the transfer function. The root locus (e.g., stability diagram) therefore is constrained to the left-hand plane. The design used is acceptable for analog systems but unacceptable for digital applications. The problem here is that changes in duty-cycle or data rate (all ones or zeros, for example) will cause an erroneous error signal. A way around this problem is to combine the data with an inverted copy of the data at the output of the photodetector. Although other techniques are available, the one described is considered superior in that it can handle the limiting all ones and zeros case with equal efficiency and accuracy. Other popular techniques rely on peak detection or data coding to remove the d.c. from the data signal. The latter, however, is somewhat complex unless the feature is already required for other purposes, in which case it is more than acceptable.

2.2.2 Thermoelectric Cooling

Thermoelectric cooling provides a means of maintaining a laser at a specified temperature under varying environmental and ambient conditions. The laser itself, when operating at a particular output power, is a source of heat as are the physical fixtures and surrounding atmosphere in contact with it. To remove this heat and therefore keep the laser's temperature constant, some form of temperature-regulating device is required. Ideally, the device should be small in size, require a minimum of power, and be relatively inexpensive. A device that comes close to meeting these requirements is a thermoelectric heat pump, a semiconductor device formed with two dissimilar junction materials.

To select a thermoelectric cooler, the designer must estimate the thermal load or total heat load presented to the thermoelectric cooler. The heat load consists of the thermal load dissipated by the device, the radiation load, conduction load, and convention load. He usually begins with the device to be cooled, along with any supporting fixtures, the operating temperature over which the device is to be operated, the ambient temperature, and device dissipation. From this information and the data supplied by the manufacturer, a heat pump possessing the required characteristics can be selected for a specific application. The designer should remember, however, not to over or under design as this will result in a design that either consumes excess power or fails to meet design objectives.

A block diagram of a thermoelectric heat pump circuit is illustrated in figure 2-5. The circuit shown is a conventional control circuit, consisting of summing node, error signal, and feedback control electronics, similar to that described earlier for the optical feedback circuit.

The thermoelectric cooler is wedged between a laser supporting fixture and a heat sink. The heat sink is used to remove excess heat from the hot side of the thermoelectric cooler and to provide a conduction path for thermal currents. The temperature of the laser is sensed by a solid state temperature sensor attached to the laser support. A minimum mass support was selected to provide fast transient response and to minimize the thermal capacity or heat load presented to the heat pump. However, a larger support would provide more uniform temperature regulation at the expense of higher heat pump capacity, including cost and powering requirements for the drive electronics. Ideally, a minimum mass system would consist of a laser pellet mounted directly on the cold surface of the cooler. Alternately, many manufacturers, including Laser Diode Labs, Exxon, and General Optics, provide a standard module, consisting of single mode or multimode laser (optional), heat pump, temperature sensor, optical feedback detector, and fiber pigtail (or connector), all of which are integrated into a 14-pin dual in-line package. The latter is recommended for users interested in reliability, maintainability, size, and powering requirements.

In operation, the temperature of the laser, sensed by the temperature sensor, is compared against a precision reference by a comparator circuit. The precision reference is temperature compensated and provides a stable reference which can be adjusted, via a potentiometer, to any value (e.g., temperature) desired by user (e.g., within the thermal range of the cooler). The reference also serves as the bias supply for the temperature sensor.

The error signal, consisting of the difference between the temperature of the laser and reference, is then highly amplified and applied to a voltage to current converter. The voltage to current converter, a high power current amplifier implemented with discrete transistors in the feedback of a conventional operational amplifier, provides the proper drive for the thermoelectric cooler. The high gain of the operational amplifier ensures good linearity in the voltage to current conversion process, as well as compensating for temperature derating and loss in current gain (beta) of the transistors at high output current levels, a critical requirement when operating at large temperature differentials.

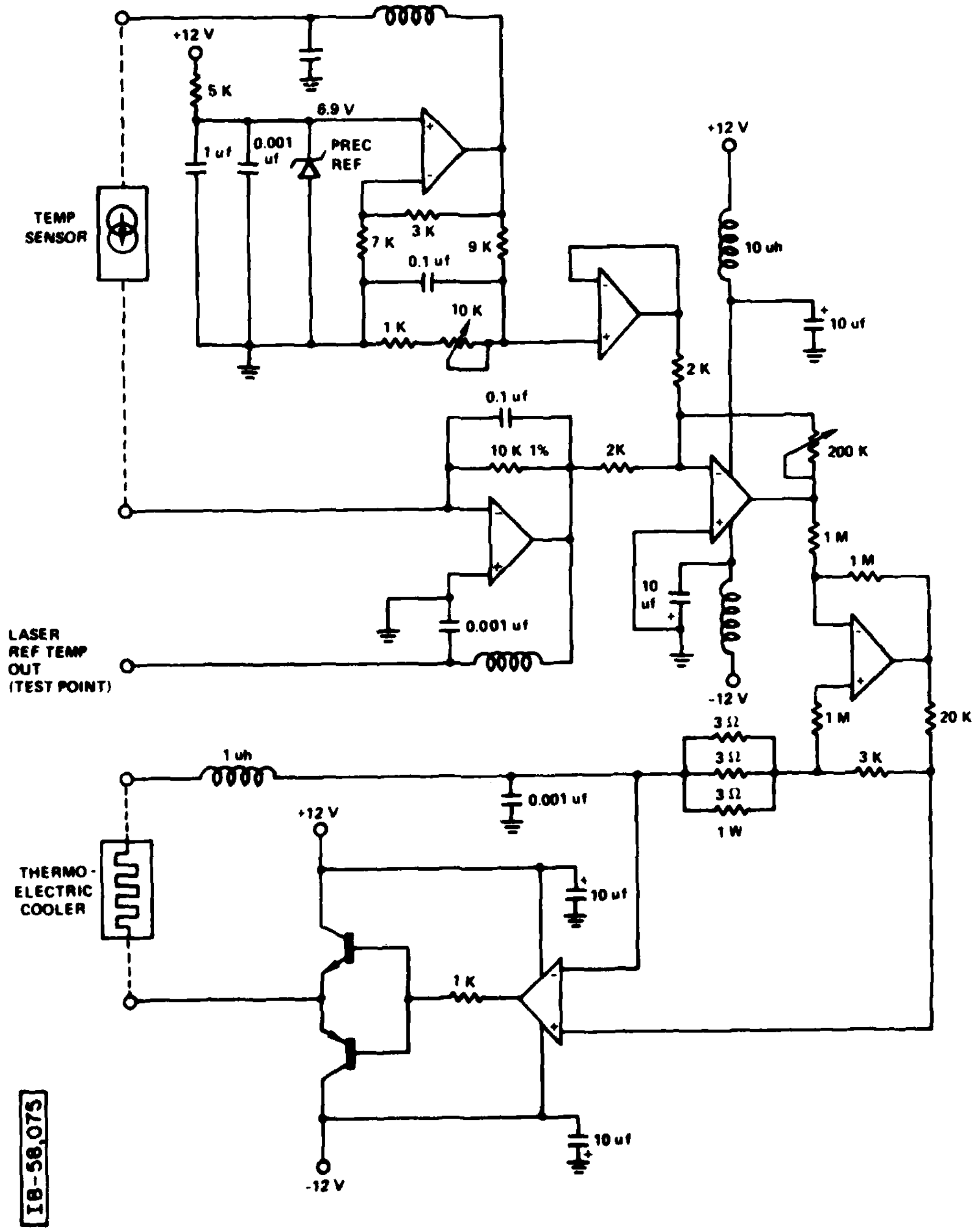

Figure 2-5. Thermoelectric Heat Pump Control Circuit

The output of the voltage to current converter is such as to reduce the error between the reference and absolute temperature of the laser. Little, if any, integration is used in the feedback path since sufficient integration is provided by the laser mass and mass of the supporting fixtures. The thermal response of the laser and support fixtures is typically around a minute for the present design.

2.3 LED TRANSMITTER DESIGN

The design of an LED transmitter is considerably less complex, involved, and costly than a laser design. A prototype LED transmitter measuring 1 inch by 2 inches and optimized for analog applications, is shown in figure 2-6. The circuit shown features a bandwidth of 240 MHz (at the 3-dB points), single supply operation (e.g., +12 V), adjustable bias control, and standard 50-ohm termination.

The design is essentially straightforward, relying on direct current modulation of the LED with a high power transistor driver. The LED is inductively coupled to the transistor with the main bias current, typically 100 mA, flowing through a 300-ohm resistor and the collector of the transistor. The amount of bias current flowing through the transistor is adjustable and should be set to achieve 50 to 100 percent modulation of the LED. Because of the relative insensitivity of an LED to changes in temperature, no temperature compensation, optical feedback, or thermoelectric cooling is required to achieve stabilized operation. In fact, LED's with integrated lenses for efficient coupling to communication fibers (50-micron core) and that cover the full military temperature range are available from various manufacturers. The present LED is a Spectronics SE 3352 surface emitter with integrated sphere (so-called "sweet pot"). The LED referenced projects a uniform 300-μm spot on the surface of the lens (e.g., cap), thus enabling efficient coupling to optical fibers without the use of fiber pigtails. For long repeaterless links, the transmitter may be easily upgraded for long wavelength operation where the dispersion and attenuation of optical fiber is at a minimum (e.g., approximately 1 ns/km and 0.5 dB/km respectively). Several manufacturers, RCA, Plessey, and others, are currently supplying LED's for operation at these wavelengths (e.g., 1.3 to 1.5 μm). The availability of compatible photodetectors, however, is presently in short supply. Recent experimental work reported by MIT Lincoln Laboratories indicates that long wavelength APD (avalanche photodiode) detectors implemented with GaInAsP/InP compound and exhibiting excellent low

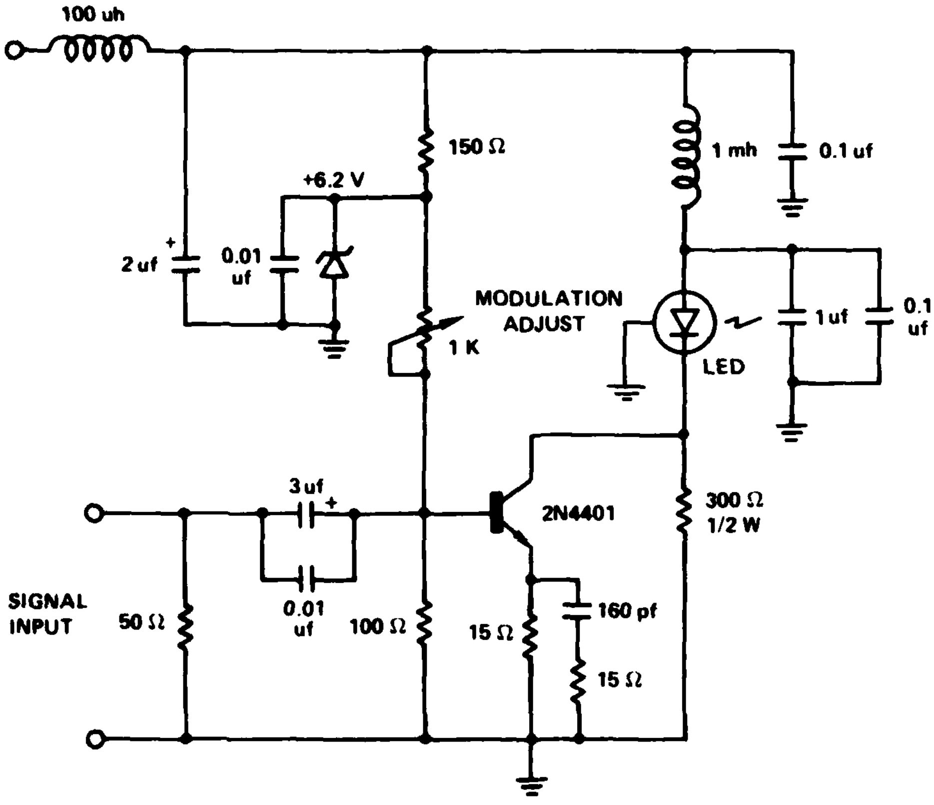

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Figure 2-6. Low-Cost, High-Speed LED Analog Transmitter noise properties will be available in the near term for development of high data rate/long-haul optical communications systems that operate within the 1.1 to 1.6 micron region.

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