Unit- V

OPTICAL FIBER COMMUNICATION

Introduction:

Conceptually, an optical fiber communication system is similar to any other type of communication system. A block diagram of a general communication system is shown in Fig.1, its function is to convey the signal from the information source over the transmission medium to the destination.

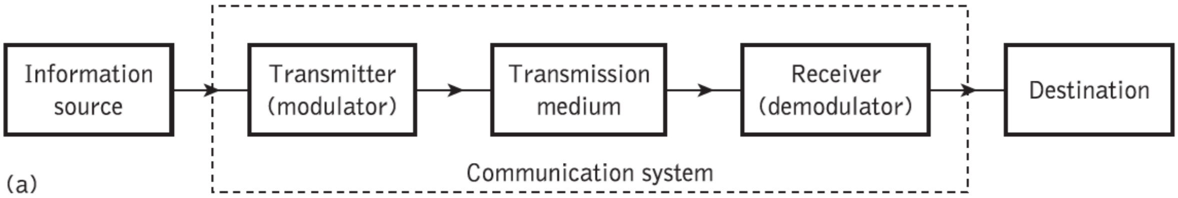


Fig.1 The general communication system.

The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a high frequency carrier, which may be an electromagnetic wave. The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination. However, in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself. Therefore, in any communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication.

For long haul applications, these factors necessitate the installation of repeaters or line amplifiers at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

Components of Optical Fiber Communication System:

The functional block diagram of an optical fiber communication system is shown in Fig.2 below.

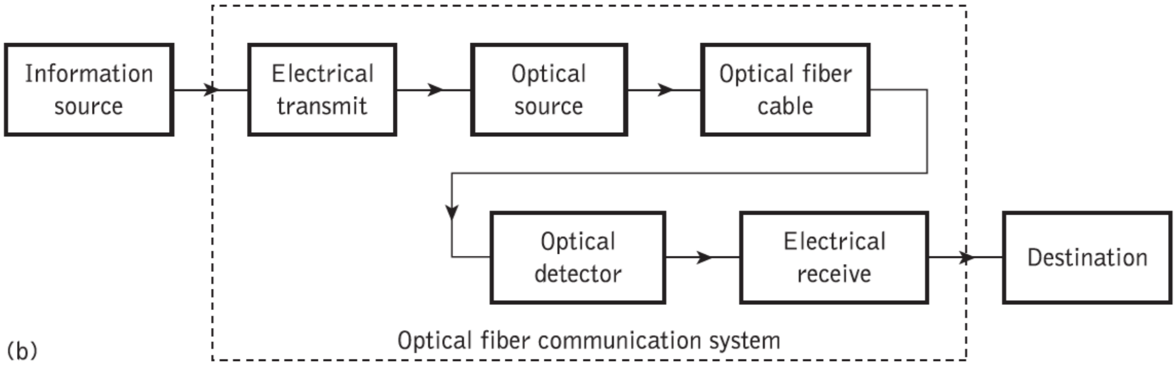


Fig.2 The optical fiber communication system.

In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (p–n, p–i–n or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Fig.2 analog modulation involves the variation of the light emitted from the optical source in a continuous manner.

With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal-to-noise ratio at the receiver than digital modulation. Also, the linearity needed for analog modulation is not always provided by semiconductor optical sources, especially at high modulation frequencies. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidth operation than digital links.

The block diagram of a typical digital optical fiber link is shown in Fig.3. Initially, the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

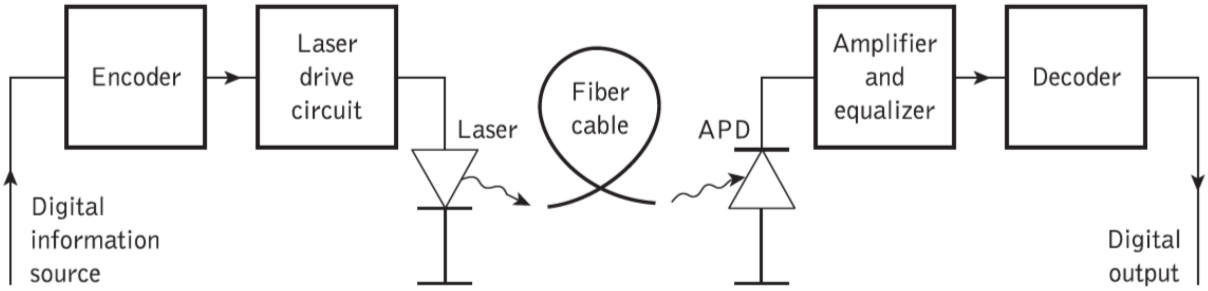


Fig.3 A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector.

Advantages of Optical Fiber Communication:

Communication using an optical carrier wave guided along a glass fiber has a number of extremely attractive features, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions, creating additional advantages. Hence it is useful to consider the merits and special features offered by optical fiber communications over more conventional electrical communications. In this context we commence with the originally foreseen advantages and then consider additional features which have become apparent as the technology has been developed.

(a) Enormous potential bandwidth; The optical carrier frequency in the range 1013 to 1016 Hz (generally in the near infrared around 1014 Hz or 105 GHz) yields a far greater potential transmission bandwidth than metallic cable systems (i.e. coaxial cable bandwidth typically around 20 MHz over distances up to a maximum of 10 km) or even millimeter wave radio systems (i.e. systems currently operating with modulation bandwidths of 700 MHz over a few hundreds of meters). Indeed, by the year 2000 the typical bandwidth multiplied by length product for an optical fiber link incorporating fiber amplifiers was 5000 GHz km in comparison with the typical bandwidth–length product for coaxial cable of around 100 MHz km. Hence at this time optical fiber was already demonstrating a factor of 50 000 bandwidth improvement over coaxial cable while also providing this superior information-carrying capacity over much longer transmission distances.

Although the usable fiber bandwidth will be extended further towards the optical carrier frequency, it is clear that this parameter is limited by the use of a single optical carrier signal. Hence a much enhance bandwidth utilization for an optical fiber can be achieved by transmitting several optical signals, each at different center wavelengths, in parallel on the same fiber. This wavelength division multiplexed operation, particularly with dense packing of the optical wavelengths (or, essentially, fine frequency spacing), offers the potential for a fiber information-carrying capacity that is many orders of magnitude in excess of that obtained using copper cables or a wideband radio system.

(b) Small size and weight; Optical fibers have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibers are covered with protective layers they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

(c) Electrical isolation; Optical fibers which are fabricated from glass, or sometimes a plastic polymer, are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fibers create no arcing or spark hazard at abrasions or short circuits.

(d) Immunity to interference and crosstalk; Optical fibers form a dielectric waveguide and are therefore free from electromagnetic interference (EMI), radio-frequency interference (RFI), or switching transients giving electromagnetic pulses (EMPs). Hence the operation of an optical fiber communication system is unaffected by transmission through an electrically noisy environment and the fiber cable requires no shielding from EMI. The fiber cable is also not susceptible to lightning strikes if used overhead rather than underground. Moreover, it is fairly easy to ensure that there is no optical interference between fibers and hence, unlike communication using electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

(e) Signal security; The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fiber in a noninvasive manner (i.e. without drawing optical power from the fiber). Therefore, in theory, any attempt to acquire a message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission (i.e. computer network) applications.

(f) Low transmission loss; The development of optical fibers over the last 20 years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fibers have been fabricated with losses as low as 0.20 dB/km and this feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide optical repeater or amplifier spacings, thus reducing both system cost and complexity. Together with the already proven modulation bandwidth capability of fiber cables, this property has provided a totally compelling case for the adoption of optical fiber communications in the majority of long-haul telecommunication applications, replacing not only copper cables, but also satellite communications, as a consequence of the very noticeable delay incurred for voice transmission when using this latter approach.

(g) Ruggedness and flexibility; Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths Perhaps surprisingly for a glassy substance, the fibers may also be bent to quite small radii or twisted without damage. Furthermore, cable structures have been developed which have proved flexible, compact and extremely rugged. Taking the size and weight advantage into account, these optical fiber cables are generally superior in terms of storage, transportation, handling and installation to corresponding copper cables, while exhibiting at least comparable strength and durability.

(h) System reliability and ease of maintenance; These features primarily stem from the low-loss property of optical fiber cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Hence with fewer optical repeaters or amplifiers, system reliability is generally enhanced in comparison with conventional electrical conductor systems. Furthermore, the reliability of the optical components is no longer a problem with predicted lifetimes of 20 to 30 years being quite common. Both these factors also tend to reduce maintenance time and costs.

(i) Potential low cost; The glass which generally provides the optical fiber transmission medium is made from sand – not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low-cost line communication. Although over recent years this potential has largely been realized in the costs of the optical fiber transmission medium which for bulk purchases has become competitive with copper wires (i.e. twisted pairs), it has not yet been achieved in all the other component areas associated with optical fiber communications. For example, the costs of high-performance semiconductor lasers and detector photodiodes are still relatively high, as well as some of those concerned with the connection technology (demountable connectors, couplers, etc.).

Overall system costs when utilizing optical fiber communication on long-haul links, however, are substantially less than those for equivalent electrical line systems because of the low-loss and wideband properties of the optical transmission medium.

Optical Transmitters & Receivers

The principal components of a general optical fiber communication system for either digital or analog transmission are shown in the system block schematic of Fig.4;

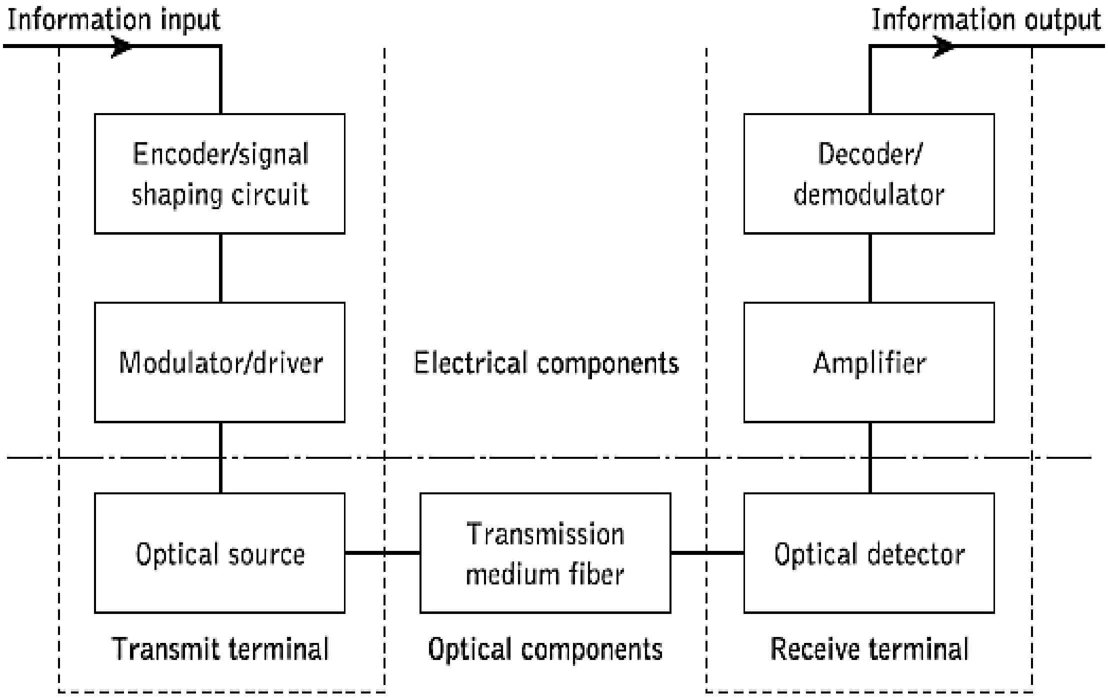


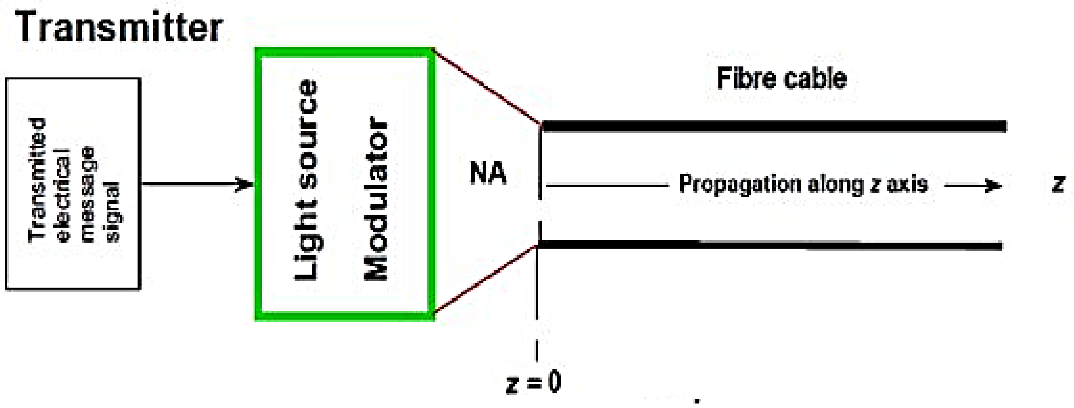
Fig.4 The principal components of an optical fiber communication system.

The optical fiber communication system mainly includes a transmitter and receiver where the transmitter is located on one ending of a fiber cable and a receiver is located on the other side of the cable. Most of the systems utilize a transceiver which means a module which includes transmitter and receiver. The transmitter terminal equipment consists of an information encoder or signal shaping circuit preceding a modulation or electronic driver stage which operates the optical source. Light emitted from the source is launched into an optical fiber incorporated within a cable which constitutes the transmission medium. The light emerging from the far end of the transmission medium is converted back into an electrical signal by an optical detector positioned at the input of the receiver terminal equipment. This electrical signal is then amplified prior to decoding or demodulation in order to obtain the information originally transmitted.

The optical transmitter circuit:

Optical transmitter is a device that generates the signal sent through optical fibers. it consists of optical sources and devices modulating optical radiation in accordance with an electric input signal. Depending on the modulation method used, optical transmitters are classified into direct (internal) and external modulation transmitters. In optical transmitters with direct modulation, the radiant power of the light source is modulated by the feed current. The main advantage of such modulators is their simple design. Their disadvantages include limited response time (rate of data transmission in digital communication systems) and the use of only one parameter (power) of the light wave for modulation purposes. Light sources in direct modulation transmitters are represented by LEDs or direct modulation lasers.

In optical transmitters with external modulation, continuous optical radiation is modulated by an external modulator controlled by an electric data signal. In such transmitters, light sources are usually narrow-band single-mode continuous-wave semiconductor lasers, such as distributed feedback lasers or distributed Bragg reflector lasers.



Typical Optical Transmitter System

Types of optical transmitter circuits:

There are two main types of optical transmitter circuits that are in use today. Both of them are based around semiconductor technology as follows:

- **LED drive circuits, and**
- **Laser drive circuits**

LED drive circuits:

Although the LED is somewhat restricted in its range of possible applications in comparison with the more powerful, higher speed injection laser, it is generally far easier to operate. Therefore, we consider some of the circuit configurations that may be used to convert the information voltage signal at the transmitter into a modulation current suitable for an LED source. In this context it is useful to discuss circuits for digital and analog transmission independently.

Digital transmission; The operation of the LED for binary digital transmission requires the switching on and off of a current in the range of several tens to several hundreds of milli amperes. This must be performed at high speed in response to logic voltage levels at the driving circuit input. A common method of achieving this current switching operation for an LED is shown in Fig.5.

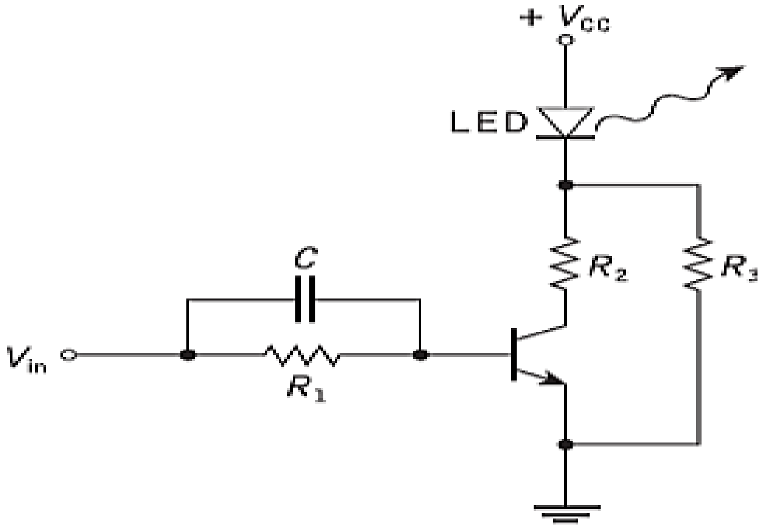


Fig.5 A simple drive circuit for binary digital transmission consisting of a common emitter saturating switch.

The circuit illustrated uses a bipolar transistor switch operated in the common emitter mode. This single-stage circuit provides current gain as well as giving only a small voltage drop across the switch when the transmitter is in saturation (i.e. when the collector–base junction is forward biased, the emitter to collector voltage VCE (sat) is around 0.3V).

The maximum current flow through the LED is limited by the resistor R2 while independent bias to the device may be provided by the incorporation of resistor R3. However, the switching speed of the common emitter configuration is limited by space charge and diffusion capacitance; thus bandwidth is traded for current gain. This may, to a certain extent, be compensated by overdriving (pre-emphasizing) the base current during the switch-on period. In the circuit shown in Figure 12.3 pre-emphasis is accomplished by use of the speed-up capacitor C.

Increased switching speed may be obtained from an LED without a pulse shaping or speed-up element by use of a low-impedance driving circuit, whereby charging of the space charge and diffusion capacitance occurs as rapidly as possible. This may be achieved with the emitter follower drive circuit shown in Fig.6.

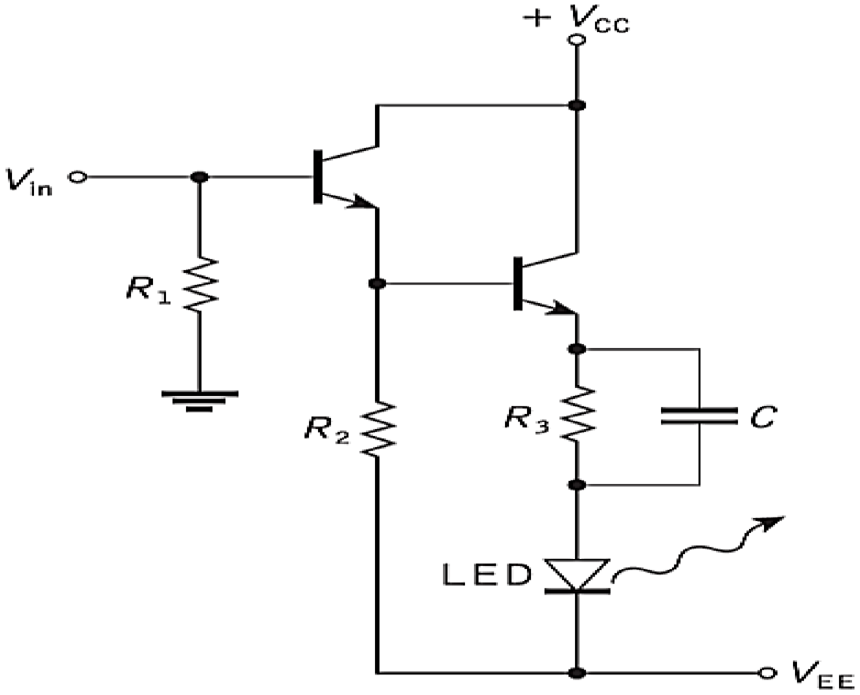


Fig.6 Low-impedance drive circuit consisting of an emitter follower with compensating matching network.

The use of this configuration with a compensating matching network (R3C) provides fast direct modulation of LEDs with relatively low drive power. A circuit, with optimum values for the matching network, is capable of giving optical rise times of 2.5 ns for LEDs with capacitance of 180 pF, thus allowing 100 Mbit/s operation.

Analog transmission; For analog transmission the drive circuit must cause the light output from an LED source to follow accurately a time-varying input voltage waveform in both amplitude and phase. Therefore, as indicated previously, it is important that the LED output power responds linearly to the input voltage or current. Unfortunately, this is not always the case because of inherent nonlinearities within LEDs which create distortion products on the signal. Thus, the LED itself tends to limit the performance of analog transmission systems unless suitable compensation is incorporated into the drive circuit. However, unless extremely low distortion levels are required, simple transistor drive circuits may be utilized.

Two possible high-speed drive circuit configurations are illustrated in Fig.7. Fig.7(a) shows a driver consisting of a common emitter transconductance amplifier which converts an input base voltage into a collector current. The circuit is biased for a class A mode of operation with the quiescent collector current about half the peak value. A similar transconductance configuration which utilizes a Darlington transistor pair in order to reduce the impedance of the source is shown in Fig.7(b). A circuit of this type has been used to drive high-radiance LEDs at frequencies of 70 MHz.

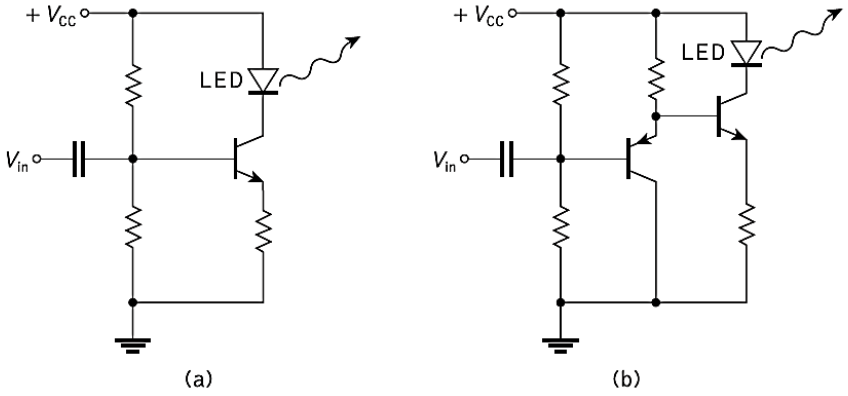


Fig.7 Transconductance drive circuits for analog transmission: (a) common emitter configuration; (b) Darlington transistor pair.

Another simple drive circuit configuration is shown in Fig.8. It consists of a differential amplifier operated over its linear region which directly modulates the LED. The LED operating point is controlled by a reference voltage V_{ref} while the current generator provided by the transistor T3 feeding the differential stage (T1 and T2) limits the maximum current through the device. The transimpedance of the driver is reduced through current series feedback provided by the two resistors R1 and R2 which are normally assigned equal values. Furthermore, variation between these feedback resistors can be used to compensate for the transfer function of both the drive circuit and the LED.

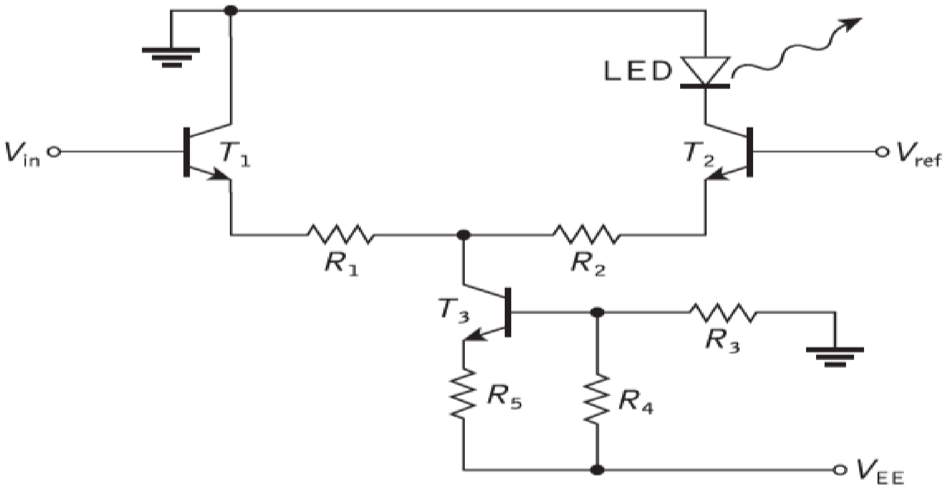


Fig.8 A differential amplifier LED drive circuit.

Laser driven circuits:

A number of configurations described for use as LED drive circuits for both digital and analog transmission may be adapted for injection laser applications with only minor changes. The laser, being a threshold device, has somewhat different drive current requirements from the LED. For instance, when digital transmission is considered, the laser is usually given a substantial applied bias, often referred to as pre-bias, in the off state. Reasons for biasing the laser near but below threshold in the off state are as follows:

- It reduces the switch-on delay and minimizes any relaxation oscillations.
- It allows easy compensation for changes in ambient temperature and device aging.
- It reduces the junction heating caused by the digital drive current since the on and off currents are not widely different for most lasers.

Although biasing near threshold causes spontaneous emission of light in the off state, this is not normally a problem for digital transmission because the stimulated emission in the on state is generally greater by, at least, a factor of 10.

A simple laser drive circuit for digital transmission is shown in Fig.9. This circuit is a shunt driver utilizing a field effect transistor (FET) to provide high-speed laser operation. Sufficient voltage is maintained in series with the laser using the resistor R_2 and the compensating capacitor C such that the FET is biased into its active or pinch-off region. Hence for a particular input voltage V_{in} (i.e. V_{GS}) a specific amount of the total current flowing through R_1 is diverted around the laser leaving the balance of the current to flow through R_2 and provide the off state for the device. Using stable gallium arsenide MESFETs the circuit shown in Fig.9 has modulated lasers at rates in excess of 1 Gbit/s.

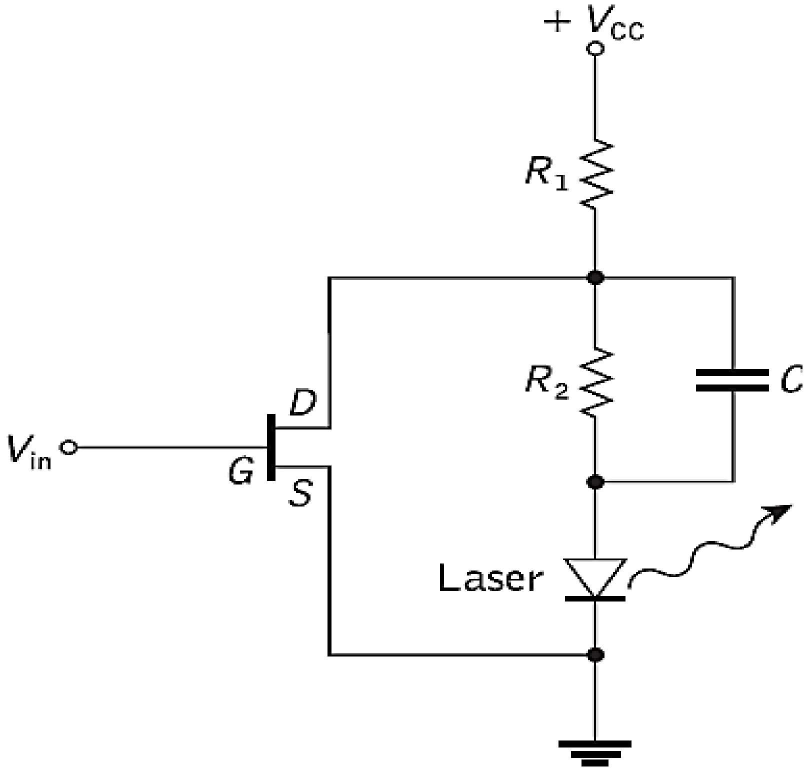


Fig.9 A shunt drive circuit for use with an injection laser.

An alternative high-speed laser drive circuit employing bipolar transistors is shown in Fig.10.

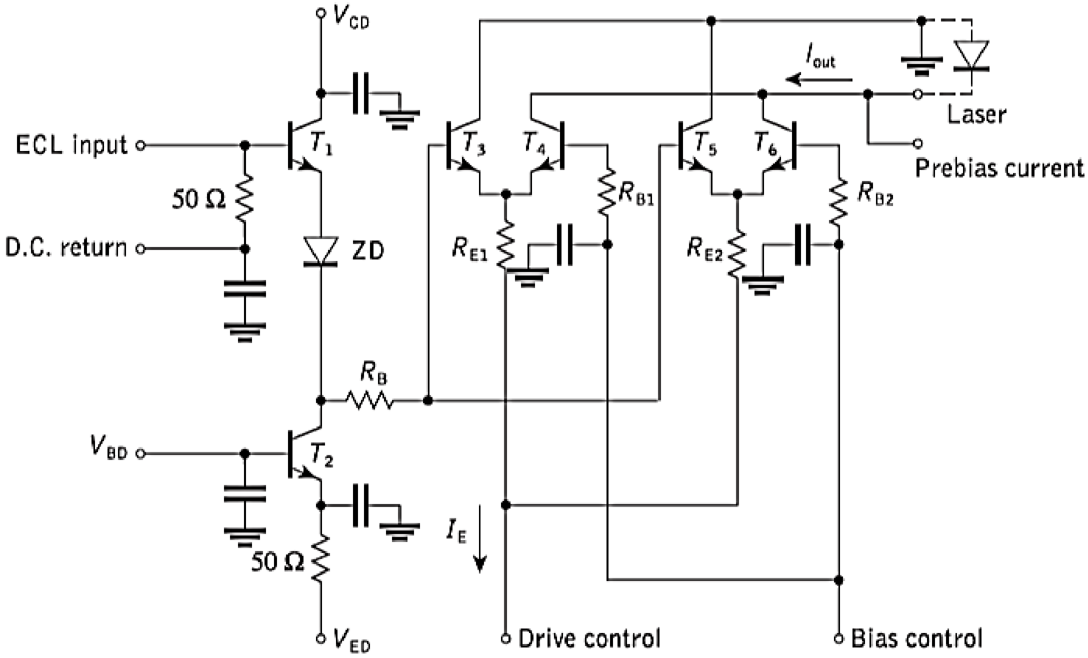


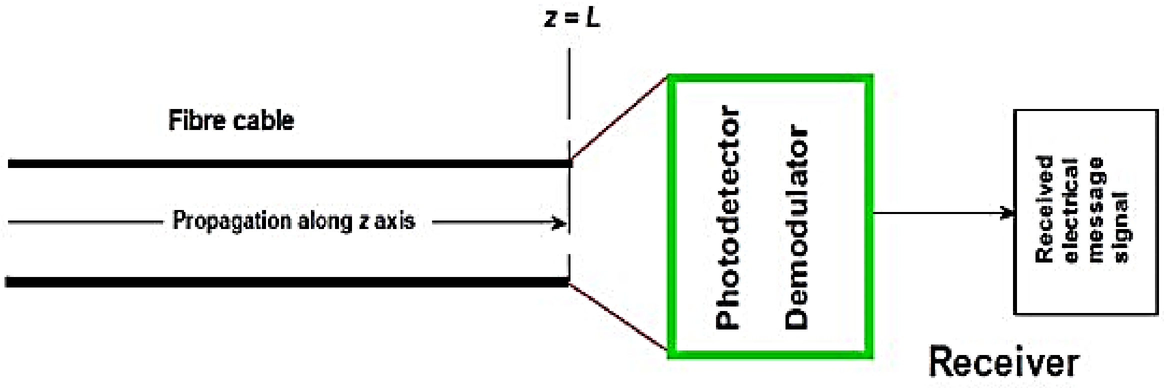
Fig.10 An ECL-compatible high-speed laser drive circuit.

This circuit configuration, again for digital transmission, consists of two differential amplifiers connected in parallel. The input stage, which is ECL compatible, exhibits a 50 Ω input impedance by use of an emitter follower T_1 and a 50 Ω resistor in parallel with the input. The transistor T_2 acts as a current source with the Zener diode ZD adjusting the signal level for ECL operation. The two differential amplifiers provide sufficient modulation current amplitude for the laser under the control of a d.c. control current IE through the two emitter resistors RE_1 and RE_2; IE is provided by an optical feedback control circuit, to be discussed shortly. Finally, a pre-bias current is applied to the laser from a separate current source. This circuit when utilizing microwave transistors was operated with a return-to-zero digital format at 1 Gbit/s.

A major difference between the drive circuits of Fig.9 and Fig.10 is the absence and use, respectively, of feedback control for adjustment of the laser output level. For this reason it is unlikely that the shunt drive circuit of Fig.9 would be used for a system application. Some form of feedback control is generally required to ensure continuous laser operation because the device lasing threshold is a sensitive function of temperature. Also, the threshold level tends to increase as the laser ages following an increase in internal device losses. Although lasers may be cooled to compensate for temperature variations, aging is not so easily accommodated by the same process. However, both problems may be overcome through control of the laser bias using a feedback technique. This may be achieved using low-speed feedback circuits which adjust the generally static bias current when necessary. For this purpose it is usually found necessary to monitor the light output from the laser in order to keep some aspect constant.

The optical receiver circuit:

The noise performance for optical fiber receivers incorporating both major detector types (the p–i–n and avalanche photodiode). Receiver noise is of great importance within optical fiber communications as it is the factor which limits receiver sensitivity and therefore can dictate the overall system design. It was necessary within the analysis to consider noise generated by electronic amplification (i.e. within the preamplifier) of the low-level signal as well as the noise sources associated with the optical detector. Also, the possible strategies for the configuration of the preamplifier were considered as a guide to optimization of the receiver noise performance for a particular application. In this section we extend the discussion to consider different possible circuit arrangements which may be implemented to achieve low-noise pre-amplification, as well as further amplification (main amplification) and processing of the detected optical signal.



Typical Optical Receiver System

Elements of Optical Receiver

A block schematic of an optical fiber receiver is shown in Fig.11.

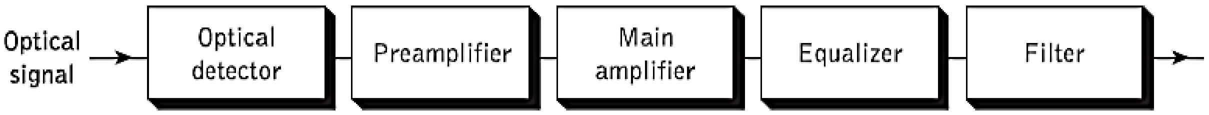


Fig.11 Block schematic showing the major elements of an optical fiber receiver.

Following the linear conversion of the received optical signal into an electric current at the **detector**, it is amplified to obtain a suitable signal level. Initial amplification is performed in the **preamplifier** circuit where it is essential that additional noise is kept to a minimum in order to avoid corruption of the received signal. As noise sources within the preamplifier may be dominant, its configuration and design are major factors in determining the receiver sensitivity. The **main amplifier** provides additional low-noise amplification of the signal to give an increased signal level for the following circuits.

Although optical detectors are very linear devices and do not themselves introduce significant distortion onto the signal, other components within the optical fiber communication system may exhibit nonlinear behavior. For instance, the received optical signal may be distorted due to the dispersive mechanisms within the optical fiber. Alternatively, the transfer function of the preamplifier–main amplifier combination may be such that the input signal becomes distorted (especially the case with the high-impedance front-end preamplifier). Hence, to compensate for this distortion and to provide a suitable signal shape for the filter, an **equalizer** is often included in the receiver. It may precede or follow the main amplifier, or may be incorporated in the functions of the amplifier and filter.

The function of the final element in the receiver, the **filter**, is to maximize the received signal-to-noise ratio while preserving the essential features of the signal. In digital systems the function of the filter is primarily to reduce inter symbol interference, whereas in analog systems it is generally required to hold the amplitude and phase response of the received signal within certain limits. The filter is also designed to reduce the noise bandwidth as well as inband noise levels.