Design Guide

RF and Microwave Fiber-Optics

Introduction

In 1984 Ortel Corporation began developing and producing lasers and detectors for linear fiberoptic links. Since that time Ortel, now Emcore has continually refined these optoelectronic components have been continually refined for integration into a variety of systems that require high fidelity, high frequency, or long-distance transportation of analog and digital signals. As a result of this widespread use and development, by the late 1980s, these link products were routinely being treated as standard RF and microwave components in many different applications.

There are several notable advantages of fiber optics that have led to its increasing use. The most immediate benefit of fiber optics is its low loss. With less than 0.4 dB/km of optical attenuation, fiber-optic links send signals tens of kilometers and still maintain nearly the original quality of the input. This low fiber loss is also independent of frequency for most practical systems. With laser and detector speeds up to 18 GHz, links can send high-frequency signals in their original form without the need to down-convert or digitize them for the transmission portion of a system. As a result, signal conversion equipment can be placed in convenient locations or even eliminated altogether, which often leads to significant cost and maintenance savings.

Savings are also realized due to the mechanical flexibility and lightweight fiber-optic cable, approximately 1/25 the weight of waveguide and 1/10 that of coax. Many transmission lines can be fed through small conduits, allowing for high signal rates without investing in expensive architectural supports. The placement of fiber cable is further simplified by the natural immunity of optical fiber to electromagnetic interference (EMI). Not only can large numbers of fibers be tightly bundled with power cables, they also provide a uniquely secure and electrically isolated transmission path. The general advantages of fiber-optics first led to their widespread use in long-haul digital telecommunications. In the most basic form of fiber-optic communications, light from a semiconductor laser or LED is switched on and off to send digitally coded information through a fiber to a photodiode receiver.

By comparison, in linear fiber-optic systems developed by Lucent, the light sent through the fiber has an intensity directly related to the input electrical current. While this places extra requirements on the quality of the lasers and photodiodes, it has been essential in many applications to transmit arbitrary RF and microwave signals. As a result, tens of thousands of Ortel's transmitters are currently in use.

The information offered here examines the basic link components, provides an overview of design calculations related to gain, bandwidth, noise, and dynamic range and distortion. A section on fiberoptic components discusses a number of key parameters, among them wavelength and loss, dispersion, reflections, and polarization and attenuation. Additional information evaluates optical isolators, distributed-feedback lasers and Fabry-Perot lasers, predistortion, and short- vs. long-wavelength transmission.

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Typical Linear Link Applications

One of the primary uses of linear fiber-optic links is sending RF and microwave signals between transmit or receive electronics and remotely located antennas.

Due to the flexibility of fiber-optic links, the antennas may be designed for analog or digital signals from any of a number of sources, including military and commercial communication satellites, global positioning satellites, telemetry/tracking beacons, or wireless cellular networks.

Another type of link is the fiber-optic delay line, which combines a transmitter, a receiver, and a long length of fiber in a single package to provide a unique combination of long delay times, high bandwidths, and low weight. These higher-frequency RF and microwave products have benefitted indirectly from another application, the overwhelming use of linear fiber optics in cable television. Here, fiber extends the transmission distance of TV signals, improves their quality and system reliability, and even reduces costs when compared with systems employing only coax cables.

Typical Linear Link Components

In each of these applications, as well as many others, Ortel's transmitters and receivers comprising the links are similar and can be treated as standard microwave components. Focusing on these common elements, this design guide describes the general technical considerations and equations necessary for engineers to choose the most appropriate Ortel components for their systems. These equations also have been incorporated into various programs, which an Ortel applications engineer can use to provide an analysis for a specific link application.

Figure 1 shows the three primary components in a fiber-optic link: an optical transmitter, a fiber-optic cable, and an optical receiver. In the transmitter, the input signal modulates the light output from a semiconductor laser diode, which is then focussed into a fiberoptic cable. This fiber carries the modulated optical signal to the receiver, which then reconverts the optical signal back to the original electrical RF signal.

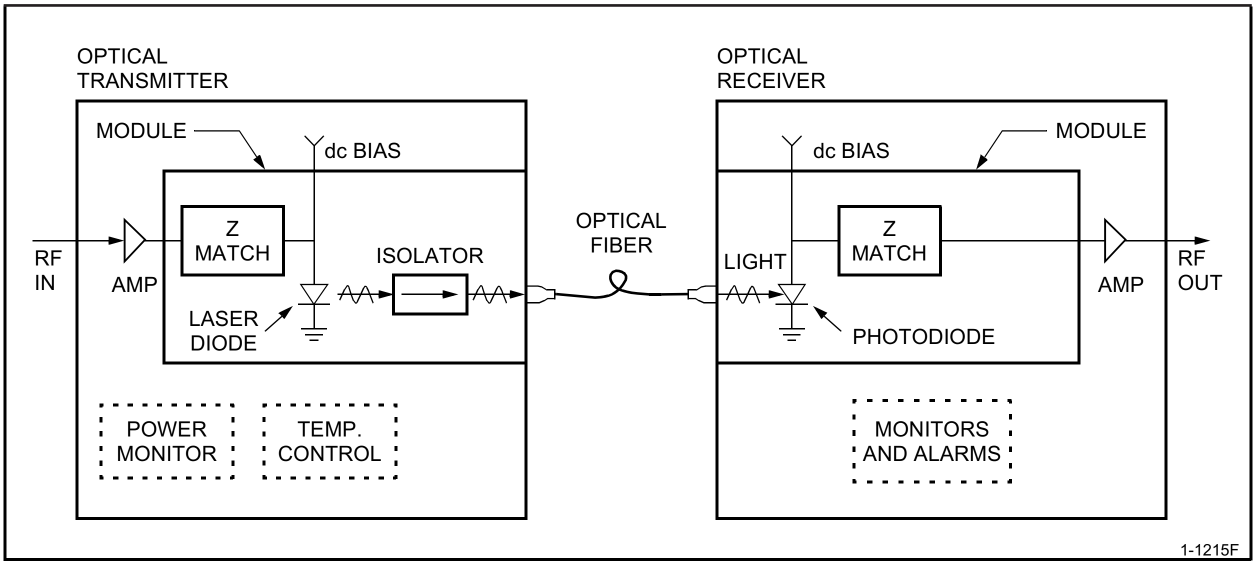

Figure1.BlockDiagramDepictingaBasicFiber-OpticLinkofTransmitter,Receiver,andOpticalFiber

Basic Link Applications and Components (continued)

Optical Transmitter

For RF systems, distributed feedback (DFB) lasers are used for low-noise, high-dynamic range applications, and Fabry-Perot lasers for less demanding applications. The wavelength of these lasers is either 1310 nm or 1550 nm.

The intensity of the laser light is described by the simplified light-current (L-I) curve in Figure 2. When the laser diode is biased with a current larger than the threshold current, ITH, the optical output power increases linearly with increasing input current. Analog links take advantage of this behavior by setting the dc operating point of the laser in the middle of this linear region. Typically, this bias current for Ortel transmitters is set somewhere between 40 mA to 90 mA. The threshold current ranges from 10 mA to 30 mA.

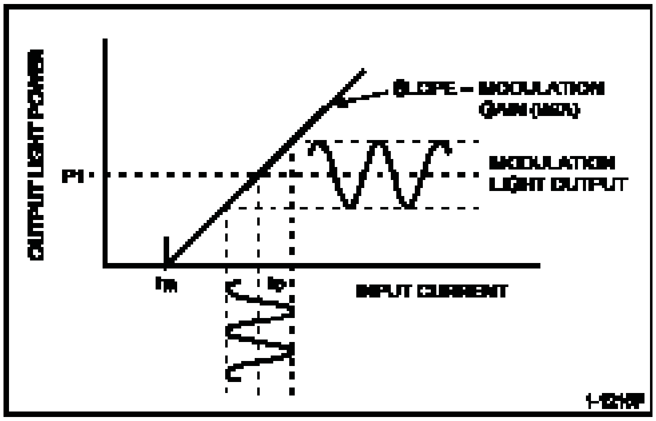

Figure2.InputCurrentvs.OutputPower

The efficiency with which the laser converts current to usable light is given by the slope of the L-I curve and is called the modulation gain. For typical Ortel lasers, this dc modulation gain ranges from 0.02 W/A to 0.3 W/A, depending on the model chosen. The wide variation is largely due to differing methods of coupling the light into the optical fiber. The modulation gain also varies somewhat with frequency, so it must be specified whether a particular value is a dc or higher-frequency gain. In addition to the laser diode, transmitters also contain a variety of other components, depending on the specific application or level of integration desired. The most basic laser module package contains the laser chip, optical fiber, and impedance-matched electrical connections in a hermetically sealed container such as the one shown in Figure 3. Modules also may contain a photodiode for monitoring the laser power, a thermistor and a thermoelectric (TE) cooler for monitoring and controlling the laser temperature, and an optical isolator for reducing the amount of light reflected back to the laser from the fiber.

Figure 3. A1612P DFB Laser Module

The basic laser module, although available as a subcomponent, is usually integrated into a complete transmitter housing such as the flange-mount and plug-in packages shown in Figure 4. These transmitters also may include dc electronics to control the laser temperature and bias current, amplifiers and other circuitry to precondition the RF signal, and various indicators for monitoring the overall transmitter performance. Because analog fiber-optic transmitters are used in a variety of applications, the exact implementation of these product features varies as well.

Figure4.TransmitterPackageStyles:Flange-Mount(left)andPlug-In(right)

Optical Receiver

At the other end of the fiber-optic link, the light is detected by the receiver PIN photodiode, which converts the light back into an electrical current. The behavior of the photodiode is given by the responsivity curve shown in Figure 5. Once again, note that the response is very linear. The slope of this curve is the responsivity, which typically is greater than 0.75 mA/mW for a photodiode chip without any impedance matching.

Similar to Lucent's laser diodes, photodiodes are packaged in a hermetic module containing an impedance matching network and electrical lines to provide dc bias and RF output. However, unlike the laser, the photodiode is relatively insensitive to temperature so a thermoelectric cooler (TEC) is not required. Special precautions also are made to minimize optical reflections from returning back through the fiber, which otherwise could degrade a link's performance.

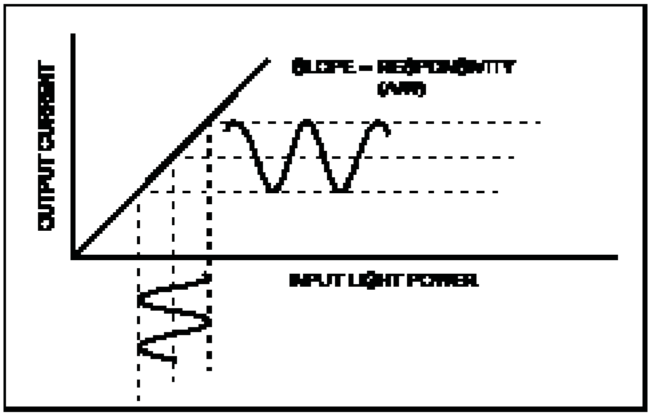

Figure5.PhotodiodeLinearResponsivityCurve

These photodiode modules are often integrated into more complete receiver packages similar to the flangemount and plug-in varieties of the transmitters. In these receivers, circuitry reverse biases the diodes to increase the response speed. Receivers also contain monitor and alarm outputs. Some receivers may include a post amplifier, broadband current transformers, and/or impedance matching networks to improve the link gain. Due to such circuitry, the efficiency of a receiver generally will differ from the responsivity of the photodiode chip alone.

Fiber-Optic Cable

A fiber-optic cable is the third primary component in a linear optical link. Single-mode fiber, as opposed to multimode fiber, is always used with Ortel links because of its low dispersion and low loss. At a wavelength of 1310 nm, the fiber attenuates the optical signal by less than 0.4 dB/km; at 1550 nm, less than 0.25 dB/km. Typically, the fiber is cabled in rugged yet flexible 3 mm diameter tubing and connected to the transmitter and receiver with reusable optical connectors. The modular nature of the cable simplifies the design of the physical architecture of the system and enables a wide range of configuration possibilities. Although Ortel does not supply optical fiber, several important considerations should be followed in selecting these components. The section entitled Selection of Optical Fiber Components, page 19, describes these issues in detail.

Link Design Calculations

When selecting the proper components for a fiber-optic link, there are several critical quantities that must be defined and calculated prior to its implementation, just as would be done with any RF or microwave communication link. Topics of discussion in this section include link gain, bandwidth, noise, dynamic range, and distortion, and the use of that information as an example for a typical link. The detailed equations in this section also have been incorporated into various design programs, which an Ortel applications engineer can use to provide the predicted performance of a link in a specific application.

Gain

The RF loss (or gain) of an optical link is a function of four variables, including transmitter efficiency, fiber loss, receiver efficiency, and the ratio of the output to input impedances. In its most basic form, the power gain of the link can be written in terms of the input and output currents as equation 1,

$$G_{LINK} = \left(\frac{I_{OUT}}{I_{IN}}\right)^2\left(\frac{R_{OUT}}{R_{IN}}\right)$$

where ROUT is the load resistance at the receiver output and RIN is the input resistance of the laser transmitter. The (IOUT/IIN) term can be expanded in terms of the link characteristics as:

equation 2

$$\frac{I_{OUT}}{I_{IN}} = \frac{(\eta_{TX, RF}(\eta_{RX, RF}))}{L_{OPT}}$$

where ηTx, RF is the efficiency of the total transmitter, including any amplifiers and matching networks, in converting input RF currents into optical power modulations. ηRx, RF is the efficiency of the total receiver in converting optical power modulations into RF output current. (This RF value is not the same as the dc photodiode responsivity, as described in the section on Bandwidth, page 8.) The units for ηTx, RF and ηRx, RF are W/A and A/W, respectively. LO is the optical loss of the fiber portion of the link measured as:

equation 3

$$L_{O, RATIO} = \frac{\text{Optical Power at Transmitter}}{\text{Optical Power at Receiver}}$$

$$L_O = 10 \log L_{O, RATIO}$$

Substituting equation 2 into equation 1 then gives the total gain of a link:

equation 4,

$$_{LINK, RATIO} = (\eta_{TX, RF})\left(\frac{(\eta_{RX, RF}\ )C}{L_{O, RATIO}}\right)^2\left(\frac{R_{OUT}}{R_{IN}}\right)$$

$$G_{LINK, dB} = 20 \log(\eta_{Tx, RF})(\eta_{Rx, RF}) - 2\,L_O + 10 \log(R_{OUT}/R_{IN})$$

The factors of ηTx, RF and ηRx, RF are sometimes converted to a form more similar to traditional RF gains by taking 20log, so that equation 4 can be simplified to:

equation 5,

$$G_{LINK, dB} = TG + RG - 2Lo + 10 \log(R_{OUT}/R_{IN})$$

GLINK, dB = TG + RG – 2Lo + 10 log(ROUT/RIN)

where TG is the transmitter gain in dB^2W/A and RG is the receiver gain in dB^2A/W. TG and RG are related to the unit's total RF efficiency expressed in W/A or A/W as follows:

equation 6,

$$TG = 20\log\ (Tx, RF)$$

equation 7,

$$RG = 20\log\ (Rx, RF)$$

For example, combining a 75 Ω transmitter with a TG of –1 dB^2W/A, a 75 Ω receiver with an RF of +20 dB^2A/W and a 12 dB optical loss, would give an RF gain for the link of:

$$G = -1\ dB^2W/A + 20\ dB^2A/W - 2\ (12\ dB) + 10\log(75/75) = -5\ dB.$$

Figure 6 shows the effects of optical loss and transmitter RF efficiency for a receiver with an efficiency of 0.375 mA/mW (RG of $-8.51dB^2A/W$), as calculated with equation 4. The Appendix, page 28, contains additional sets of curves for other typical transmitter and receiver efficiencies.

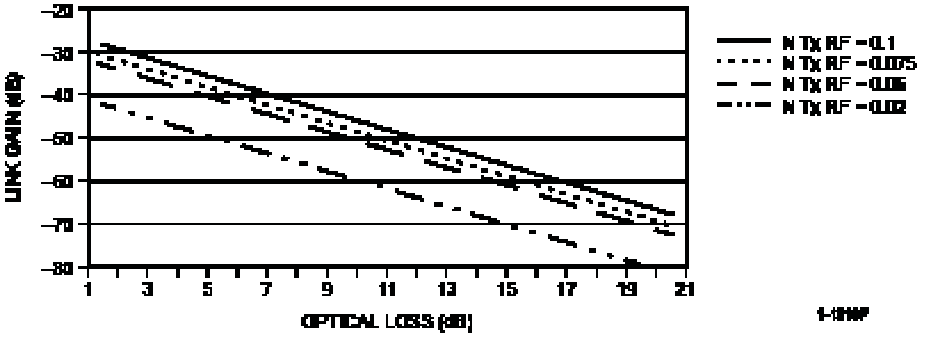

Figure6.EffectsofOpticalLossandTransmitterRFEfficiency

Doubling the Optical Loss Term

An interesting and often overlooked aspect of equation 4 is the 2 LO term. As this indicates, for each additional dB of optical loss, there is an additional 2 dB of RF loss. This oddity occurs as a result of converting optical power to RF energy. Here, the RF current is directly proportional to the optical power, but the RF power equals the square of the RF current. When taking the log, this squared term turns into a factor of 2 in front of the optical loss. For example, a transmitter and receiver pair that have a –35 dB RF gain when they are directly connected with 0 dB of optical loss, would have a –39 dB RF gain when connected with a 2 dB loss fiber.

Resistively Matched Components

To calculate the total insertion loss for a specific link, consider the broadband resistively matched link shown in Figure 7. In this case, the laser transmitter includes the laser diode, with a typical impedance of 5 Ω, and a resistor to raise the total input impedance, RIN, up to the impedance of the external signal source. The photodiode module includes the photodiode, with a typical impedance of several kΩ, and a resistor RPD to match to the output impedance RL. Such matching resistors substantially improve the VSWR of the link over that of an unmatched link. Due to this extra photodiode resistor, the current output from the receiver, IOUT, will be less than the total current produced by the photodiode chip, IPD. The RF efficiency of the receiver, ηRx, RF, is therefore correspondingly smaller than the responsivity of the photodiode chip alone, RPD:

GLINK = –35 dB

equation 8,

$$\eta_{Rx,\,RF} = \left[\frac{R_{PD}}{R_{PD} + R_{OUT}}\right] \cdot R_{PD}$$

For a 50 Ω matched system, RPD and ROUT each would be approximately 50 Ω, therefore, the receiver RF efficiency would be half that of the photodiode chip on its own. This decreases the overall link gain by 6 dB. For a resistively-matched photodiode receiver:

equation 9,

ηRx, RF = RPD/2

The transmitter RF efficiency, on the other hand, does not experience such a drop of 6 dB due to the fact that the matching resistor is placed in series rather than in parallel. Therefore, within the bandwidth of a transmitter, its RF efficiency is approximately equal to the dc modulation gain of the laser diode. As an example, consider a transmitter with a dc modulation gain of 0.1 W/A, a resistively matched receiver with a dc responsivity of 0.75 and a fiber with an optical loss of 3 dB. To the first order, RF efficiency of the transmitter will be 0.1 W/A and the RF efficiency of the receiver will be 0.375 A/W. If both the transmitter and receiver are matched to 50 Ω, then the impedance matching term of equation 4 drops out, leaving an RF link gain of approximately:

equation 10,

$$G_{LINK,\,dB} = 20\log(\eta_{Tx,\,RF}(\eta_{Rx,\,RF})) - 2\,L_{OPT,\,dB} + 10\log\left(\frac{R_{OUT}}{R_{IN}}\right)$$

$$G_{LINK}\ (20\log[(0.1\ \text{mW/mA})\ (0.375\ \text{mA/mW})] - 2 \times 3\ \text{dB} + 0$$

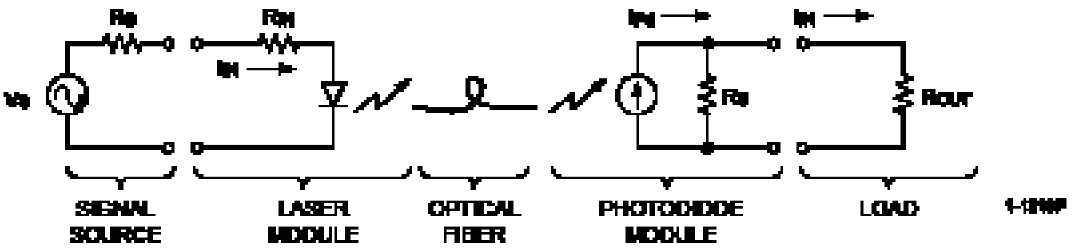

Figure7.ResistivelyMatchedLink

Reactively Matched Link

To overcome such a loss, many links incorporate additional amplifiers, which are described more fully in the sections on Receiver Noise, page 10; Placement of Amplifiers, page 15; and in the section entitled Example, page 15. As an alternative for narrowband systems, the link gain can be improved by impedance matching so that the laser diode and photodiode see an effective ROUT/RIN > 1. The matching electronics used in such links are carefully designed to produce this extra gain without creating reflections or poor VSWR.

Bandwidth

The range of frequencies over which a fiber-optic link can transmit is limited by the bandwidth of the transmitter and receiver and by the dispersion of the optical fiber. The bandwidth limit of a link generally is defined as the frequency at which the microwave modulation response decreases by 3 dB. In most cases, the bandwidth of the laser transmitter limits a link's frequency response, therefore, the response of the basic laser diode chip shown in Figure 8 is of prime interest. As can be seen, the frequency response of the chip varies with the bias current, thus an optimum point is chosen to balance this frequency response and other current-sensitive parameters such as noise, linearity, and life of the device. When integrating the laser chip into a complete transmitter, other components such as amplifiers or matching networks also can limit the response. The bandwidth of receivers is limited by the capacitance and carrier transient times of the photodiode chip or by additional electrical components such as amplifiers and matching networks. In most cases, the speeds of these receivers are faster than that of the other components in the link. In certain situations, the fiber itself may smear out rapidly varying signals due to the fact that different wavelengths travel at different speeds along a fiber. To avoid this chromatic dispersion, lasers with narrow optical bandwidths, such as Lucent's DFB lasers, are used with fiber that has low dispersion. Using a DFB at 1310 nm, where fibers have a natural minimum in their dispersion, bandwidths in excess of 15 GHz can be achieved over fibers as long as tens of kilometers. The section on Dispersion, page 20, describes these fiber effects more fully.

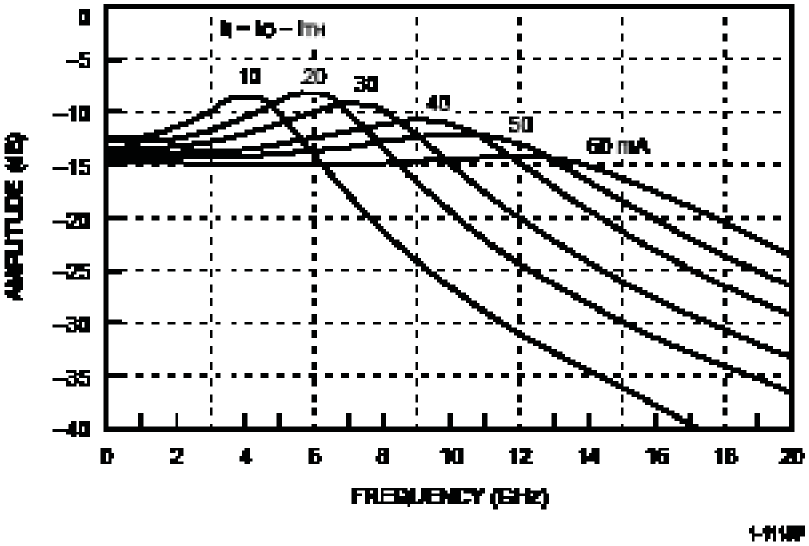

Figure8.LaserFrequencyResponseasaFunctionofIncreasingBiasCurrent

Noise

Within the bandwidth of the link, the contribution of noise from the various components must also be considered. When specifying the noise of a link, the tendency is to use equivalent input noise (EIN). EIN is defined as the amount of RF noise at the input of a link that would be needed to produce the amount of noise observed at the output of the link if the total link itself were noiseless. Its units can be mW/Hz or dBm/Hz:

equation 11,

$$\mathrm{EIN}_{\mathrm{LINK,\,mW}} = \mathrm{Noise}_{\mathrm{OUTPUT,\,mW}}/G_{\mathrm{RATIO}}$$

$$\mathrm{EIN}_{\mathrm{LINK,\,dBm}} = \mathrm{Noise}_{\mathrm{OUTPUT,\,dBm}} - G_{\mathrm{dB}}$$

An alternate measure of noise is the noise figure (NF), which is the ratio in dB of the actual noise power to the amount that would be produced by a similar device with perfect noise performance. It is further defined that the inputs of this ideal device are terminated by a passive load at the standard temperature of 290 K(TO). Since the available noise power from such a load is:

$$KT_O = (1.38 \times 10^{-20}\ \mathrm{mW/(k - Hz)})\ (290\ \mathrm{K})$$
$$= 4.0 \times 10^{-18}\ \mathrm{mW/Hz}$$
$$= -174\ \mathrm{dBm/Hz}$$

EIN is related to NF by:

equation 12,

$$\mathrm{NF} = 10 \log (\mathrm{EIN}_{\mathrm{mW/Hz}}/KT_O)$$

$$\mathrm{NF} = \mathrm{EIN}_{\mathrm{dBm/Hz}} + 174\ \mathrm{dBm/Hz}$$

The noise also can be specified in terms of the equivalent input temperature, T, which is given by:

equation 13, $\mathrm{EIN}_{\mathrm{mW/Hz}} = KT_O + KT$

$$T = \frac{10[(\mathrm{EIN,\ dBm/Hz})/10]}{K - T_O}$$

For example, a link that has an output noise of –85 dBm/Hz and a gain of –40 dB would have an EIN of –125 dBm/Hz, an NF of 49 dB, and a T of 2.3 x 107 K. Equations 11 and 12 require that EIN be expressed over a 1 Hz bandwidth. With these terms defined, the four primary noise sources in a fiber-optic link can be defined:

1. Noise from amplifiers in the transmitter
2. Noise from the laser diode
3. Shot noise at the photodiode
4. Noise from amplifiers and/or matching components at the receiver

Since fiber-optic links typically exhibit a significant amount of signal loss, the noise from the transmitter amplifiers are generally much less than that from the other components, and will be neglected. The calculations discussed in this section are also summarized in the performance curves in the Appendix, page 28.

Laser Noise

Laser noise arises from random fluctuations in the intensity of the optical signal. There are two main contributions to this effect. The first is the actual fluctuations in the intensity of the light as it is generated at the laser diode. The second is fluctuations in the frequency of the light, which can degrade the signal if the fiber is dispersive. This second set of effects will be discussed more fully in the sections on Reflections and Interferometric Noise, page 24; Polarization Mode Dispersion, page 25; and Distributed-Feedback (DFB) vs. Fabry-Perot (FP) Lasers, page 25.

The laser noise measured directly at the transmitter is often referred to as relative intensity noise (RIN), so named because it is the ratio of the mean square amplitude of the noise fluctuations per unit bandwidth, <P2>, to the square of the dc optical power, Po:

$$\mathrm{RIN}_{\mathrm{RATIO}} = \langle P^2 \rangle / P_O^2$$

This value is related to EIN by: equation 14,

$$\mathrm{EIN}_{\mathrm{LASER,\,mW/Hz}} =$$
$$\mathrm{RIN}_{\mathrm{RATIO}}((I_{dc} - I_{TH})^2 \cdot R_{IN}\left[\frac{M_{dc}}{\eta_{Tx,\,RF}}\right]^2 / 1000$$

$$\mathrm{IN}_{\mathrm{LASER,\,mW/Hz}} =$$
$$\mathrm{IN}_{\mathrm{dB}} + 10\log\left[(I_{dc} - I_{TH})^2 (R_{IN}) \left[\frac{M_{dc}}{\eta_{Tx,\,RF}}\right]^2\right](-30)$$

where Idc is the dc bias current in mA applied to the laser diode, ITH is the laser threshold current, RIN is the laser input dc impedance, Mdc is the dc modulation gain of the laser diode, and ηTx, RF is the RF efficiency of the transmitter at the frequency of interest. As an example, a laser biased 60 mA above threshold with an RIN of –153 dB/Hz, an input impedance of 50 Ω, and a modulation gain ratio Mdc/ηTx, RF of 1 would have an EINLASER of –130 dBm/Hz. In general, both RIN and EIN vary with the bias current and frequency.

Shot Noise

The second main contributor to link noise is from a subtle effect called shot noise. Shot noise occurs because light is composed of discrete packets of energy called photons, which convey a signal not as a smooth flow of energy but instead as a stream of infinitesimal quanta of energy. The randomness of the arrival time of each photon generates a random noisiness in the current at the output of the photodiode:

equation 15,

$$i_{SHOT} = (2 \cdot e \cdot I_{dc} \cdot BW)^{1/2}$$

where iSHOT is the rms value of the shot noise at the photodiode chip; e is 1.6 x 10–19 Coulombs; Idc is the dc electrical current through the photodiode, and BW is the channel or resolution bandwidth of the measurement. The amount of shot noise that leaves the receiver, iSHOT, OUT will depend on the ratio of the photodiode responsivity and the efficiency of the total receiver:

$$i_{SHOT,\,OUT} = i_{SHOT} \cdot \left(\frac{R_{X,\,RF}}{R_{PD}}\right)$$

The contribution from shot noise per unit bandwidth can be referred back to the input of the total link to give:

equation 16,

$$EIN_{SHOT,\,mW} = 2e\left[\frac{P_{LASER} \cdot RIN}{(\eta_{Tx,\,RF})^{2}(R_{PD})}\right] \cdot L_{OPT,\,RATIO}$$

where PLASER is the optical power launched into the fiber immediately after the laser. For example, if PLASER is 4 mW, R is 50 Ω, ηTx, RF is 0.1 W/A, RPD is 0.75 A/W, and LOPT,RATIO is 2 (i.e.,3 dB) then:

equation 17,

$$EIN_{SHOT,\,mW} =$$

$$2(1.6 \times 10^{-19}C)\left[\frac{(4\ mW)(50\ \Omega)}{(0.1\ W/A)^{2}(0.75 A/W)}\right](2)$$

$$EIN_{SHOT,\,mW} = 1.71 \times 10^{-14}\ mW/Hz$$

$$EIN_{SHOT,\,dBm} = -137\ dBm/Hz.$$

Receiver Noise

The receiver also will add noise from any amplifiers or resistive matching elements incorporated in or immediately after the receiver. Since it is necessary to have such amplifiers in most situations, it is important to carefully consider its contribution as well. The receiver noise is referred back to the input just as in equation 10 on page 7.

$$EIN_{Rx,\,dBm} = Noise_{Rx,\,OUTPUT,\,dBm} - G_{LINK,\,dB}$$

Receiver noise often is specified by the equivalent noise current. Similar to EIN, the equivalent noise current is the theoretical amount of rms current at the photodiode that would be required to create the actual amount observed noise leaving the photodiode, imagining that all other components in the receiver had nonoise.

equation 18,

$$ENC = i_{N,\,OUTPUT}\left(\frac{R_{PD}}{\eta_{Rx,RF}}\right)$$

where iENC is the rms equivalent noise current at the photodiode and iN,OUTPUT is the actual rms noise out of the receiver. As an example, consider the 50 Ω resistively-matched receiver in Figure 7 on page 7. The thermal noise of a resistor, here RPD, can be modeled as a current source in parallel with the resistor with an rms current of:

$$i_{RESISTOR\ NOISE} = \left[\frac{4\ KT(BW)}{R}\right]^{1/2}$$

$$i_{RESISTOR\ NOISE} = 18\ pA/Hz$$

In Figure 7, half of this 18 pA/Hz will pass through the matching resistor, RPD, and half will pass through the load, thus the output noise current is 9 pA/Hz (or in power is –174 dBm/Hz). Using equation 17 and remembering from section on Resistively Matched Components, page 7, that the ratio of RPD/ηRx, RF = 2 for a resistively-matched receiver, the equivalent noise current for a resistively-matched 50 Ω receiver is simply 18 pA/Hz.

To convert this equivalent noise current into EIN of the link use the following:

$$EIN_{LINK,\,mW/Hz} = EIN_{LASER,\,mW/Hz} + EIN_{SHOT,\,mW/Hz} + EIN_{TH,\,mW/Hz}$$

Total Link Noise

When the laser noise and photodiode shot noise are added together with receiver thermal noise, as in Figure 9, each noise source obeys a different law with respect to the amount of optical loss in a given system. Specifically, the laser EIN stays constant, the photodiode EIN grows proportional to the optical loss, and the receiver thermal EIN grows proportional to the square of the optical loss (Of course, the actual thermal noise is constant, but since it is referred back to the link input its contribution relative to the input signal grows as the losses of the link increase.) equation 19,

$$\mathrm{EIN}_{\mathrm{LINK,\ mW/Hz}} = \mathrm{EIN}_{\mathrm{LASER,\ mW/Hz}} + \mathrm{EIN}_{\mathrm{SHOT,\ mW/Hz}} + \mathrm{EIN}_{\mathrm{THERMAL,\ mW/Hz}}$$

Figure 10 shows the benefits that can be achieved when reactive matching is used. Reactive matching at the transmitter decreases the level of all three components of the link noise, which means that lower gain pre-amps are needed to achieve the same signal to noise ratio. Reactive matching at the receiver further reduces amplification requirements by increasing the link gain, but it also specifically lowers the relative contribution of receiver thermal noise, which is often the limiting factor in longer links.The Appendix, page 28 includes a more complete set of EIN curves. Highpower photodiodes also can improve the noise performance of a link because generally they do not require extra optical attenuation for protection, thus the optical losses of link can be lower.

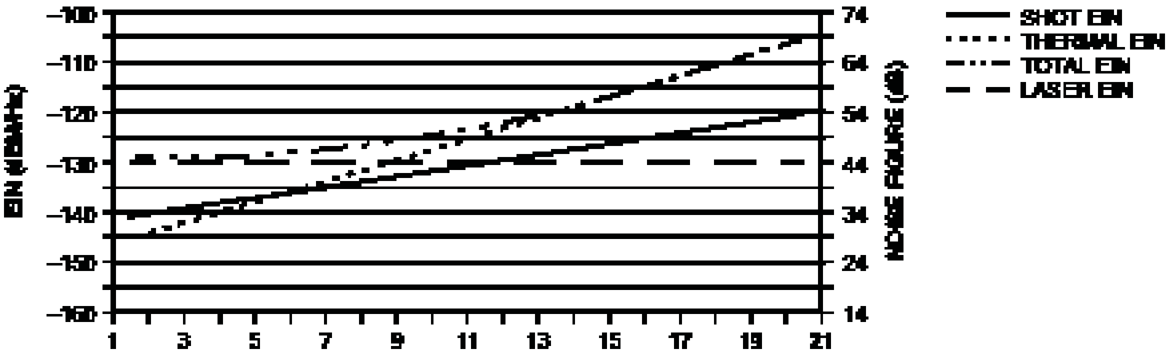

Figure9.CumulativeLossEffectsofLaserNoise,PhotodiodeShotNoise,andReceiverThermal Noise on Total Link Performance

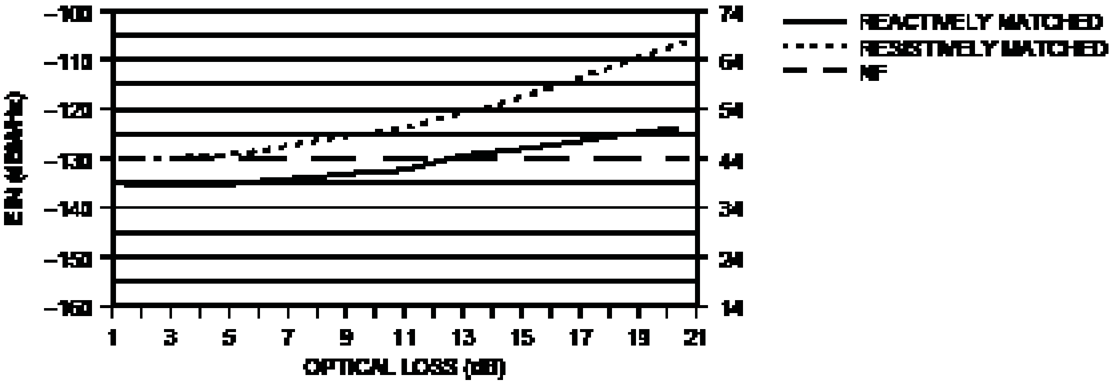

Figure10.ReactiveMatchingattheTransmitterandReceiverImpartsImprovedNoisePerformance

Cascading Noise Figures

Once the noise contributions of an optical link are calculated and reduced to a single quantity for the EINLINK, this noise can be cascaded with other microwave components in the system. Friis' formula states that if a single component with a noise figure of NF1 and gain of G1 is followed by another component with a noise figure of NF2, then the total noise figure will be:

equation 20,

$$NF_{TOTAL,\ RATIO} = NF_{1,\ RATIO}\left(\frac{NF,\ RATIO - 1}{G_{1,\ RATIO}}\right)$$

where both the NF and G must be expressed as ratios when computing the algebra. Friis' formula also can be converted to EIN and T by using the definitions in equation 12 and equation 13 on page 9:

equation 21,

$$EIN_{TOTAL,\ mW/Hz} = EIN_{1,\ mW/Hz} + \left(\frac{EIN_{2\ mW/Hz} - KT_O}{G_{1,\ RATIO}}\right)$$

equation 22,

$$T_{TOTAL} = \frac{T_1 + T_2}{G_{1,\ RATIO}}$$

Unconverted Noise and SNR

The noise phenomena described in the previous section all occur independent of the presence of an RF signal; however, there is another class of noise phenomena that occur only when a signal is present. Such noise is present at low frequencies even without a signal, but is translated to the neighborhood of the signal when the light is modulated, as shown in Figure 11. This upconverted noise may reduce the signal to noise ratio (SNR, C/N, or CNR) below what would be calculated if only the EIN was considered. Fabry-Perot lasers are especially susceptible to this noise and this is reflected in their SNR specification. For a Fabry-Perot laser, this low-frequency noise results largely from mode partition noise, which increases with fiber length and modulation frequency. For DFB lasers there is only one optical mode (or-wavelength) so these effects are absent. The remaining low-frequency noise for DFBs primarily results from Rayleigh scattering in the fiber, which only becomes apparent for links on the order of 20 km or more and for high SNRs. These upconverted noise sources are described in more detail in the sections on Reflections and Interferometric Noise, page 24, and Distributed-Feedback (DFB) vs. Fabry-Perot (FP) Lasers, page 25.

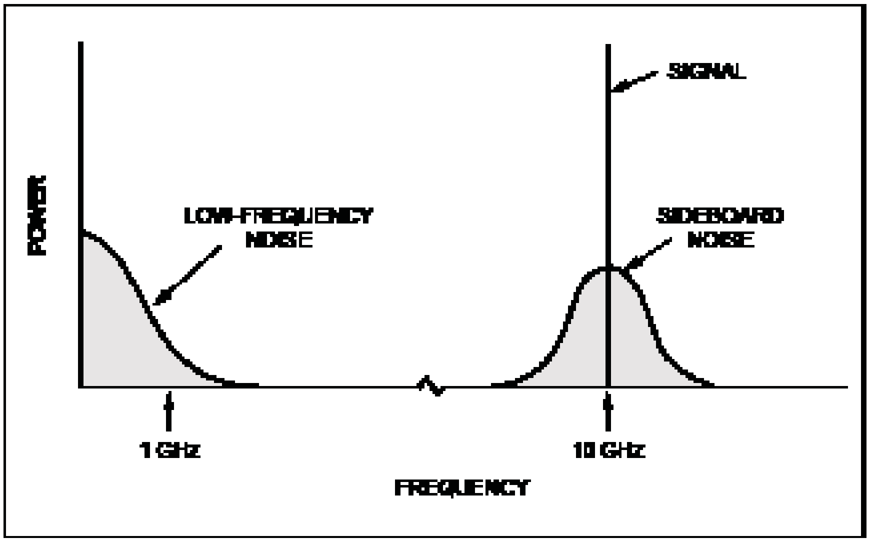

Figure11.EffectsofUnconvertedLow-FrequencyNoiseonSNR

Noise-Equivalent Bandwidth

The SNR of the link depends not only on the RF signal level outlined above, but also on the noise-equivalent bandwidth. Wider channel widths will include more noise power and thus reduce the SNR. Although the link may be passing many channels over a wide band, the receiver can be tuned to a single channel within this band. This single-channel bandwidth is important in determining the SNR and, in the next section, the dynamic range.

equation 23,

$$\mathrm{Noise}_{\mathrm{CHANNEL}} = \mathrm{EIN}_{\mathrm{dBm/Hz}} + \mathrm{BW}_{\mathrm{dB,\ Hz}}$$

Dynamic Range and Distortion

While the noise floor determines the minimum RF signal detectable for a given link, non-linearizes in the laser and amplifiers tend to limit the maximum RF signal that can be transmitted. For links transmitting a single tone where there is little concern for it interfering with other signals, the 1 dB compression point is generally used to specify the dynamic range. For links transmitting a larger number of signals, the third-order intercept point is frequently used to calculate the spurfree dynamic range. Both definitions are discussed below.

1 dB Compression Point

The most straightforward limitation on the power of an input signal is the 1 dB compression point, P1dB. At this RF input power, the output signal is 1 dB less than what would be predicted by the small signal gain of the link. Returning to the L-I curve of the transmitter, Figure 2 on page 4, it can be seen that once the magnitude of the signal approaches that of the bias current, the signal will clip at the lower level of the curve. This limit defines the 1 dB dynamic range, DR1dB, as follows:

equation 24,

$$\mathrm{DR}_{1\mathrm{dB}} = \mathrm{P}_{1\mathrm{dB}} - \mathrm{Noise}_{\mathrm{CHANNEL}}$$

$$\mathrm{DR}_{1\mathrm{dB}} = \mathrm{P}_{1\mathrm{dB}} - \mathrm{EIN}_{\mathrm{dBm/Hz}} - 10\log(\mathrm{BW}_{\mathrm{Hz}})$$

Third-Order Intercept and Spur-Free Dynamic Range

A more precise treatment for a large number of carriers uses the third-order intercept. Even in the middle of the linear portion of a laser's L-I curve, non-idealities distort the output and cause higher order, intermodulation signals. In particular, if two equilevel sinusoidal tones at f1 and f2 modulate the fiber-optic link, third-order distortion products are generated at 2f1– f2 and at 2f2 – f1, as shown in Figure 12. The magnitude of these distortion products expressed in dBm has a slope of three when plotted against the input or output power level, as shown in Figure 13 on page 14.

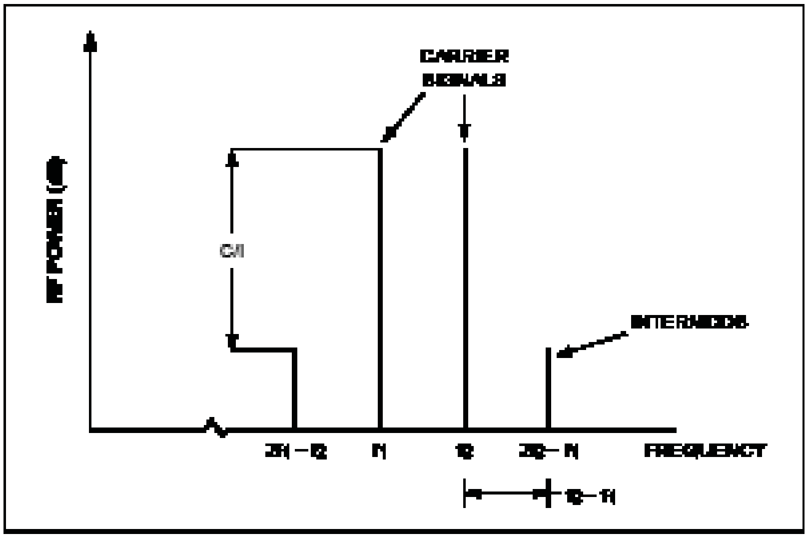

Figure12.Third-OrderIntermodulationDistortionSpectrum

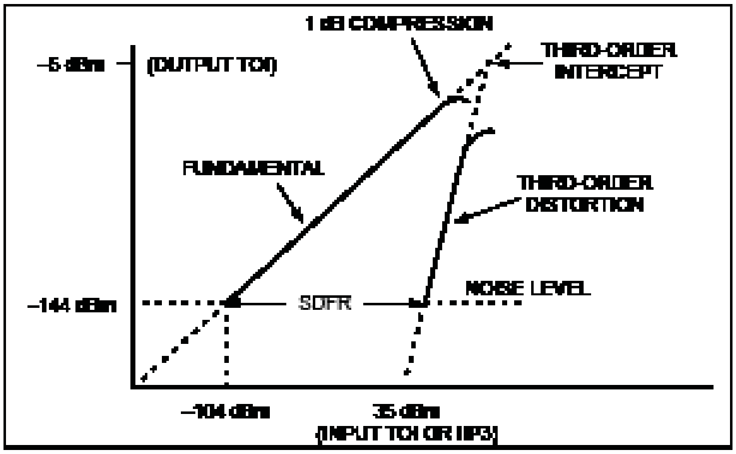

Figure13.Third-OrderInterceptandSpur-FreeDynamicRange

To quantify this effect, the slopes of the output signal and distortion terms are extrapolated to higher power until they intercept. The input power corresponding to this intersection is defined as the input third-order intercept point (IIP3 or input TOI), which can be calculated by: equation 25,

$$IIP3_{dBm} = S_{IN,\,dBm} + \left(\frac{C}{I_{2\ TONE,\ dB}}\right)/2$$

SIN, dBm is the input power of one of the carriers and C/IdB is the ratio of the output power of the carrier to that of one of the intermodulation distortion signals. (For Ortel components, the input TOI rather than the output TOI is usually specified because the input TOI will be independent of the link gain. To find the output TOI, simply add the input TOI to the link gain in dB.) Equation 25 also can be used to approximate the worst-case distortion terms for a given input power. For example, if the IIP3 of a transmitter is 35 dBm and a pair of signals is input with –5 dBm in each, then the third-order terms will be 80 dB below these at –85 dBm. equation 26,

$$C/I_{2\ TONE,\ dB} = 2\ (IIP3dBm - S_{IN,\ dBm})$$

$$C/I_{2\ TONE,\ dB} = 2\ (35\ dBm - (-5\ dBm))$$

$$C/I_{2\ TONE,\ dB} = 80\ dB$$

An important note to make is that this IIP3 power level is never measured directly because it is strictly a small signal linearity measurement. The IIP3 of a laser also does not follow the traditional relationship observed in amplifiers because it is roughly 10 dB above the 1 dB compression point. For lasers, the difference between these two powers is very dependent on both the frequency and the dc bias current. Additionally, some transmitters include predistorters, which specifically improve the IIP3 without necessarily affecting the 1 dB compression point. Once the IIP3 is determined, the spur-free dynamic range (SFDR) can be calculated. The SFDR corresponds to the case of a link transmitting two input signals of equal power. The SFDR is defined as the range of the two input signals in which the signals are above the noise floor and the third-order products are below the noise floor. Graphically, this is shown in Figure 13. If the noise floor is lowered either by using a quieter laser or by operating over a narrower frequency band then the SFDR will increase at a 2/3 rate, which is the difference between the slope of the output signal and distortion curves. In dB this gives: equation 27,

$$SFDR = 2/3\ (IIP3_{dBm} - Noise_{CHANNEL})\ (dB - BW)^{2/3}$$

$$SFDR = 2/3\ (IIP3_{dBm} - EIN_{dBm/Hz} - 10\log BW)\ (dB\text{-}Hz^{2/3})$$

For example, a link with an IIP3 of 35 dBm and an EIN of –130 dBm/Hz would have a SFDR of 110 dB-Hz2/3 over a 1 Hz bandwidth. If the same link had a bandwidth of 1 kHz, then its SFDR would be 90 dB-kHz2/3. The SFDR value that results from these calculations can be applied to either the input or output.

Large Number of Carriers

If a large number of carriers (or channels) are transmitted through a link, then, in certain situations, the distortion products can be higher than those predicted by the two-tone IIP3 and SFDR. In particular, when the input channels are evenly spaced, several different intermodulationtones may add together at the same frequency, creating a stronger third-order term than what would be produced by only two carriers. To approximate the increase in the C/I, the following equation is commonly used: equation 28,

$$C/I_{\mathrm{TOTAL,\,dB}} = C/I_{\mathrm{2\ TONE,\,dB}} - [6_{\mathrm{dB}} + 10\log(x)]$$

where x is a counting term that accounts for the overlap of intermods, and the 6 dB term normalizes the result to the two-tone case. This equation assumes that all of the input carriers are equally spaced, add in power (not voltage), and have equal powers. If they are not equally spaced, then the two-tone calculations of the section on Third-Order Intercept and Spur-Free Dynamic Range, page 13, will be more appropriate.

Table1.CarrierandCountingTermCalculations

Carriers	X	6 dB + 10 log (x)
2	0.25	0 dB
3	1	6 dB
4	2.3	9.6 dB
5	4.5	12.5 dB
6	7.5	14.8 dB
7	11.5	16.6 dB
8	15.5	17.9 dB
9	20	19.0 dB
10	26	20.1 dB
11	33	21.2 dB
12	40	22.0 dB
13	48	22.8 dB
14	57	23.6 dB
15	67	24.3 dB
16	77	24.9 dB
n > 16	~ (3/8) n2	6 dB + 10 log ((3/8) n2)

Placement of Amplifiers

For optical links that incorporate amplifiers, the amount of distortion produced will be affected by where the amplifiers are placed. Specifically, a trade-off must be made between the noise and distortion performance of the link. Placing an amplifier before the transmitter raises the signal above the noise floor and, therefore, lessens the noise figure of the link. However, if the amplification is too large, then the transmitter or the amplifier itself may begin to distort the signal. To avoid such distortion some intermediate level pre-amp is chosen appropriate to the given application. If necessary, another amp after the receiver can then be used to provide any additional gain.

EXAMPLE:

Consider an X-band antenna that needs to be remotely operated 5 km from the receiver electronics and has the following RF requirements:

Frequency range: 7.9 GHz to 8.4 GHz,

Five channels,

Channel width = 35 MHz,
$S_{\mathrm{CHANNEL,\,RF(MIN)}} = -60$ dBm,
$S_{\mathrm{CHANNEL,\,RF(MAX)}} = -35$ dBm,
SNR = 12 dB,
Total link gain = 0 dB,
Input and output impedances = 50 Ω.

Transmitter and Receiver Choice

Several transmitter/receiver pairs cover the range of interest. For this example, the minimum data sheet specifications for a typical DFB transmitter are used. (Because performance varies for different products, other values can be appropriate, depending on the specific transmitter chosen.)

$EIN_{\mathrm{LASER}} < -120$ dBm/Hz
$P_{\mathrm{LASER}} > 2.4$ mW
IIP3 > +25 dBm
$P_{1\,\mathrm{dB}} > +13$ dBm
dc modulation gain > 0.06 mW/mA

For the receiver, consider one that is resistively matched to 50 Ω and has no built-in amplifiers:

$R_{\mathrm{PD}} > 0.75$ mA/mW

$\eta_{\mathrm{Rx,\,RF}} > 0.375$ mA/mW

Throughout the example, these minimum specification values will be used with the understanding that the actual link would be expected to perform better than the final answers.

Gain

The first thing to consider is the gain. Since the transmitter is resistively matched for broadband operation, its RF efficiency will be approximately equal to the modulation gain of 0.06 mW/mA. The optical losses can be determined with:

equation 29,

$$L_{OPT,\ dB} = (\text{fiber length}) \bullet (\text{fiber attenuation}) + (\#\ \text{connectors}) \bullet (\text{connector loss})$$

$$L_{OPT,\ dB} = (5\ \text{km}) \cdot \left(\frac{0.4\ \text{dB (OPT)}}{\text{km}}\right) + (2) \cdot (0.5\ \text{dB max})$$

$$L_{OPT,\ dB} = 3\ \text{dB}.$$

Substituting these values into equation 4 on page 6 gives for the gain of the optical transmitter, receiver, and fiber:

equation 30,

$$G_{OPTICAL\ LINK} = 20\log(\eta_{Tx,\ RF}(\eta_{Rx,\ RF}) - 2\ L_{OPT,\ dB} + 10\log(R_{OUT}/R_{IN})$$

$$G_{OPTICAL\ LINK} = 20\log\left[(0.06\ \text{mW/mA})(0.375\ \text{mA/mW})\right] - 2 \times 3\ \text{dB} + 0$$

$$G_{OPTICAL\ LINK} = -39\ \text{dB}.$$

Alternatively, this value could have been read directly off of the gain curves in the Appendix. To offset this loss, amplifiers must be added prior to the transmitter and/or after the receiver. The placement of the amps will affect both the noise performance and distortion, as described below.

Noise

Before calculating the noise of the optical link, the overall link requirements should be converted into a noise figure. Due to the SNR requirement of 12 dB, the minimum detectable signal will need to be –72 dBm (i.e., –60 dBm – 12 dB). Therefore, the total noise in any given channel bandwidth must be less than –72 dBm. A rearranged equation 22 on page 12 can then be used to determine the maximum acceptable EIN:

equation 31,

$$EIN_{TOTAL\ LINK} = NOISE_{CHANNEL} - BW_{dB,\ Hz}$$

$$EIN_{TOTAL\ LINK} < -72\ \text{dBm} - 10\log(35 \times 10^{6})$$

$$EIN_{TOTAL\ LINK} < -147\ \text{dBm/Hz}.$$

Converting this to a noise figure with equation 12 on page 9 gives:

$$NF_{TOTAL\ LINK} = EIN + 174\ \text{dBm/Hz}$$

$$NF_{TOTAL\ LINK} < -147\ \text{dBm/Hz} + 174\ \text{dBm/Hz}$$

$$NF_{TOTAL\ LINK} < 27\ \text{dB}.$$

Now, the actual performance of the optical link can computed. The performance curves resented in the appendix (or equations 15, 17, and 18 on page 10) predict that the above specified transmitter and receiver pair, with an optical loss of 3 dB, will have a NF of better than approximately:

$$NF_{OPTICAL\ LINK} = 54\ \text{dB}.$$

The preamplifier and postamplifier also will affect the total link NF. If, for example, the selected components are a preamp with a gain of 30 dB and an NF of 5 dB, and a postamp with a gain of 9 dB and an NF of 6 dB, then Friis' formula (equation 19 on page 11) can be used to cascade the noise figures. First, the optical link and the postamp should be cascaded as follows:

equation 32,

$$NF_{OPTICAL\ LINK\ AND\ POSTAMP} = NF_{OPTICALLINK,\ RATIO} + \frac{(NF_{POSTAMP,\ RATIO} - 1)}{G_{OPTICAL\ LINK,\ RATIO}}$$

$$NF_{OPTICAL\ LINK\ AND\ POSTAMP} = 0^{\left(\frac{54\ \text{dB}}{10}\right)} + \frac{(10^{\left(\frac{6\ \text{dB}}{10}\right)} - 1)}{10^{\left(\frac{-39\ \text{dB}}{10}\right)}}$$

$$NF_{OPTICAL\ LINK\ AND\ POSTAMP} = 275{,}000 = 54.4\ \text{dB}.$$

Next, the result can be cascaded with the NF of the preamp:

$$NF_{TOTAL\ LINK} = NF_{PREAMP,\ RATIO} + \frac{(NF_{OPTICAL\ LINK\ AND\ POSTAMP} - 1}{G_{PREAMP}}$$

$$NF_{TOTAL\ LINK} = 10^{\left(\frac{5\ \text{dB}}{10}\right)} + \left(\frac{275,000 - 1}{10^{\left(\frac{30\text{dB}}{10}\right)}}\right)$$

$$F_{OPTICAL\ LINK} = 278 = 24.4\ \text{dB}.$$

Thus, the link satisfies the 27 dB NF requirement.

Dynamic Range

Next, it must be ensured that the maximum signals do not saturate the transmitter. With the 30 dB preamp chosen, the maximum input per channel to the optical transmitter would be:

$$S_{\text{CHANNEL, Tx (MAX)}} = -35\text{ dBm} + 30\text{ dB}$$

$$S_{\text{CHANNEL, Tx (MAX)}} = -5\text{ dBm}$$

Since there are five channels, the total RF power into the transmitter is:

$$S_{\text{TOTAL, Tx (MAX)}} = -5\text{ dBm} + 10\log(5)$$

$$S_{\text{TOTAL, Tx (MAX)}} = 2\text{ dBm}$$

The 1 dB compression of the laser is greater than 13 dBm, therefore, the optical link has at least another 11 dB of dynamic range before the laser transmitter begins to clip significantly. (Alternatively, a rough check of the dynamic range of only the optical portion of the link without any amplifiers can be calculated quickly with equation 24 on page 13.)

The dynamic range requirements of the entire application are:

equation 33,

$$DR_{\text{1dB}} = P_{\text{1dB}} - EIN_{\text{dBm/Hz}} - BW_{\text{dB, Hz}}$$

$$DR_{\text{1dB}} = +13\text{ dBm} - (-120\text{ dBm/Hz}) - 10\log(35 \times 10^{6})$$

$$DR_{\text{1dB}} = 57\text{ dB}$$

This quick calculation indicates that, by adding a preamplifier with an appropriate gain and reasonable noise, the optical link can satisfy the dynamic range requirements of the application for a single channel input.

$$DR_{\text{APPLICATION}} = [S_{\text{CHANNEL, RF (MAX)}} - S_{\text{CHANNEL, RF (MIN)}}] + SNR$$

$$DR_{\text{APPLICATION}} = [-35\text{ dBm} - (-60\text{ dBm})] + 12\text{ dB}$$

$$DR_{\text{APPLICATION}} = 37\text{ dB}$$

Distortion

For a multitone input, the third-order intermodulation terms must not interfere with other signals. As a quick check of such distortion, the spur-free dynamic range can be calculated:

equation 34,

$$SFDR = 2/3\,(IIP3_{\text{dBm}} - EIN_{\text{dBm/Hz}} - 10\log BW)$$

$$SFDR = 2/3\,(+25\text{ dBm} - (-120\text{ dBm/Hz}) - 10\log(35 \times 10^{6}\text{ Hz}))$$

$$SFDR = 47\text{ dB}$$

which again indicates that with the correct choice of a preamp, the optical link can satisfy the 37 dB dynamic range calculated above.

To verify that the amplifier chosen is correct, the actual power of the intermodulation terms can be calculated using equation 25 on page 14:

$$C/I_{\text{2 TONE}} = 2\,(IIP3 - S_{\text{CHANNEL, Tx (MAX)}})$$

$$C/I_{\text{2 TONE}} > 2\,(25\text{ dBm} - (-5\text{ dBm}))$$

$$C/I_{\text{2 TONE}} > 60\text{ dB}$$

This corresponds to an intermodulation signal level of:

$$I_{\text{2 TONE}} <= S_{\text{CHANNEL, Tx(MAX)}} - C/I_{\text{2 TONE}}$$

$$I_{\text{2 TONE}} < < -5\text{ dBm} - 60\text{ dB}$$

$$I_{\text{2 TONE}} < -65\text{ dBm}$$

The distortion can then be compared with the lowest power signal at the transmitter input. Although the sensitivity of the total link needs to be better than –72 dBm, at the transmitter the minimum input signal will be 30 dB higher due to the preamp:

$$S_{\text{CHANNEL, Tx (MIN)}} = -72\text{ dBm} + 30\text{ dB}$$

$$S_{\text{CHANNEL, Tx (MIN)}} = -42\text{ dBm}$$

Since I2 TONE is well below this lowest input signal of –42 dBm, two tones of –5 dBm in each can be input into the transmitter without creating third-order distortion terms above the noise floor.

Distortion (continued)

Alternatively, if the input signal of all five channels wer- raised equally to the maximum, and if they were equally spaced in frequency, then their intermodulation products could accumulate, as described in the section on Large Number of Carriers, page 15.

Using the counting factor of equation 28 on page 15, the C/I would decrease by 12.5 dB:

$$C/I_{5\ \text{CHANNELS}} = C/I_{2\ \text{TONE}} - [6\text{ dB} + 10\log(x)]$$

$$C/I_{5\ \text{CHANNELS}} = 60\text{ dB} - 12.5\text{ dB}$$

$$C/I_{5\ \text{CHANNELs}} = 47.5\text{ dB}$$

Similarly, the intermodulation term would increase by 12.5 dB to:

$$I_{5\ \text{CHANNELS}} = -5\text{ dBm} - 47.5\text{ dB}$$

$$I_{5\ \text{CHANNELS}} = -52.5\text{ dBm}$$

The result is still better than the minimum detectable signal of –45 dBm. (In fact, for this case, the –45 dBm is more demanding than necessary. Since it was assumed that all the channels were raised to the same power, the lowest power signals that would need to be detected would be within the SNR of the carrier power level. Since the SNR is only 12 dB, the C/I5 CHANNELS of 47.5 dB far exceed the linearity requirements of this application.) In summary, the above described link should work well in remoting an X-band antenna.

Although Ortel does not manufacture optical fiber cable, the performance of the transmitters and receivers in linear fiber-optic links depends on the characteristics of the optical fiber being used. The chief parameters for the cable are wavelength, loss, dispersion, ruggedization, and connectorization.

Wavelength and Loss

The fundamental part of an optical fiber consists of an inner core and an outer cladding of glass, as shown in Figure 14. When light is launched in this inner core at a low enough angle, it will remain trapped by the effect of total internal reflection and propagate down the length of the fiber. Total internal reflection occurs because the inner core is composed of a glass with a slightly higher index of refraction than that of the outer cladding. While propagating down the fiber, some of the light is lost due to optical absorption from impurities in the glass, scattering from non-uniformities in the material, and bend loss (when the fiber bend radius is smaller than roughly 1 inch). The unavoidable scattering and absorption losses depend on the wavelength of the light, as shown in Figure 15. Due to the two minima of this curve, the most common fiber wavelengths used today are 1310 nm and 1550 nm, although some 840 nm fiber is still used for some less demanding applications. Typically, the loss in single-mode fiber at 1310 nm fiber is less than 0.4 dB/km; and at 1550 nm, 0.25 dB/km.

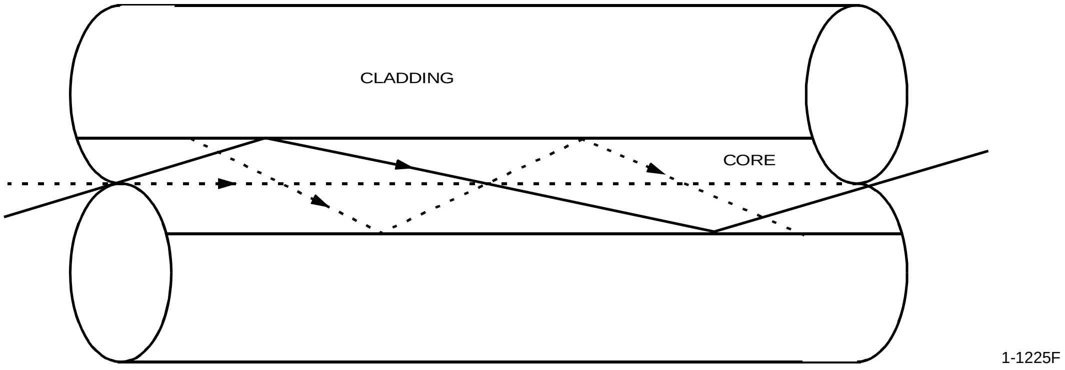

Figure 14. Precise Indices of Refractions Enables Total Internal Reflection in Optical Fiber

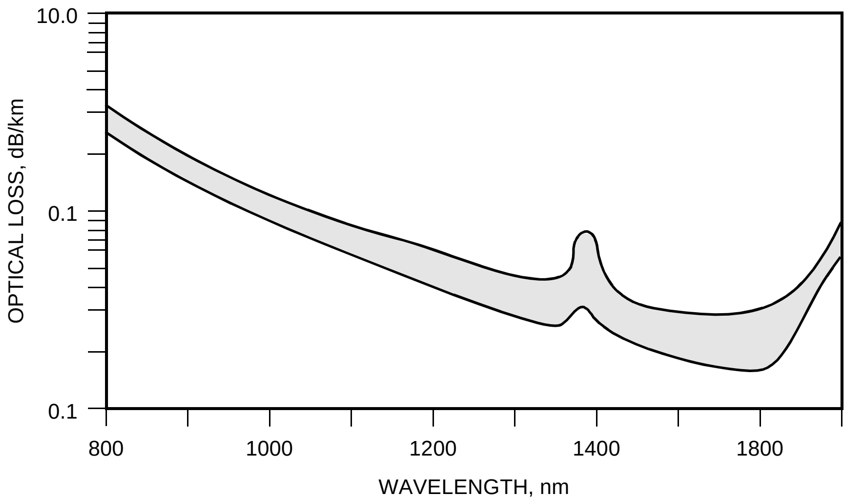

Figure 15. Scattering and Absorption Losses vs. Wavelength

Dispersion

In addition to loss, a given fiber will have a characteristic dispersion, which also depends on the wavelength of the optical signal. If a square pulse of light is launched into a fiber, it will emerge at the end somewhat rounded and broadened due to a combination of chromatic dispersion (wavelength spreading) and modal dispersion. This modal dispersion occurs in multimode fibers, such as the one shown in Figure 14 on page 19. These fibers have cores with diameters 50 µm or larger, which allow light to follow a number of different paths, each with differing lengths and transit times. An optical signal that is sent down such a fiber will therefore break up into some combination of these modes and become smeared out by the time it reaches the end of the fiber. To avoid this dispersion problem of multimode fiber, single-mode fiber is always used for Lucent's fiberoptic links. Single-mode fiber has a core with a typical diameter of 9 µm, which allows only a single spatial mode to propagate straight down the center. This single transverse mode also will experience some chromatic dispersion, albeit much smaller than modal dispersion due to the fact that light of different wavelengths travels at different speeds in a fiber. Figure 16 shows the wavelength dependency of this dispersion for standard telecommunication fiber and for special dispersion shifted fiber. Roughly 90% of fiber presently installed is the standard type centered at 1310 nm. The bandwidth limit due to dispersion is given approximately by:
equation 35,

$$BW = \lambda\ 1/(2s\cdot\eta(L))$$

where s is the fiber dispersion coefficient in ps/(kmnm), λ is the wavelength spread of the optical signal, and L is the length of the fiber. This wavelength spread includes both the intrinsic linewidth of the unmodulated laser and any additional wavelength chirp which may result from modulating the laser. (This chirp will be discussed more fully in the section on Distributed-Feedback (DFB) vs. Fabry-Perot (FP) Lasers, page 25.) As an example, a laser with a spectral width of 1 nm transmitting down a 10 km fiber with a dispersion coefficient of 5 ps/km-nm would produce a blurred output for signals faster than 10 GHz. In most cases, this chromatic dispersion is not a limitation for single-mode DFB transmitters used with fiber of the correct wavelength.

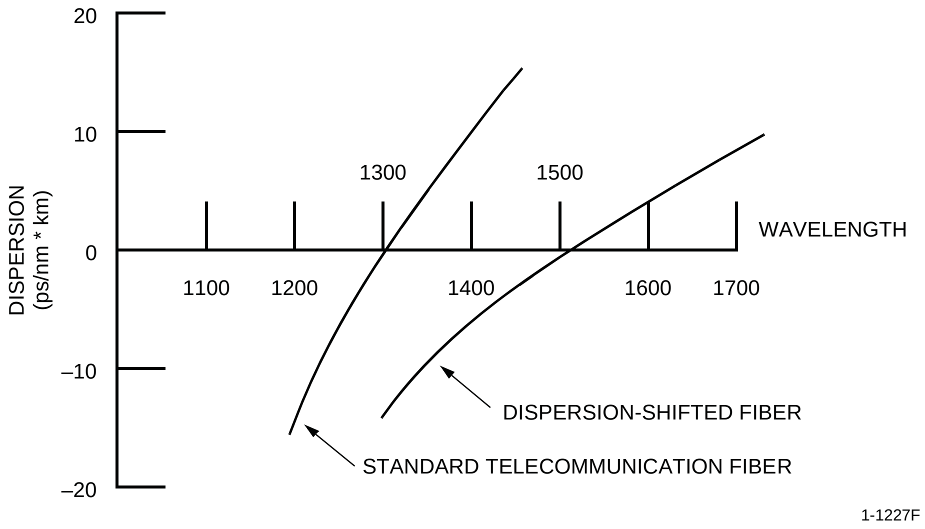

Figure16.WavelengthDependencyofDispersionforStandardandDispersion-ShiftedFIber

Ruggedization

Once a particular fiber is chosen, the cable style must be appropriately specified for the application. One of the more popular styles is the ruggedized simplex shown in Figure 17. In this fiber, the 9 µm diameter core is surrounded by a 125 µm cladding of glass. Next, a coating typically 250 µm in diameter is applied to help keep water and other impurities from a layer of nylon up to 900 µm in diameter and a layer of Kevlar * strands to provide extra strength. Finally, the entire assembly is surrounded by a roughly 3 mm diameter yellow PVC jacket. While simplex cable is convenient for indoor applications, for long haul applications exposed to weather more rugged designs featuring additional water resistant layers and more heavily armored jackets are typically used. These cables may contain anywhere from 2 to 200 fibers.

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* Kevlar is a registered trademark of E. I. du Pont de Nemours and Co.

Fusion Splice

Several techniques are commonly used to connect fibers and components. The lowest loss and lowest reflection method is a fusion splice. In this approach, the ends of two fibers are precisely lined up under a microscope and thermally fused together to produce a nearly seamless connection. Typical optical losses are less than 0.1 dB.

Mechanical Splices

Mechanical splices also can be used. A number of varieties exist which generally involve cleaving the fiber and guiding the fiber ends together in a capillary tube. Once aligned, the fibers are glued or mechanically held in place. To improve the reflection characteristics, an index matching gel fills any gap between the fiber tips. While mechanical splices are fairly inexpensive and are easier to use than fusion splicing equipment, usually losses of 0.5 dB to 1 dB are observed. These losses also may vary significantly if the temperature is changed.

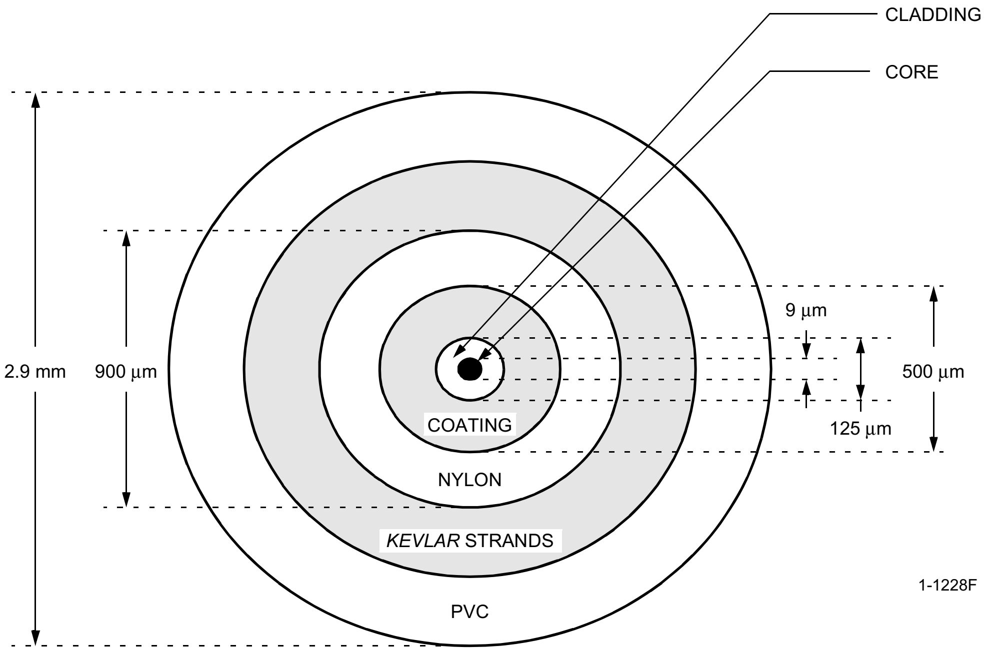


Figure17.CrossSectionofTypicalRuggedized,SimplexCable

Connectors

Perhaps the easiest method for joining fibers, which also produces good results, is reusable connectors. Although a wide variety of connectors have been developed for fibers, only a few are appropriate for analog fiber optic applications. One of the best performers is the FC/APC (angle physical contact) style of connectors. In this connector, the fiber is glued inside of a precise ferrule and then polished at an angle of 8°. When two appropriately keyed connectors are brought together in a mating sleeve, this angle steers the majority of any reflected light out of the fiber. As a result the return loss of APC connectors is typically better than –60 dB.

Another popular set of connectors are the FC/PC (physical contact) and FC/SPC (super PC). These connectors are identical to the FC/APC except that the polish on the end of the ferrule is not angled. Instead, the ferrule is polished to form a convex surface so when two connectors are mated, the centers of their tips physically contact each other to provide a smooth optical path. Depending on the quality of the polish, which is indicated by the PC or SPC name, the optical back reflections are better than –30 dB or –40 dB, respectively.

Although this return loss is acceptable for many applications, if a speck of dust separates the connectors slightly, then the reflections increase dramatically, which can degrade the performance of a link.

In contrast, if a pair of APC connectors is separated slightly, then the reflected light in the fiber core will still remain low due to the angle of the polish. Therefore, it is recommended that angle-polished connectors be used whenever possible with Ortel links to ensure best performance. The following table summarizes typical performance of FC connectors, although performance will vary for different manufacturers.

Table2.FCConnectorPerformance

Connector Type	Back Reflections	Insertion Loss
FC/PC	< –30 dB	< 0.5 dB, 0.25 dB typ
FC/SPC	< –40 dB	< 0.5 dB, 0.25 dB typ
FC/APC	< –60 dB	< 0.5 dB, 0.25 dB typ

To achieve the performance described above, the connectors must be kept clean and free from scratches. To clean a connector, gently wipe it with a cotton swab wetted with isopropyl alcohol and then dry it with dustfree compressed air (available in convenient cans).

Reflections and Laser Noise

The care that is taken in selecting low-reflection optical connectors and fiber components minimizes several phenomena that can degrade the performance of an analog fiber-optic link. The most noticeable effect of optical back reflections are those that destabilize the laser itself. If a large amount of light is reflected from a discrete component, then the laser output will include periodic spikes, as shown in Figure 18. This noiseenhancement can be as much as 30 to 40 dB, which is unacceptable for most applications. If the source of reflections is due to unavoidable Rayleigh scattering in long optical fibers rather than distinct reflectors (such as poor connectors), then the entire noise spectrum is enhanced without any spiky features. Although Rayleigh scattering is small (evidenced by the low loss of fiber of 0.4 dB/km), backscattered light can accumulate over a long length of fiber. Even reflections as low as –70 dB can cause noticeable noise enhancement. Since Rayleigh reflections are inevitable, high-performance transmitters incorporate optical isolators to block any returning light. The section on Additional Transmitter Considerations, page 25, describes the integration of such isolators in transmitters.

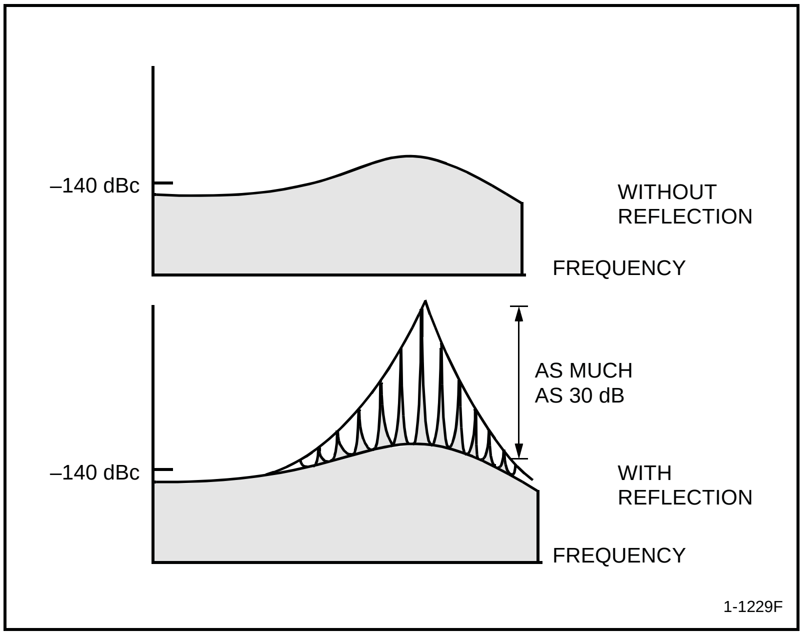


Figure18.PeriodicSpikesCanDegradePerformanceinAnalogFiber-OpticLinks

Reflections and Interferometric Noise

Even with an optical isolator, care must be taken to minimize reflections from connectors or optical splitters because of the effect of interferometric noise. In fiberoptic links, the signal that arrives at the photodetector is a combination of the primary signal plus a low-level signal that is the result of reflections and re-reflections throughout the length of the fiber. These various doubly reflected versions of the primary signal mix electrically with the signal and cause excess noise. The total amount of this noise depends on the percentage of doubly reflected light, which can be significant for discrete reflections from poor connectors, splices, or other optical components.

As an example of how interferometric noise is avoided, the spare fibers from an optical splitter in Figure 19 are polished at an angle to provide a clean optical termination. If this were not done, some of the laser light would be reflected from the termination, pass back through the optical splitter, reflect off the termination near the laser, pass again through the splitter, finally striking the receivers to create noise. When such discrete reflections are eliminated by careful design practices, then only the much smaller effects of Rayleigh scattering remains.

Polarization Mode Dispersion

The fiber itself can also distort a signal by the effect of polarization-mode dispersion. This problem tends to occur only in some older fibers that were not manufactured to the higher-quality standards used today. For newer fibers this should not be an issue.

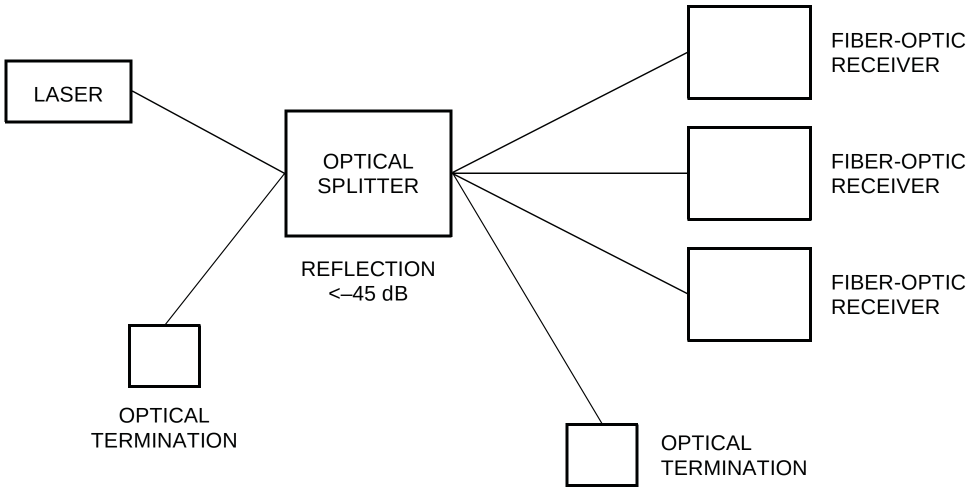


Figure 19. Low-Reflection Components (Terminators and Optical Noise Splitters) Help To Avoid Interferometric Noise

Optical Attenuators

Once a fiber and style of connector have been chosen, a link also might need optical attenuators, as mentioned in section on Laser Noise, page 9. For a short link, the power from the laser can be high enough at the receiver to saturate or damage the photodetector. In these cases where an attenuator is needed, it should be chosen to provide sufficient attenuation for the maximum laser power, which may be significantly more than the minimum specified on the data sheet. The attenuator also should have a low back reflection to avoid creating noise.

The section on Link Design Calculations, page 5, discusses the basic equations necessary to predict the performance of a link based on the values available in the data sheets. Although for many applications this information should be sufficient to allow for a good choice of components, this section discusses a few of the more subtle considerations that can affect the performance of a given link.

Additional Transmitter Considerations

Optical Isolators

One of the simplest methods to improve the performance of a laser is the use of an optical isolator. These isolators take advantage of a phenomenon known as the Faraday effect to pass light in one direction, but block light in the other direction. Moreover, they can be made small enough to be incorporated into the laser module itself.

The more common isolator used in Ortel transmitters is a single-stage isolator, which provides approximately 35 dB of isolation. For systems requiring long lengths of fiber or exceptionally good noise performance a 1.5 stage isolator can be used instead, which provides approximately 50 dB of isolation.

Alternatively, many applications that have lower noise requirements and less reflection do not require the use of a discrete isolator. Some isolation is still needed even in these applications, so lasers without isolators are purposely fiber-coupled with lower efficiency to help attenuate any reflected light. As a result, the gain of transmitters using isolators is higher than those without isolators.

Distributed-Feedback (DFB) vs. Fabry-Perot (FP) Lasers

Of the two types of laser diodes used in analog fiberoptic links, DFBs provide superior performance for lownoise, high dynamic range systems. Fabry-Perot type lasers provide a more economical alternative for less demanding applications. A DFB laser is a special type of laser diode designed to operate in a single longitudinal mode (optical frequency), as compared to a conventional F-P laser, which typically lases in many longitudinal modes (i.e., wavelengths) at once. DFB lasers acquire this singlemode behavior because of a grating structure in the laser chip design. The resulting single-mode output is therefore immune to chromatic dispersion and allows for wider bandwidths over longer fibers than can be achieved with F-P lasers. DFBs are clearly superior for longer distances. For comparably shorter distances, however, it might appear that F-P lasers would perform as well despite their multimode pattern, since bandwidth spreading due to chromatic dispersion would be small. In fact, this is not the case due to the effect of mode partition noise present with F-P lasers (see the section on Unconverted Noise and SNR, page 12). In an F-P laser, power constantly shifts between the modes in such a way that the total power remains relatively constant. Therefore, when the total optical power is detected directly from an F-P transmitter, little noise is observed. However, when propagated in a fiber, dispersion causes the modes to walk off in time relative to one another. The modes' fluctuations now no longer compensate for one another and the total optical power shows fluctuations originating from this power exchange process. The resulting noise occurs at a low frequency, but is upconverted to higher frequencies when a modulating signal is present. Besides this noise, low-frequency mode-hopping noise can manifest itself directly from the FP, even without fiber dispersion.

Distributed-Feedback (DFB) vs. Fabry-Perot (FP) Lasers (continued)

For single-frequency lasers such as DFBs, both modepartition and mode-hopping noises are absent. Figure 20 shows how this noise affects the comparative performance of F-P and DFB lasers. Of particular note for the F-P is the dramatic increase in the noise level near the signal for longer lengths of fiber. When the signal modulation is turned off, this noise disappears as shown in the clean spots in the Figure 20. In contrast, sideband noise is negligible for DFB lasers with and without modulation and for distances as long as 20 km. The only additional noise for the DFB is the comparably small interferometric noise from Rayleigh scattering.

Predistortion

While DFB lasers provide intrinsically high dynamic ranges because of their low noise and distortion, their performance is improved still further for some transmitters by adding predistortion electronics. Predistortion is a linearization technique that has been known for many years in the fields of RF and microwave electronics. With predistortion, the RF signals are first passed through a device carefully designed to generate distortion, which is equal in amplitude and opposite in sign to that produced by the primary device (the laser in this case).

The original RF signals plus the distortion signals are then applied to the primary device. The distortion generated by the primary device will then cancel the injected distortion, resulting in a highly linear output signal.

The challenge for linearizing DFB lasers is that the distortion is often strongly frequency-dependent and is often not strictly in phase or 180° out of phase with the input signals. Ortel has pioneered the development of predistortion circuits to linearize devices with complex distortion characteristics, such as DFB lasers. The complex nature of the nonlinearities of DFB lasers does not limit the effectiveness of predistortion, but it is necessary to generate a similarly complex distortion signal to linearize the DFB lasers.

1310 nm vs. 1550 nm Wavelengths

Recently, DFB lasers also have been developed for the 1550 nm wavelength to complement the capabilities of established 1310 nm systems. The strongest advantage of 1550 nm is its lower attenuation in single-mode fiber, as shown in Figure 15 on page 19 and in Table 3. For a given input power, a 1550 nm signal can travel approximately 60% farther in a fiber than a similar 1310 nm signal can. This is especially advantageous in long links or delay lines. However, since 1310 nm lasers can produce more power than can 1550 nm lasers, shorter links still favor 1310 nm transmitters.

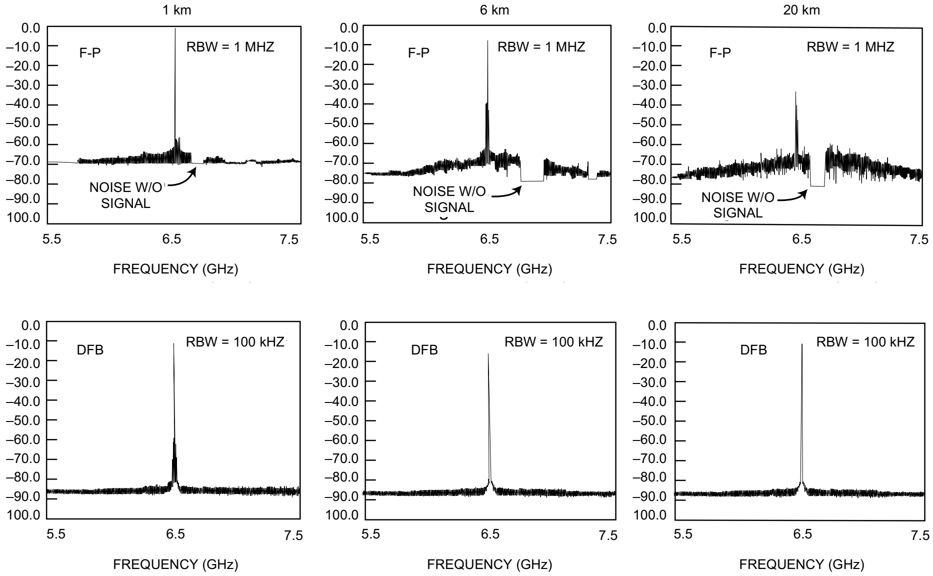


Figure20.ComparativeNoisePerformanceforDFBandF-PLasers

1310 nm vs. 1550 nm Wavelengths (continued)

Table3.Comparisonof1310nmand1550nmFiber-OpticLinks

Parameter	1310 nm	1550 nm
Fiber Attenuation	0.4 dB/km	0.25 dB/km
Fiber Dispersion	Nearly Zero	Zero Only for Special Fiber
Laser Chirp	Lower	Higher
Power	Higher	Lower
Noise	Lower	Higher
Optical Amps	Laboratory Based	Commercially Mature

Another advantage of 1310 nm lasers is the zero dispersion point in single-mode fibers, which naturally occurs near this wavelength. For lasers with wide optical bandwidths, chromatic dispersion (see the section on Dispersion, page 20) will limit the transmission distance for high frequency 1550 nm systems using standard single-mode fiber. By using a single wavelength 1550 nm laser and/or special dispersion-shifted fiber, this particular limit usually can be overcome. Even with single-frequency DFBs at 1550 nm, the high dispersion of standard fiber can still pose a problem at this wavelength due to laser chirp. When the intensity of the light from a DFB is modulated, the optical frequency (wavelength) is inadvertently modulated as well. As light from such a modulated laser travels down the fiber, the portions of the signal corresponding to different wavelengths will travel at different speeds due to the chromatic dispersion of the fiber. By the time the signal reaches the receiver, these various wavelengths will be spread out in proportion to both the intensity of the modulating signal and the value of the fiber dispersion. This leads primarily to second-order distortion, which increases as the square of the frequency of the distortion products.

A 1550 nm laser transmitting down a sufficiently long length of standard single-mode fiber intended for 1310 nm will therefore have higher distortion products than a similar 1310 nm laser. In fact, even with dispersion-shifted fiber intended for 1550 nm, both the distortion and the noise of a 1550 nm laser will be worse than that for a 1310 nm laser transmitting down a standardfiber due to the fact that presently 1310 nm lasers have inherently lower chirp and noise than comparable 1550 nm lasers.

While 1310 nm lasers have better noise and distortion performance than 1550 nm lasers, 1550 nm lasers have a different advantage in their capability to be used with optical amplifiers. Such amplifiers increase the power of an optical signal without the need for traditional repeaters, which convert the light to an RF signal, amplify it electrically, and then reconvert it back into light. Due to the physics of the materials used in these fiber-optic amplifiers, 1550 nm amplifies much better than does 1310 nm, therefore nearly all systems incorporating optical amplifiers are designed for 1550 nm.

Another application where 1550 nm lasers complement 1310 nm lasers is in wavelength-division multiplexing (WDM). In WDM, a single fiber can be used to send two sets of signals, one at 1310 nm and the other at 1550 nm. By using wavelength-selective components, these signals can be separated from each other and returned to their original RF format. This type of application is especially popular where the cost of laying additional fibers is prohibitive. In a typical implementation, a 1550 nm transmitter sends a signal on a fiber to a remote antenna where another transmitter at 1310 nm sends a return signal down the same fiber back to the base station.

Summary

In this guide, the primary technical issues involved in using Ortel's linear fiber-optic links are discussed. By taking advantage of the high performance and reliability of solid-state transmitters and receivers, and the low loss and high bandwidth of optical fibers, a diverse set of applications has been enabled, including RF and microwave antenna remoting, broadband CATV distribution, and compact optical delay lines. In addition, due to the modularity of these fundamental optical components, other forthcoming RF and microwave applications can be expected to take advantage of these capabilities as well.

Performance Characteristics

Gain

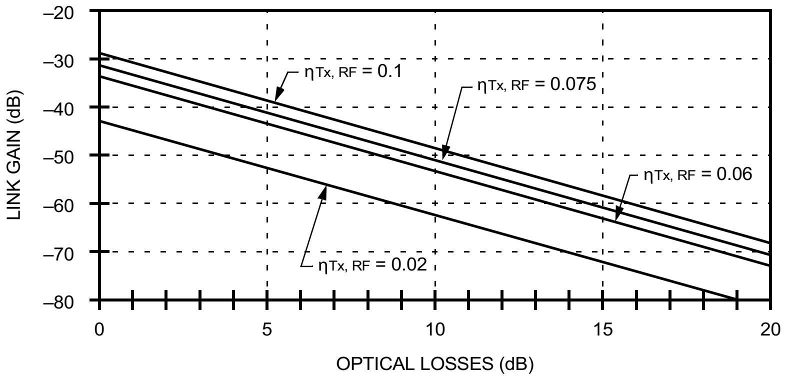
The following curves are calculated from the gain equation below. In all cases, the links are assumed to have ROUT = RIN.

$$G_{LINK,\,dB} = 20\log\underbrace{(\eta_{Tx\,RF})(\eta_{Rx,\,RF})}_{\text{Electrical/Optical Efficiency}} - \underbrace{2L_{O,\,dB}}_{\text{Optical Loss}} + \underbrace{10\log(R_{OUT}/R_{IN})}_{\text{Impedance Difference}}$$

Where

$\eta_{Tx,\,RF}$ = transmitter RF efficiency (mW/mA),
$\eta_{Rx,\,RF}$ = receiver RF efficiency (mW/mA),
R_{PD} = photodiode responsivity (mW/mA),
$2L_{O,\,dB}$ = optical losses in dB
R_{OUT} = output impedance
R_{IN} = input impedance

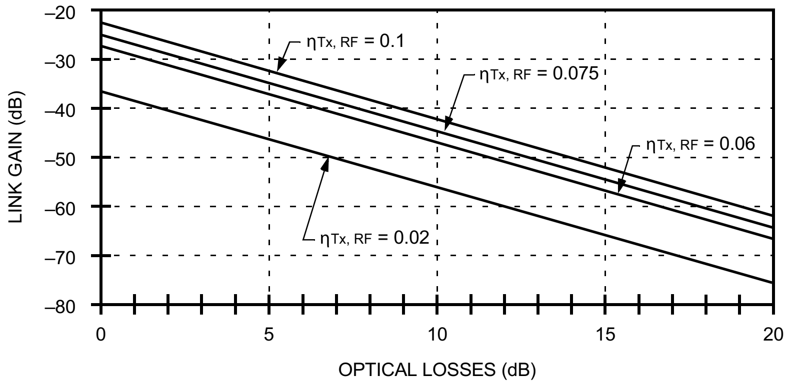
For some receivers, in cases where a link is too short, it might be necessary to add optical attenuators to prevent damage to the photodiode, which thereby determines a minimum optical loss for a given transmitter/receiver pair. Reactively matched or amplified transmitters and receivers provide higher gain due to these extra components. To calculate the total gain for such links, use the unmatched or unamplified efficiencies then add the improvement specified in the data sheet.



Note: R_{PD} = 0.75; $\eta_{RX,\,RF}$ = 0.375.

1-1119F

Figure21.GainCurve1,ResistivelyMatchedPhotodiodefor50Ω

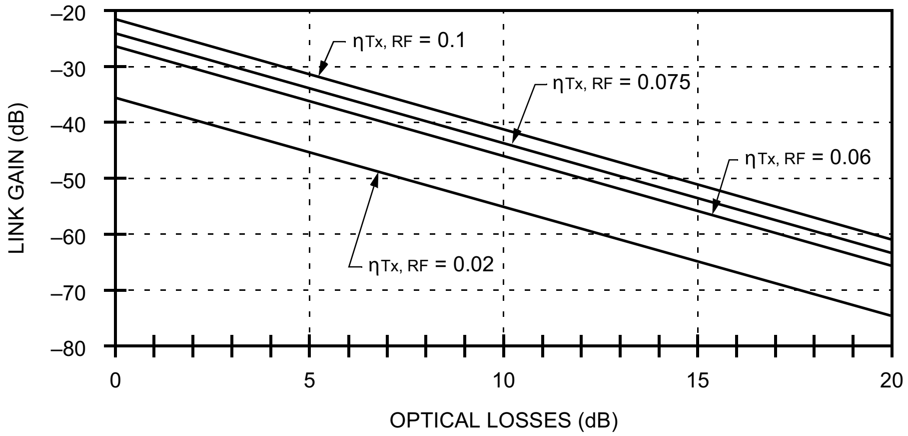


Note: R_{PD} = 0.75; $\eta_{RX,\,RF}$ = 0.75.

1-1120F

Figure22.GainCurve2,UnmatchedPhotodiode

Gain (continued)

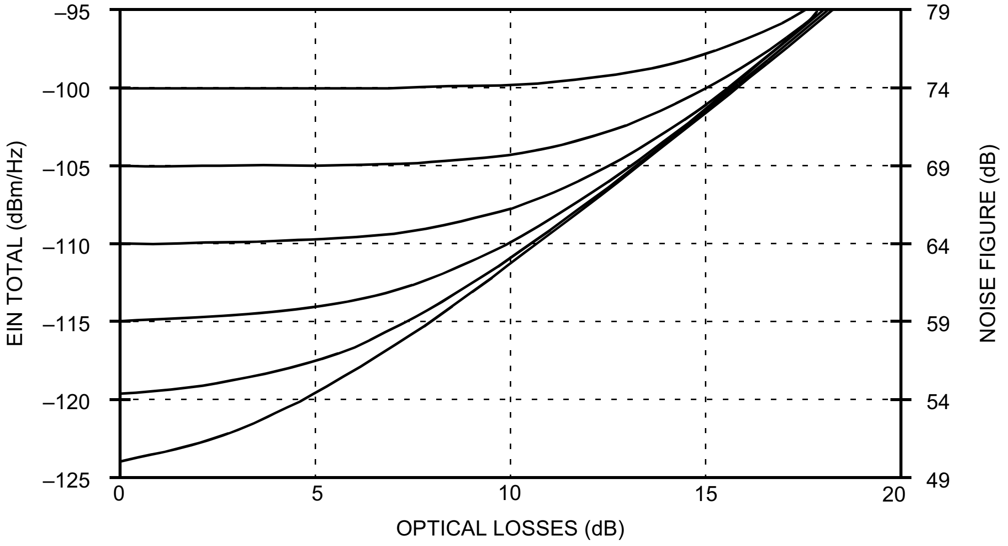


Note: RPD = 0.85; ηRX, RF = 0.85.

Figure21.GainCurve1,ResistivelyMatchedPhotodiodefor50Ω

Total Link Noise

The following equivalent input noise (EIN) curves represent the combined effect of shot noise, receiver thermal noise, and laser noise when referenced to the input of the transmitter. Neither fiber-induced effects nor up-converted noise, most notably mode-partition noise for Fabry-Perot lasers, are accounted for in these calculations. To find the EIN or noise figure for a given link, first determine the appropriate set of curves based on the transmitter and receiver efficiencies and the laser power. Next, determine the EIN of the transmitter for the frequency of interest and locate the appropriate curve. Each curve below corresponds to a specific laser EIN, separated by increments of 5 dB, and corresponds to the value at the intersection of the left axis. (For 0 dB, optical losses, the total EIN is approximately equal to the EIN of only the laser.) For example, if a transmitter and receiver corresponds to Noise Curve 1, and if the transmitter EIN is –110 dBm/Hz and the optical link losses are 10 dB, then the graph predicts an EIN for the complete optical link of –107.5 dBm/Hz and a noise figure of (NF) of 66.5 dB.

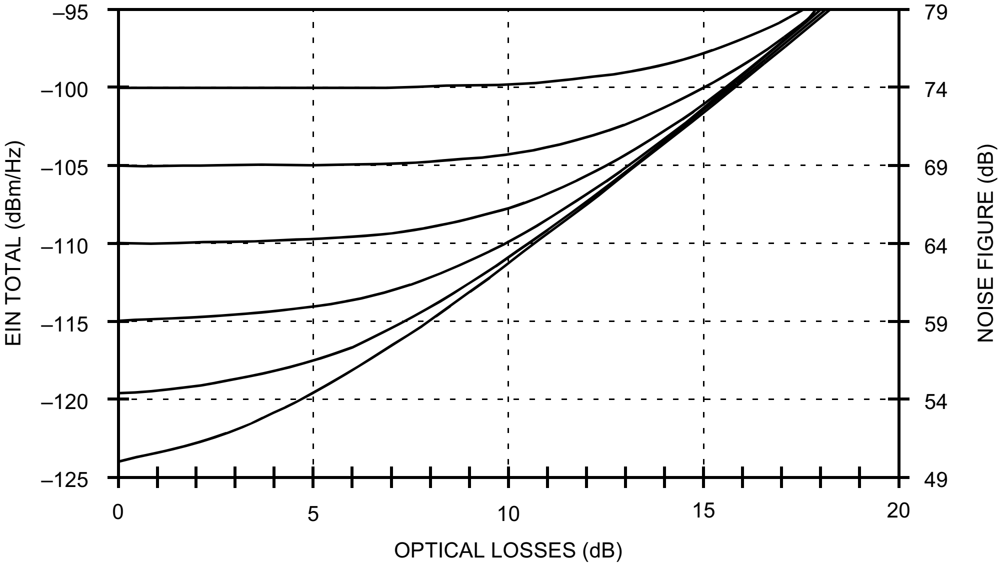


Note: ηTx, RF = 0.02 mW/mA; PLASER = 0.4 mW; ηRx, RF = 0.375 mA/mW; RPD = 0.75 mA/mW.

1-1122F

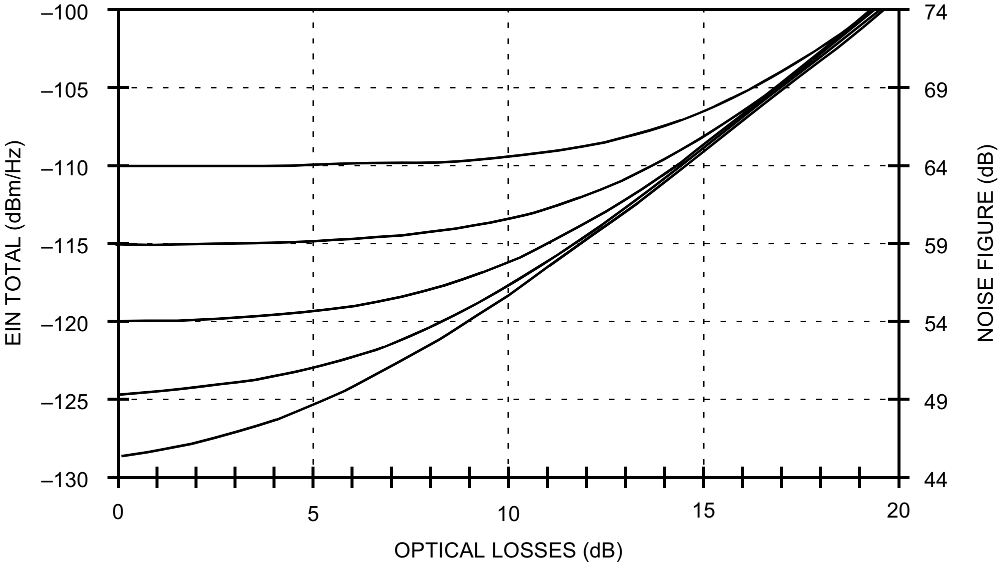
Figure24.NoiseCurve1,EquivalentInputNoisevs.OpticalLosses

Total Link Noise (continued)



Note: $\eta_{Tx, RF}$ = 0.02 mW/mA; P_{LASER} = 0.8 mW; $\eta_{Rx, RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1123F

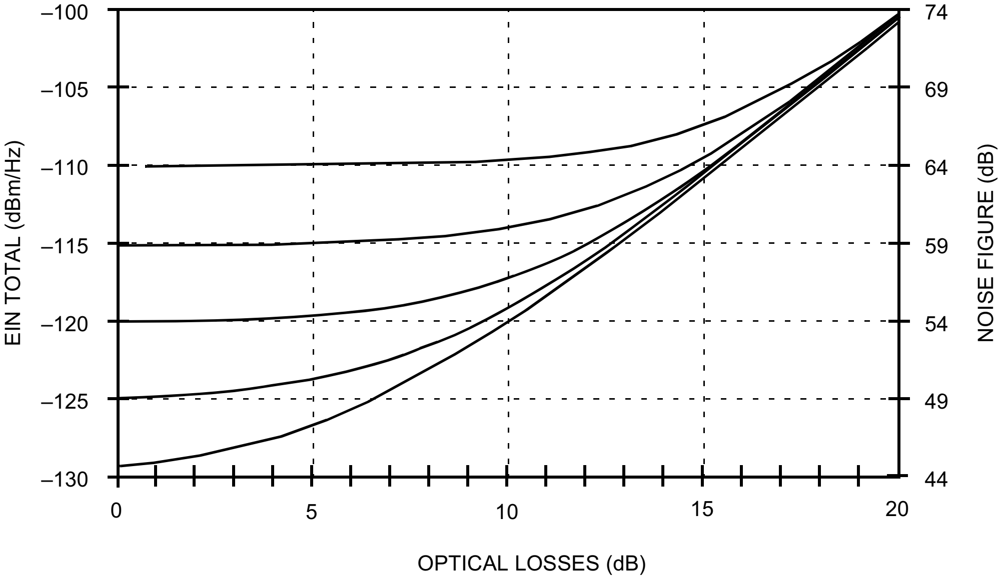
Figure25.NoiseCurve2,EquivalentInputNoisevs.OpticalLosses



Note: $\eta_{Tx, RF}$ = 0.05 mW/mA; P_{LASER} = 3.0 mW; $\eta_{Rx, RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1124F

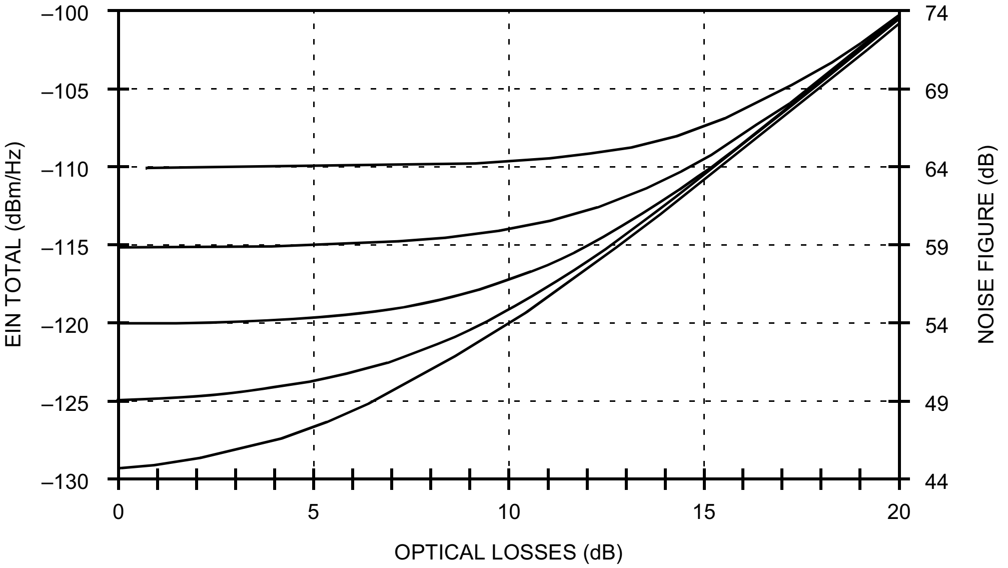
Figure26.NoiseCurve3,EquivalentInputNoisevs.OpticalLosses

Total Link Noise (continued)



Note: $\eta_{Tx,\,RF}$ = 0.06 mW/mA; P_{LASER} =2.4 mW; $\eta_{Rx,\,RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1125F

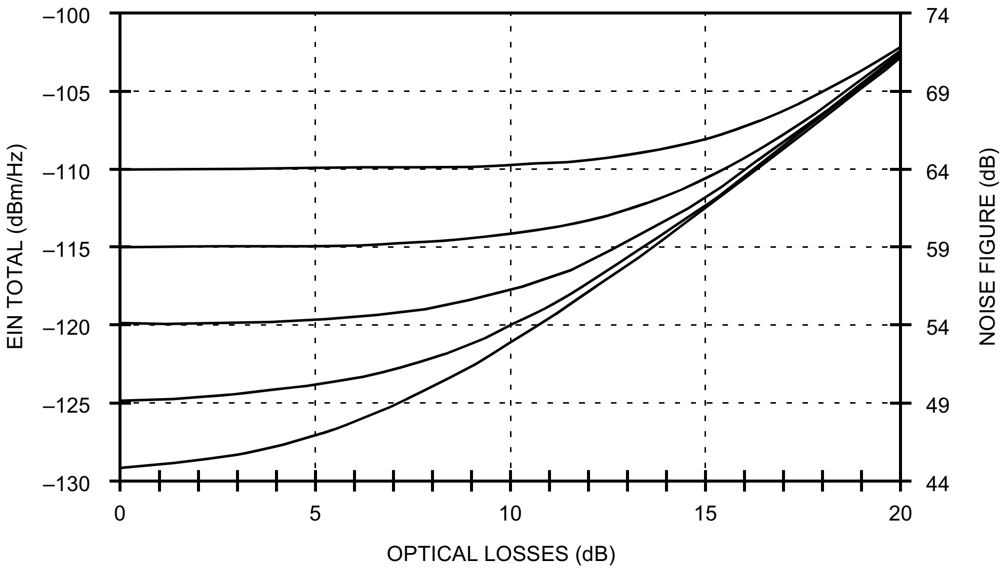
Figure27.NoiseCurve4,EquivalentInputNoisevs.OpticalLosses



Note: $\eta_{Tx,\,RF}$ = 0.06 mW/mA; P_{LASER} = 3.0 mW; $\eta_{Rx,\,RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1126F

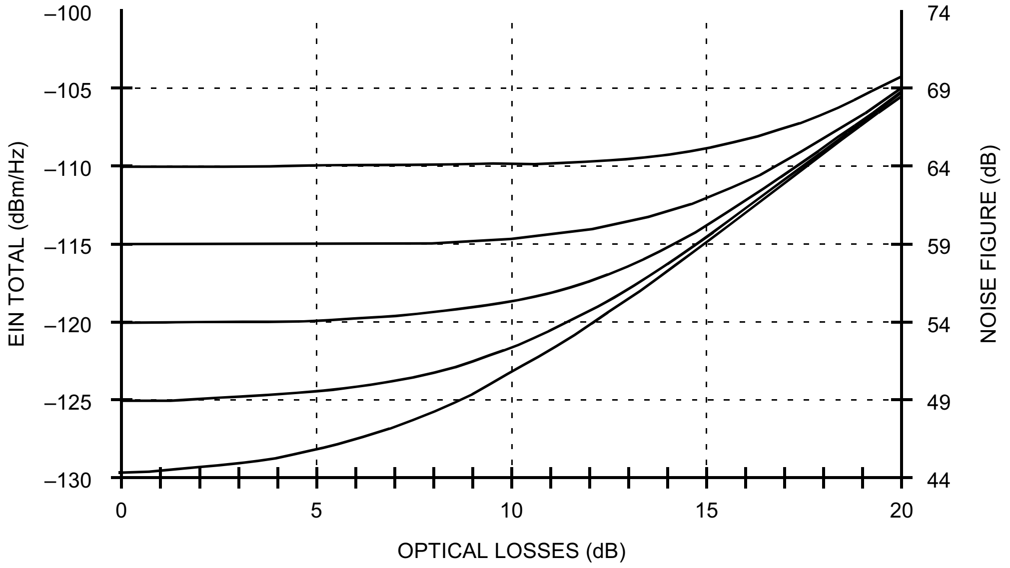
Figure28.NoiseCurve5,EquivalentInputNoisevs.OpticalLosses

Total Link Noise (continued)



Note: $\eta_{Tx,\,RF}$ = 0.75mW/mA; P_{LASER} = 3.0 mW; $\eta_{Rx,\,RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1127F

Figure 29. Noise Curve 6, Equivalent Input Noise vs. Optical Losses



Note: $\eta_{Tx,\,RF}$ = 0.1 mW/mA; P_{LASER} = 4.0 mW; $\eta_{Rx,\,RF}$ = 0.375 mA/mW; R_{PD} = 0.75 mA/mW. 1-1128F

Figure 30. Noise Curve 7, Equivalent Input Noise vs. Optical Losses

ac	Alternating current.
ALC	Automatic leveling control. A feedback circuit that maintains constant laser optical power.
AM	Amplitude modulation.
Amplification	Strengthening of a signal by an electrical device.
Analog	A type of signal that represents information as a continuously varying voltage, current, or intensity level. Analog transmission is typically used for video and POTS (plain old telephony service).
Available output power	The maximum RF power that can be delivered by a device to a load; occurs when the load impedance is the complex conjugate of the device output impedance.
Backbone	The part of the communications network intended to carry the bulk of the traffic.
Bandwidth	The information-carrying capacity of a communications channel measured in bits-per-second for digital systems or in megaHertz for analog systems.
Fiber bandwidth-length product	Fiber acts as a low-pass filter on the optical modulation because of dispersion. The bandwidth-length product gives the frequency at which the modulation is effectively attenuated by 3 dB after a given length of fiber (usually 1 km). Note that dispersion does not attenuate the light, only the modulation. (See Dispersion, page 20.)
Laser modulation bandwidth	Modulation of the laser input injection current causes the laser optical output intensity to be modulated at the same rate. The frequency at which the amplitude of the optical modulation has dropped to 0.707 ($1/\sqrt{2}$) of its mean value is the laser modulation bandwidth. When detected by a photodiode with a flat frequency response, the laser modulation bandwidth corresponds to the 3 dB electrical bandwidth.
Photodiode modulation bandwidth	Intensity modulation of the light incident on a photodiode causes the photodiode output current to be modulated at the same frequency. The photodiode modulation bandwidth is that frequency at which the square of the amplitude of the photodiode output current is one-half its mean value (given a light source with a flat frequency response).
Noise-equivalent bandwidth	Given the amplitude frequency response of an RF device, the noise-equivalent bandwidth is defined as the width of a rectangle whose area is equal to the total area under the response curve and whose height is that of the maximum amplitude of the response. This is the bandwidth used to compute the total noise power passed by a device and is generally not the same as the 3 dB bandwidth.

Baseband	A transmission scheme in which the signal is sent in its native format, without modulation to a higher frequency carrier.
Bellcore	Bell Communications Research, Inc. Focuses on standards, procedures and research and development of interest to the RBOCs. Now called Telcordia Technologies*.
Bend radius	The radius to which either a coaxial or fiber cable can be bent before breaking. More typically, it is the radius to which a cable can be bent before the signal being carried is affected.
Buffered fiber	Also called tight buffered fiber. Coated fiber surrounded by a 900 µm layer of plastic or nylon.
Broadband	A communication network or channel capable of carrying large amounts of information.
Broadcast	To send information over a data communications network to two or more devices simultaneously.
Cable Wires	Wires or groups of wires carrying voice or data transmissions.
CATV	Community antenna television; cable television.
C band	In electrical networks, a portion of the radio frequency spectrum. Communication satellites operate on C-band frequencies from 5.925 to 6.425 GHz for uplinks and 3.700 to 4.200 GHz for downlinks. In optical networks, a range of wavelengths between 1535 nm and 1565 nm.
CE certified	Signifies that a company has met the applicable health, safety, and conformity requirements to market its products in the European Union.
CENELEC	Comite European de Normalisation Electrotechnique or the European Committee for standardization. Responsible for European standards in the electrotechnical field.
Central office	The building that houses the switching equipment to which are connected circuits of business and residence phones; also called exchange.
Cladding	The glass that surrounds the central fiber core and has a lower index of refraction than the core.
C/N	Carrier-to-noise ratio. The ratio of carrier power to noise power in a communication channel.
Coaxial cable	A transmission medium consisting of insulated core surrounded by a braided shield.

Coaxial network	A network that uses coaxial cable.
Coaxial run	Any length of coaxial cable that connects devices.
Composite fiber cable	A fiber-optic cable with copper conducts included for dc transmission.
Compression	Refers to the nonlinear behavior of the RF device. As the input RF power is increased, the output power increases by less and less. When the output power is 1 dB lower than it would be if the device were perfectly linear, the device is said to be operating at its 1 dB compression point.
Conductor	Any material, such as aluminum or copper, capable of transmitting electric current.
Convergence	The gradual blurring of telecommunications, computers, cable, and the Internet into a single system.
CSO	Composite second-order distortion. In CATV systems or devices, a measure of the undesired second-order distortion.
CTB	Composite triple-beat distortion. In CATV systems or devices, a measure of the undesired third-order distortion.In electrical networks, a portion of the radio frequency spectrum.
Core	Central glass (in an optical fiber) having an index of refraction larger than that of the surrounding cladding glass. The region of the core serves as a waveguide for the light propagating through the fiber.
Data communications	The transfer of data between points.
Dark current	The current through a photodiode when no light is present.
dB	Decibel, defined as 10 multiplied by the logarithm of the ratio of two power levels.
DBS	Direct broadcast satellite.
dc	Direct current.
Delay	Wait time between two events. For example, the time between when a signal is sent and when it is received.
Direct broadcast satellite	System of delivering satellite television signals direct to the home.
Diplexer	A device that allows the feeding of signals from two transmitters to a single antenna at the same time without interference.
Direct modulation	The process in which an RF or digital signal is applied directly to a laser for transmission.

Dispersion	The delay distortion in a fiber that results in the spreading of a narrow pulse as it propagates through the fiber. Specified in ps/(km-nm); the amount of spreading of a 1 nm-wide pulse through 1 km of fiber.
Chromatic (spectral) dispersion	This dispersion is the sum of the material and waveguide dispersions and occurs in both multimode and single-mode fiber. Since fiber has optical wavelength-dependent propagation characteristics, this phenomenon occurs when using a multiwavelength laser.
Modal dispersion	This dispersion occurs in cases where the multimode fiber core diameter is large compared to the wavelength of light. The light inside the fiber breaks into numerous spatial modes, each arriving at the fiber output a different time.
Distortion	The variance between two measures of a signal; for example, a signal as it is transmitted versus the signal as it is received.
Distributed-feedback (DFB) laser	Instead of using end reflectors (see Fabry-Perot lasers), the DFB laser structure uses a periodic variation of the refractive index within the optical waveguide. The result is a laser with single optical wavelength, which produces a lower-noise output that is usually observed with multimode lasers.
DTH	Direct to home. Predecessor to DBS (direct broadcast satellite).
DWDM	Dense wavelength-division multiplexing. Using optical multiplexers and optical amplifiers, DWDM increases capacity by combining multiple optical signals so they can be amplified as a group and transported over a single fiber.
Dynamic range	The range of a signal power (input or output) that can be handled by a system. It is limited by the sensitivity requirement at the low end and the linearity requirement at the high end. The linearity limit is usually specified by the 1 dB compression or the third-order intercept. (See also spur-free dynamic range.)
E2000 *	A type of optical connector.
Earth station	A ground-based antenna system used to send or receive signals to or from a satellite.
EDFA	Erbium-doped fiber amplifier. A means of fiber optic amplification. The transmitted light signal is passed through a section of fiber doped with erbium, a rare earth element, and is amplified by a pump diode.
EMI	Electromagnetic interference.
External modulation	Modulation of a light source by an external device such as an interferometricor electoabsorbtive modulator.

Fabry-Perot (FP) laser	A laser that uses the reflection from the laser facets to provide the feedback necessary for the lasing process. Many varieties of these lasers simultaneously emit multiple optical modes. (See laser noise.)
FC/PC, /APC, or /APC	A popular style of fiber-optic connectors, commonly used with linear fiberoptic links. The terms following the slash indicate the type and quality of polish, for example, FC/APC is face-contacted/angled polished connector.
Ferrule	A component of a fiber optic connection that holds the fiber in place and aids in its alignment.
Fiber	In fiber optics terms, refers to fiber made of very pure glass.
Fiber length	The physical length of the fiber. This length can then be translated to optical loss.
Fiber optics	A technology that uses light to transmit information from one point to another.
Flatness	The peak-to-peak deviation in amplitude of a signal over a given frequency or wavelength range.
Frequency stacking	The process in which allows two identical frequency bands can be sent over a single cable. This occurs by upconverting one of the frequencies and stacking it with the other.
FTTC	Fiber to the curb.
FTTH	Fiber to the home.
Fusion splice	A splice created by applying heat to fuse or melt the ends of two optical fiber cables, forming a continuous single fiber.
Gigabit	One thousand million bits.
GHz	Gigahertz (Hz x 10^{9}).
GPS	Global positioning satellite.
Headend	The originating point of a signal in a cable TV system.
Hot swappable	The ability of a component to be added or removed from a device without requiring that the device be powered down.
IF	Intermediate frequency. Typically refers to 70 MHz/140 MHz for satcom applications. In headend applications, it refers to the 950 MHz to 2050 MHz (L band).
IGC	Input gain control.
Index of refraction	The ratio of the phase velocity of light in a vacuum to that in the medium.

Input power	See optical input.
IP telephony	The transmission of voice over an internet protocol (IP) network. Also called voice over IP (VOIP), IP telephony allows users to make phone calls over the Internet, intranets, or private LANs and WANs that use the TCP/IP protocol.
ITU	A committee of the International Telecommunications Union that recommends international standards for radio, television, and telecommunication signals.
ITU grid	In DWDM systems, an assignment of standard wavelengths.
Ku band	A portion of the radio-frequency spectrum. Communication satellites operate on Ku-band frequencies from 14.0 MHz to 15.5 MHz for uplinks and 12.2 MHz to 12.7 for downlinks. DBS satellites operate on Ku-band frequencies from 17.3 GHz to 17.8 GHz for uplinks and 12.2 GHz to 12.7 GHz for downlinks.
LAN	Local area network. A network that interconnects devices over a geographically small area, typically in one building or a part of a building.
Laser	A device that produces a single frequency of light.
L band	In electrical systems, a portion of the radio-frequency spectrum, 950 MHz to 2050 MHz, used in satellite, microwave, and GPS applications. In optical systems, the range of wavelengths between 1570 nm and 1620 nm.
LEC	Local exchange carrier. An organization that provides local telephone service and includes the RBOCs, large companies such as GTE, and hundreds of small, rural telephone companies. A LEC controls the service from its central office (CO) to subscribers within a local geographic area.
Link budget	A means of calculating the overall system's performance based upon a set criteria.
Link gain	The amount a signal's power has gained, expressed in dB. This occurs when the loss in the components in the system is less than the gain of the system's components.
Link loss	The amount of a signal's power lost, expressed in dB. This occurs when the loss in the components in the system exceeds the gain of the system's components.
Link margin	The available power remaining in the system once its operating point has been obtained.
LNB	Low-noise block-converter.
LNBF	Low-noise block-converted frequencies.

Mbits/s	A measurement of the speed of digital communications channel; one million bits per second.
MDU	Multiple dwelling units. Apartment and condominium complexes, hospitals, dormitories.
Mechanical splicing	An optical fiber splice accomplished by fixtures or material rather than thermal fusion.
Metro	Metropolitan fiber ring. High-speed local network that connects local telephone users to long distance networks.
MHz	Megahertz. Refers to a frequency equal to one million hertz.
Micron	A unit of measurement, equaling one-millionth of a meter.
Microwave	Line of sight, point-to-point transmission of signals at high frequency.
Modem	Modulator/demodulator. A DCE (data circuit-terminating equipment) installed between a DTE (data terminal equipment) and an analog transmission channel, such as a telephone line. A DTE refers to a device that an operator uses, such as a computer or a terminal.
Modulation depth	The ratio of the peak amplitude of the laser intensity modulation to the average laser intensity.
Modulation gain	The efficiency with which the laser converts input injection current to light output power coupled into the fiber.
Monitor photodiode	A photodiode included in a laser module to convert the detected laser power to a current that is used for automatic leveling control.
MSO	Multiple system operator. MSO modulation gain is a function of the frequency of the modulation. At dc, it is equal to the light vs. current slope; specified in mW/mA.
Multimode fiber	Optical fiber with a core diameter that is large compared to the wavelength of light. This results in many (hundreds) spatial modes inside the fiber. For this reason, multimode fiber is not used with linear fiber-optic links.
Multiple system operator	Cable television company that operates more than one cable system.
Multiple-user	The ability to have simultaneous users.
mW	Milliwatt. A unit of measure for power equal to one one-thousandth of a watt.
Noise	On a communications channel, extraneous signals that degrade the quality or performance of the link.

Equivalent input noise (EIN)	The noise power at the input of an RF device that would produce the observed available output noise power if the device itself were noiseless. Specified as noise density in mW/Hz or dBm/Hz.
Laser noise	Fluctuations in the optical output of a laser generally due to any of three major effects: First, the intrinsic laser noise is due to a number of fundamental processes within the laser diode. Second, optical feedback noise is due to light reflected back into the laser diode, disturbing the laser oscillation. Third, partition-mode noise occurs with Fabry-Perot lasers with multiple longitudinal modes coupled into a long length of fiber. Optical power is continuously and randomly being transferred from one mode to another in the new laser spectrum. This phenomenon, together with the chromatic dispersion of the fiber, produces noise at the fiber output. Using a fiber with a zero dispersion point at the laser center wavelength minimizes this noise.
Noise-equivalent power (NEP)	The amount of optical power incident on a photodiode that would generate a photocurrent equal to the total photodiode noise current.
Noise figure	The ratio of the available output noise power of an RF device to that of a noiseless but identical device when the input is passively terminated with a conjugate match at a standard temperature (290 K).
Relative intensity noise (RIN)	When a laser diode is biased above the threshold, the emitted light exhibits small intensity fluctuations around the average value. The RIN is defined as the ratio of the mean square intensity fluctuations to the square of the average intensity.
Shot noise	The noise generated in a photodiode (when detecting optical signals) due to the discrete photon nature of light.
Thermal noise (Johnson or Nyquist noise)	Voltage fluctuations at the terminals of a device due to the random thermal motion of charge carriers.
NTSC	National Television Systems Committee. Sets television standards in the United States. Also the video format used in the United States.
OC-192	Optical carrier level 192. SONET channel capable of carrying 10 gigabits per second.
OC-48	Optical carrier level 48. SONET channel capable of carrying 2.488 gigabits per second.
Optical fiber	Long strands of glass, thinner than a human hair, that propagate a lightwave signal for use in broadband communications.

Optical input	The optical input to a photodiode or optical receiver.
Optical isolator	A device used to suppress or redirect backscattered or backreflected light.
Optical loss	The amount of a signal's power lost, expressed in dB. This is due to the length of a fiber, amount of splices, bend radius, or any mechanical external factors placed on the fiber.
Optical output	The optical output power of a laser or optical transmitter.
Optical reflections	The optical power (expressed in dB) reflected by a component or an assembly.
Optical return loss	The ratio (expressed in dB) of optical power reflected by a component or an assembly to the optical power incident on a component port when that component or assembly is introduced into a link or system.
Optoelectronics	Materials and devices associated with fiber-optic and infrared transmission systems. Optoelectronic light sources convert electrical signals to an optical signal that is transmitted to a light receiver and converted back to an electrical signal.
Output power	See optical output.
PAL	Phase-alternate line, a video format used in most parts of the world.
Photodiode	Light detector in a fiber-optic signal transport system that generates an electric current in proportion to the intensity of the light falling on it.
APD	Avalanche photodiode. A semiconductor device that combines the detection of optical signals with internal amplification of the photocurrent.
PIN Photodiode	A particular type of photodiode structure (positive-intrinsic-negative) characterized by favorable noise, bandwidth, and linearity properties.
Photodiode current monitor	A device that converts electrical current to a dc voltage used to monitor optical power. This conversion is typically a 1:1.
Photonics	In communication technology, the use of fundamental particles of light, called photons, to form coded light pulses that convey information in digital form.
Pigtail	A short piece of unconnectorized optical fiber connected to either the transmitter or receiver. The pigtail, in turn, would be spliced to the transmission fiber.
Polarization	A technique used in satellite communications to increase the capacity of the satellite transmission channels by reusing the satellite transponder frequencies. Also, the direction of the electric field in the lightwave.

Radio frequency	The RF carrier frequency of a given device.
RBOC	Regional Bell operating company.
Receiver	A device that receives a transmitted signal.
Receiver gain	The difference between the RF signal presented to the input of the receiver versus the RF signal at the receiver output. This gain will not always represent itself as an increase in signal, since the losses in the receiver may be greater than its internal amplifier.
Redundancy	Having one or more backup systems available in case the primary system fails.
Redundant link	A second connection between transmission and receive devices that operates only when integrity is lost on the active link.
Responsivity	The efficiency with which a photodiode converts incident optical power into output electrical current. Specified in units of mA/mW.
Return loss	A comparison of impedance at the point of transmission and at termination.
RF	Radio frequency.
RF efficiency, receiver	The efficiency with which a complete optical receiver, including the photodiode and any other electronics, converts light into usable RF signals; specified in mA/mW.
RF efficiency, transmitter	The efficiency with which a complete optical transmitter, including the laser diode and any other electronics, converts RF signals into modulated light; specified in mA/mW.
RF Input	The signal in dBm as presented to the input of a device.
RF Loss	A measure of RF signal loss through a device or link.
RF Output	The signal, measured in dBm, at the output of a device.
RG	Receiver gain.
SBS	Stimulated Brillouin scattering.
SC/APC	Subscription channel/angled polished connector.
Semiconductor	A crystalline solid that offers the behavior properties of a conductor (e.g., iron) and an insulator (e.g., glass). Semiconductors are the raw materials used in active electronic and optical devices.
Sensitivity	The input level required for a device to provide a predetermined output.
Short haul	According to some definitions, a distance between several hundred yards and 20 miles.

Single-mode (monomode) fiber	Optical fiber having a core diameter small enough to allow only one spatial mode (of each polarization) to propagate at the wavelengths of interest.
Single thread	A connection between transmission and receive device that operates without the benefit of redundancy.
SONET	Synchronous optical network. SONET is a Telcordia Technologies (formerly Bellcore) specification currently used in worldwide public data networks (PDNs). It defines a synchronous optical network-based user-network interface (UNI), either public or private, operating at speeds from 51 Mbits/s.
Source laser	A laser used as a light source in an externally modulated system.
Stimulated Brillouin scattering	A nonlinear phenomenon that can cause distortion of an optical signal in a fiber.
Spectral width	The full-width half maximum (FWHM) of the output optical spectrum of a laser.
Splice	Any number of permanent and semipermanent fiber connections.
Spur-free dynamic range (SFDR)	The range in power of a pair of equilevel input signals in which the signals are above the noise floor and the third-order products are above the noise floor.
TEC	Thermoelectric cooler. A device that uses the Peltier effect to heat or cool as necessary to keep the laser temperature constant.
Telecommunications	The transmission, reception, and switching of electrical or optical signals over wire, cable, or air.
TG	Transmitter gain.
Third-order intercept (TOI)	A specification used to characterize the small signal nonlinearity of an RF device. An extrapolation of the results of a small signal two-tone test to the point where the level of the third-order intermodulation would be equal to that of the two tones.
Third-order intermodulation product	A spurious output signal produced by the nonlinear mixing of multiple input signals.
Threshold current (I_{TH})	The input electrical current into the laser diode, above which the diode emits light as a laser.
TIA	Transimpedance amplifier. An electrical circuit or device that accepts a current at its input and generates a voltage at its output.

Transmitter	In fiber-optic communications, a light source that emits a beam that can be modulated and sent along an optical fiber, and the electronics that support it.
TVRO	Television, receive only. An earth station designed to handle downlink signals only.
Twisted pair cable	A cable consisting of two or more copper wires twisted together in pairs. Telephone wiring is an example of twisted-pair cable.
Vdc	Volts dc.
Video on demand	The ability for a subscriber to an interactive TV service to select and view a specific program provided by a device such as an interactive video server.
Voice over IP	The delivery of voice information in digital form over the Internet instead of in analog form over the public switched telephone system.
Volt	The force required to produce a current of 1 A through a resistance or impedance of 1 Ω.
VSAT	Very small aperture terminal. Relatively small satellite antenna used for satellite-based, point-to-multipoint data communications applications.
WAN	Wide area network. A data network typically extending a LAN outside a building or beyond a campus, over IXC or LEC lines to link to other LANs at remote sites. Typically created by using bridges or routers to connect geo graphically separated LANs.
Wavelength	The physical distance between two adjacent peaks or valleys in a wave; the property of light that determines its color.
Wideband	Digital communication between 1.5 Mbits/s and 45 Mbits/s.
X band	A portion of the radio frequency spectrum, 7 GHz and 8 GHz, used by military satellites.
Zero dispersion point	For single-mode fiber, the wavelength at which the chromatic dispersion is zero.

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