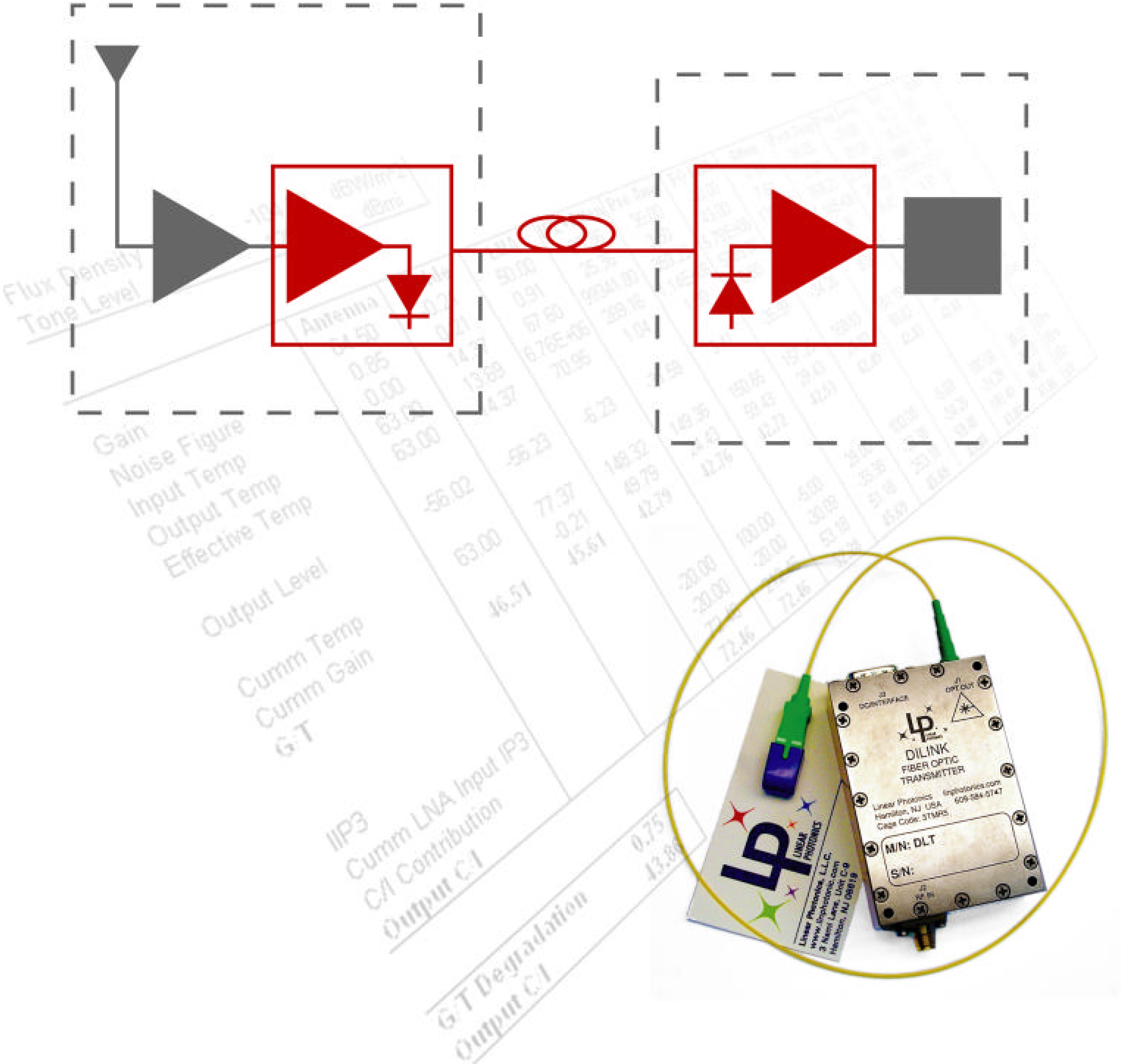
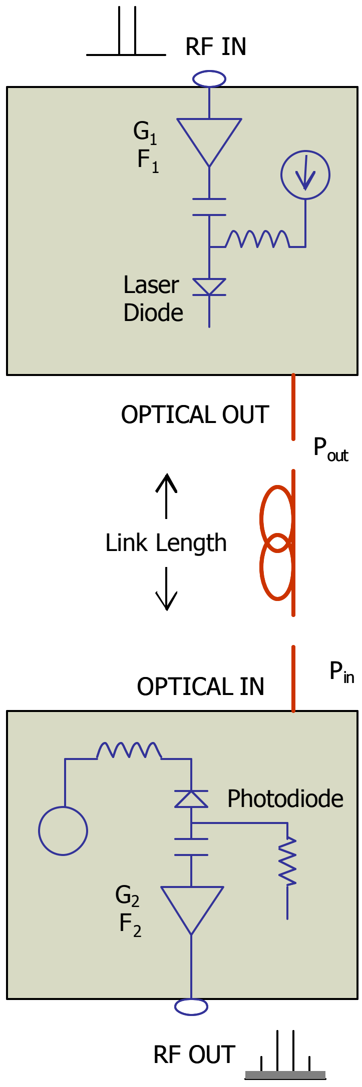
LINEAR PHOTONICS

System Design Using Direct Modulation Fiber Optic Links

Application Note 106-1



INTRODUCTION



Today's system designer may be faced with several technology choices for communications links for satellite microwave remoting, cellular/broadband services, or distribution of microwave signals. In a system that requires transport of microwave signals over appreciable distances, fiber optic transport becomes a key tradeoff. What is needed are a set of simple "black box" parameters that the system designer can use to readily evaluate the benefits and drawbacks of fiber links in the overall design.

Many claim that microwave-on-fiber is the answer to all communications transport needs. These statements, while indicative of the passion some have for the art, unfortunately do not address the reality of today's technology. It is true that the applications of fiber communications are widespread, and growing as the technology advances. But it should also be clear to the system designer that fiber optic transport is not always the best solution. For example, tradeoffs might be made between fiber, coax, or wireless transport. Fiber optic transport involves signal level changes (gain/loss), adds thermal and spurious noise, and may add nonlinear interference. This paper intends to define the key technical parameters of fiber links in such a way that the system designer can easily implement them into an analysis, without having to perform a detailed review of the fiber optic components themselves.

As with any technology discussion, certain underlying assumptions need to be identified prior to examining the results. This paper will provide the system designer with pluggable link parameters, based on the following:

1. *Directly modulated fiber optic transmitters:*
   Intensity modulation of the optical carrier is accomplished by directly varying the laser bias current. The Linear Photonics *DiLink* series of microwave fiber optic transmitters and receivers are used as a technical performance baseline. These units provide microwave links operating up to about 4 GHz. Operation at higher frequencies may require externally-modulated transmitters, which are the topic of a separate application paper.

2. *Direct detection fiber optic receivers:*
A single-ended PIN diode photoreceiver is the best example, and most readily available. No coherent or balanced detection architectures are employed.

3. *No optical amplifiers or active optical components:*
Optical amplifiers, such as erbium-doped fiber amplifiers or semiconductor optical amplifiers, can be used to increase optical level and offset optical loss. These components change the noise and linearity relationships of the link. The analysis in this paper assumes that no active optical components are used in the link.

This type of "standard" link is most cost effective for analog transport applications. Better performance may be obtained through the use of band-specific links, or different link architectures. These will typically cost more than standard hardware, and should be investigated in the event that standard links cannot fulfill the system requirements.

What's Important?

It is intended to provide system parameters that treat the fiber optic link as an RF "black box", whether the link stretches across a room or across a city. In this case, it can be modeled as an RF amplifier, with the same primary characteristics:

- Gain
- Noise
- Linearity

Another common metric for links is the spur-free dynamic range. As will be shown, this is a direct result of the three primary factors mentioned above.

An understanding of the parameters that affect these performance characteristics will allow the system designer to readily evaluate the impact and utility of the link.

DIRECT CONVERSION/DIRECT DETECTION LINKS

A brief description of microwave analog directly modulated fiber optic links is beneficial to an overall understanding of the resultant system parameters. The three basic components of interest are the transmitter, receiver and fiber medium.

Receiver

First consider the output side of the link: the fiber optic receiver. This will consist of a PIN diode aligned to a fiber optic cable. The diode acts as a current source whose amplitude is proportional to the intensity (power) of the applied optical signal. The efficiency of the conversion is the *Responsivity*, R, in Amps/Watt. An intensity-modulated light source will generate both a DC current proportional to the average power of the laser beam, and an RF signal current, proportional to the small signal intensity variation of the beam (the microwave modulation envelope).

The PIN diode is reverse-biased, and therefore its impedance is large, and capacitive. The microwave output of the diode must be matched to the characteristic system impedance (50 or 75 Ω). There is a resulting microwave loss associated with the transformation. The loss increases with the total matched bandwidth. Failure to properly match the receiver output impedance may result in excessive VSWR ripple in the system, and should be avoided.

Transmitter

The fiber optic transmitter generates the intensity modulated light source. This process is similar to amplitude modulation, where the laser beam acts as the carrier.

Direct modulation of laser sources is most cost effective, and is used almost exclusively for general purpose communications at lower microwave frequencies (up to about 3-4 GHz). Externally modulated laser carriers can be used at much higher frequencies, and are usually required at about 12 GHz and above. Between 3 and 12 GHz a mixture of the two technology choices may be used, the choice ultimately dependent upon the particulars of the system design. See Figure 1.

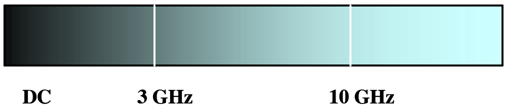


Figure 1. Direct modulation (dark background) is used almost exclusively through 3 GHz, and overlaps with external modulation (light background) between 3 and 12 GHz. External modulation is necessary above about 12 GHz.

External modulation is also used at lower frequencies when very high dynamic range is required, such as in CATV distribution.

In a direct modulation transmitter the laser diode is driven *directly* by both a bias current and the modulating RF current, as shown in Figure 2. The output light intensity varies directly with the RF signal and a proportionality constant known as the *Modulation Efficiency*, η_L. It includes the loss associated with the launch of the optical beam from the laser diode into the fiber.

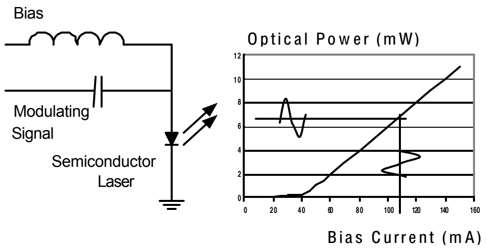


Figure 2. In a directly-modulated link, the laser bias is varied by the applied RF signal. The resulting optical carrier is envelop-modulated by the RF information.

Unlike a photoreceiver, a laser diode is forward-biased, so its impedance is typically very low (several ohms, and capacitive). Again, effort must be made to reduce VSWR interaction in the system by providing a well-matched RF launch. This effort will result in loss, which increases with the total bandwidth.

Fiber

An intensity modulated transmitter and direct-detect receiver form the key active elements in a fiber optic link. These are connected together through a single-mode optical fiber.

Loss

The fiber presents length and wavelength dependent optical attenuation. Many installations use Corning SMF-28 or equivalent single-mode fiber. It is readily available and carries the benefit of many millions of years of combined operational service in the field. There are two primary wavelength ranges available in modern semiconductor communications lasers; 1310 and 1550 nm. SMF-28 exhibits approximately 0.25 dB/km attenuation at 1550 nm, and about 0.4 dB/km at 1310 nm.

Other sources of loss include fiber connectors, switches, splitters and other passive components, that must be taken into consideration during the system design. Table 1 lists some typical values for passive component loss:

Component	Optical Loss
Connector (SC or FC)	0.25 dB
Splitter	3.5 dB
Switch	0.5 dB
Fusion Splice	0.1 dB

Table 1. Typical optical losses associated with common passive components.

Dispersion

Chromatic dispersion (the variation in group velocity as a function of wavelength) may also affect the performance of the fiber optic link, when the link lengths are very long. Because different optical wavelengths propagate at different rates, the upper and lower sidebands of the intensity-modulated laser carrier will arrive at the receiver at different times. Nulling will occur when the delay is equal to 180°. The null frequencies are dependent on the dispersion characteristics of the fiber and the link length, as well as the characteristics of the laser carrier (wavelength and linewidth). SMF-28 fiber at 1550 nm exhibits appreciable dispersion at 1550 nm, and near-zero at 1310 nm.

For link lengths up to 10 km and frequency bands below 4 GHz, there should be no dispersion penalty at either 1310 or 1550 nm.

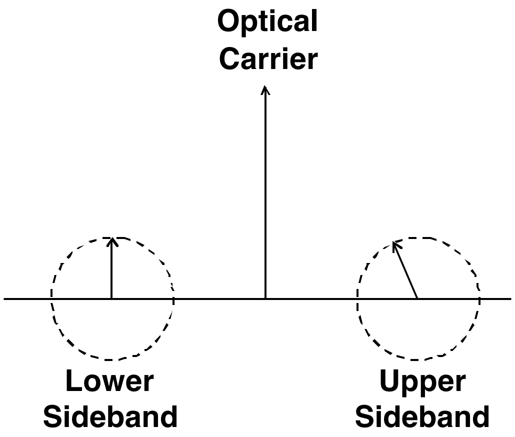


Figure 3. Dispersion causes phase delay between the AM sidebands. The detected signal is attenuated by the cosine of the phase angle. If the phase is 180°, the output is nulled.

Fiber Nonlinearities

Fiber is a nonlinear transmission medium. Two basic phenomena can lead to a series of nonlinear effects: photon scattering and refractive index change. These effects can lead to one or several of the following nonlinearities:

- Stimulated Brillouin Scattering (SBS)
- Stimulated Raman Scattering (SRS)
- Four-Wave Mixing (FWM)
- Cross-phase Modulation (XPM)
- Self-phase Modulation (SPM)

A brief description of these nonlinearities follows. All of these nonlinearities are generally irrelevant for the type of link system described in this paper. For links with optical gain, high optical power level, and those that employ wavelength-division multiplexing (WDM), a more in-depth study of the nonlinear effects of the fiber would be advisable.

SBS is a backscattering effect caused by high instantaneous optical power. It is a threshold phenomenon, below which little or no scattering occurs. The threshold is typically at about +9 dBm of optical power for very long links, and increases if the links are shorter, and when the carrier is directly-modulated.

SRS is another threshold-induced scattering phenomenon. It occurs at optical power levels approaching 30 dBm.

FWM and XPM can occur in WDM systems, when there are multiple optical carriers in the fiber. Both are caused by the nonlinear refractive index of the fiber core. They lead to intermodulation distortion and cross-talk between the information on the carriers.

SPM is also due to index nonlinearity. It can cause the group delay to vary nonlinearly through the fiber, further complicating the dispersion response.

As mentioned above, fiber nonlinearities can generally be disregarded for single-wavelength fiber optic links such as the *DiLink* series.

SYSTEM PARAMETERS

Using the basic understanding of the fiber transmitters, receivers, and transmission medium as described above, definitions for the key system parameters of gain, noise and linearity can be defined.

Gain

The gain of a fiber optic link is often tailored to meet system requirements through the use of RF preamplifiers, postamplifiers, or both. These are often embedded directly into the transmitter and receiver modules. An understanding of the parameters that affect the gain is most relevant to a system analysis.

Linear Photonics *DiLink* series direct-modulation fiber optic link modules include both pre- and post-amplification stages in various configurations. Standard *DiLink* unit pairs have specified RF link gain, G_{ref}, of 0 or 15 dB, with no optical loss. Gain variability due to laser efficiency, receiver responsivity, and RF matching have been designed into the links, so that the only remaining impact on RF link gain will be the optical loss of the system.

Because the receiver provides a current that is proportional to the optical power (not the optical field amplitude), the RF gain will vary by twice the optical attenuation (in dB). For example, a 10 km link at 1550 nm with SMF-28 fiber will exhibit about 2.5 dB lengh-dependent optical loss. This corresponds to a 5 dB decrease in RF gain from the nominal values given in the link spec.

As mentioned above, the *DiLink* modules already include pre- and/or postamplification. The specification for link gain is provided for the case of no optical loss. The system designer must estimate the optical loss and decrease the specified gain by <u>twice</u> that amount, in dB.

Noise

Noise may be an important system limitation when employing fiber optic links. There are three inherent sources of link noise: laser relative intensity noise (RIN), receiver shot noise, and thermal noise. If amplifiers are embedded in the link, they will also contribute additional noise.

Laser Noise

RIN is the result of undesired spurious optical transitions in the laser, leading to a background optical output that is specified in a reference bandwidth with respect to the optical carrier in dB/Hz. This spurious optical level is detected by the photoreceiver and is delivered to the output load, appearing as noise in the microwave spectrum. Since the RIN current generated in the photoreceiver is a function of the optical power, its microwave output level increases (or decreases) by 2 dB for every 1 dB increase (or decrease) in optical power at the receiver, just as the RF gain behaves. At the transmit side, the RIN at the laser output is a function of both the laser bias and the spectral distance from the carrier (detected microwave frequency).

Shot Noise

Photons are quantized packets of energy. A multitude of these energy packets strike the photoreceiver active area, similar to shotgun pellets striking a target. Each photon generates a pseudo-delta function current. The frequency response of this random process is a DC average value, plus a mean-square current that is proportional to the average optical power. This undesired current is delivered to the output load and appears as white noise. Since the mean-square photocurrent is proportional to optical power, the noise power delivered to the load will change 1:1 (in dB) in relation to the receiver-incident optical power.

Thermal Noise

Thermal noise at the output is due to the real resistance of the photoreceiver, as well as the added and transferred thermal noise from any RF amplification, and from the laser diode real resistance. If the level of RF preamplification is less than the inherent link loss, the output thermal noise will be essentially constant, irrespective of receiver-incident optical power.

Total Output Noise Power

Because each of the three noise components appear as independent white noise at the microwave output, they are additive. Note that the three noise contributors vary differently as a function of detected optical power (or receiver photocurrent). At very high optical power levels, RIN noise will dominate the output. At very low power, thermal noise will dominate, and in the intermediate region, shot noise will contribute. Figure 4 shows an example of the output noise power density of a link as a function of optical power, for a link with no RF amplification.

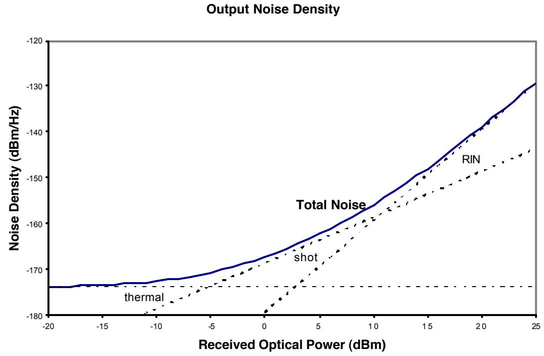


Figure 4. The output noise density of a directly-modulated fiber optic link consists of thermal, shot and RIN components. Each has a different relationship with respect to received optical power (optical loss).

Desirability of Low Optical Loss

At high received optical power level (low optical loss) the noise continues to increase 2:1 in dB with the optical power. Also, recall from the earlier section that the RF gain of the link is increasing at the same rate. The output signal-to-noise ratio (SNR) will therefore be constant, and maximum, when the link is driven at very high optical level, known as RIN-limited. As we increase the optical loss, we enter into a region where the noise power decreases only 1:1 with optical power. Still, the RF gain continues to drop at 2:1, so SNR will decrease 1 dB for every added dB of optical loss in this region, known as the shot-noise limited region. For even higher optical loss, the output noise is constant at the thermal limit. Again, the gain continues to drop as optical loss increases, so the SNR drops 2 dB for every dB of optical loss in this, the thermal-noise limited region.

This highlights the desirability of high optical drive level into the receiver. For a given laser operating point, link noise figure increases as optical loss is added. The amount of increase is not linear, but it can be approximated through the use of the system equations provided herein.

Noise Figure

Generally, the link output noise can be computed directly from three specified noise constants, and the optical loss (OL), as follows:

$N_{th} = c_{th}$ (dBm/Hz)

$N_{shot} = c_{shot} - OL$ (dBm/Hz)

$N_{rin} = c_{rin} - 2OL$ (dBm/Hz)

The total output noise, N_{out}, in dBm/Hz is the linear summation of the three noise contributions:

$$N_{out} = 10 \cdot \log\left[10^{\frac{c_{th}}{10}} + 10^{\frac{c_{shot}-OL}{10}} + 10^{\frac{c_{rin}-2OL}{10}}\right]$$

and the noise figure (F) is given in dB by:

$$F = N_{out}(dBm/Hz) + 174 - G_L(dB)$$

where G_L is the total link gain, found by

$$G_L(dB) = G_{ref}(dB) - 2OL(dB)$$

To aid the system design process, LPL specifies the three noise constants, c_{th}, c_{shot} and c_{rin} for each of its *DiLink* pairs. The noise constants include the effects of the photonic link, plus contributions from pre and/or postamplifiers. LPL also specifies the reference gain, G_{ref}, with no optical loss

Linearity

A fiber optic link consists of active components and therefore generates both noise and nonlinear distortion, similar to an RF amplifier. The linearity of a fiber optic link generally refers to the amount of second and/or third order distortion that is generated. Sometimes higher order distortion terms are also of interest.

Linearity is a complicated subject, requiring extensive study in its own right. The amount of “linearity” a system requires will ultimately depend on the bandwidth, the dynamic range requirements, the type of modulation employed, and the number of carriers of modulated signals transferred through the link.

Third-order Distortion

A common definition of linearity for microwave-over-fiber applications is that of third-order intermodulation distortion in the presence of two carriers (two-tone IMD).

The sources of nonlinearity include the following:

- The laser diode
- The fiber (transmission medium)
- The photoreceiver
- RF pre- and/or post-amplifiers

In this paper, we consider direct modulation links similar to the LPL *DiLink* series. In this type of link, the optical power level from the laser is not sufficient to cause appreciable fiber or photoreceiver nonlinearity. The link linearity is dependent only on the laser diode and the RF amplifiers.

IIP_3, the input third-order intercept, is the (imaginary) input power at which the output third-order two-tone intermodulation power and the fundamental power are equal. Ideally, the two-tone IMD power decreases 3 dB for every dB decrease in applied fundamental power level.

For a link with pre and/or post-amplifiers, such as the DiLink series, both the integrated transmitter input intercept and the integrated receiver output intercept will impact the overall linearity. The receiver intercept will improve as optical loss is increased, while the transmitter intercept is fixed. The overall link input intercept is the cascaded effect of the transmitter and receiver.

For each of the DiLink pairs, LPL specifies an overall intercept with no optical loss, as well as equivalent input-side and output-side contributors. The system designer can determine the overall link input intercept, in dBm, by the cascaded equivalent input and output contributors:

$$IIP_3 = 10 \cdot \log \left[\frac{10^{\frac{OIP_{eq} + IIP_{eq}}{10}}}{10^{\frac{OIP_{eq}}{10}} + 10^{\frac{IIP_{eq} + G_L}{10}}} \right]$$

where IIP_{eq} and OIP_{eq} are the equivalent input and output third-order intercept power levels in dBm, respectively, and G_L is the end-to-end link gain in dB. Only the optical loss is needed to solve for the overall IIP_3.

Second-order Distortion

Second order distortion includes the nonlinear spectral components of the sum and difference frequencies of the input signals, as well as the harmonics. The second-order distortion is generally not a concern for system bandwidths less than one octave.

Dynamic Range

A common figure of merit for fiber optic links is the spur free dynamic range (SFDR). This is defined as the difference, in dB, between the output noise floor and the power level of each of two equal-power signals that produce a spurious signal that is equal in power to the noise floor. Often, third-order SFDR ($SFDR_3$) dominates, and is given in general by the following relation:

$$SFDR_3(dB) = \frac{2}{3}\left[174 - BW - F + IIP_3\right]$$

where BW is the system or receiver (processing) bandwidth in dB, F is in dB, and IIP3 is in dBm.

$SFDR_3$ can be calculated directly from the primary link performance parameters defined above.

SUMMARY

A set of equations has been defined for directly modulated fiber optic links that allow the system designer to readily determine the characteristics of gain, noise and linearity. *DiLink* fiber optic link pairs have specified gain, noise and linearity constants that allow link definition, knowing only the system optical loss. These equations are summarized here:

Specified Values:

- G_{ref} (dB)
  Reference Gain with no optical loss
- c_{th} (dBm/Hz)
  Thermal noise constant
- c_{shot} (dBm/Hz)
  Shot noise constant
- c_{rin} (dBm/Hz)
  RIN noise constant
- IIP_{eq} (dBm)
  Equivalent input 3rd order intercept
- OIP_{eq} (dBm)
  Equivalent output 3rd order intercept

System Calculations, where OL is optical loss in dB:

Link Gain

$$G_L(dB) = G_{ref} - 2 \cdot OL$$

Link Noise Figure

$$F(dB) = N_{out}(dBm/Hz) + 174 - G_L(dB)$$

$$N_{out} = 10\log\left[10^{\frac{c_{th}}{10}} + 10^{\frac{c_{shot}-OL}{10}} + 10^{\frac{c_{rin}-2OL}{10}}\right]$$

Link Input Intercept

$$IIP_3(dBm) = 10\log\left[\frac{10^{\frac{OIP_{eq}+IIP_{eq}}{10}}}{10^{\frac{OIP_{eq}}{10}} + 10^{\frac{IIP_{eq}+G_L}{10}}}\right]$$

EXAMPLE

As a further example, consider the system shown in Figure 5. A 2300 - 3400 MHz signal is input to a directly modulated broadband laser transmitter. The transmitter optical output is split. One path consists of 4 optical connectors and 500 m of SMF-28 fiber. The other path consists of 6 optical connectors and 5 km of SMF-28. This is one type of architecture that might be used in an antenna-remoting system.

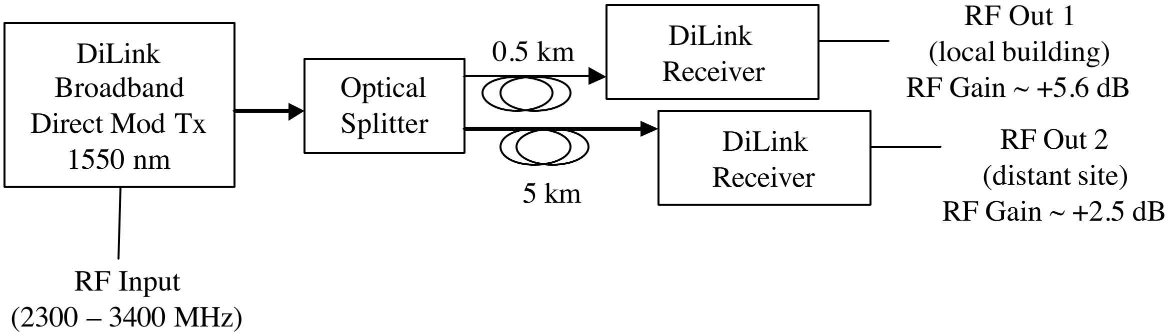


Figure 5. An example antenna-remoting link system. The transmitter is a DiLink DLT5N81, and the receivers are DLR5N81.

Specified Module Parameters

From Appendix A:

$G_{ref} = 15$
$c_{th} = -139.9$
$c_{shot} = -144$
$c_{rin} = -139$
$IIP_{eq} = 13.6$
$OIP_{eq} = 27.0$

System Optical Losses

Using the optical loss estimates from Table 1, the total optical loss in path 1 is 3.5 dB for the splitter, plus 1.0 dB for the 4 connectors, plus 0.13 dB for the 500 m of fiber, or about 4.7 dB. Similarly for path 2, the total optical loss is 6.25 dB.

$OL_1 = 4.7$ dB
$OL_2 = 6.25$ dB

Link Parameters

Gain

The reference RF gain (with no optical loss) is 15 dB. In this system, the 500 m path will have 9.4 dB RF loss (twice the optical loss), so the path 1 link gain will be about 5.6 dB. Similarly for the 5 km path, the RF gain will be 15 – 2(6.25) = 2.5 dB.

Noise

In path 1,

$$N_{out,1} = 10\log\left[10^{-13.99} + 10^{\frac{-144-4.7}{10}} + 10^{\frac{-139-2(4.7)}{10}}\right] = -138.9$$

dBm/Hz

$$F_1 = -140.9 + 174 - 5.6 = 29.5 \text{ dB}$$

Similarly, in path 2, the output noise is -139.3 dBm/Hz, and the noise figure is 33.3 dB.

Input Intercept

In path 1,

$$IIP_{3,1} = 10 \cdot \log\left[\frac{10^{\frac{27+13.6}{10}}}{10^{\frac{27}{10}} + 10^{\frac{13.6+5.6}{10}}}\right] = 12.9 \text{ dBm}$$

Solving for path 2, the link gain is 2.5 dB, and IIP3 is 13.3 dBm.

SFDR

Using the noise figure and input intercept, we can calculate SFDR$_3$:

$$SFDR_{3,1} = \frac{2}{3}\left[174 + 12.9 - 29.5\right] = 104.9 \text{ dB·Hz}^{2/3}$$

and

$$SFDR_{3,2} = \frac{2}{3}\left[174 + 13.3 - 32.3\right] = 103.3 \text{ dB·Hz}^{2/3}$$

APPENDIX A

DiLink Noise and Linearity Constants

For each of the DiLink series fiber optic link pairs, noise and linearity constants are shown in Table A-1. The specified link gain should be used as the reference gain in the system equations (0 or 15 dB).

Style	Spec Link Gain (dB)*	Spec Freq (MHz)	Spec RF Input IP3 (dBm)*	Spec Link Noise Figure (F)*	cth (dBm/Hz)	cshot (dBm/Hz)	crin (dBm/Hz)	IIPeq (dBm)	OIPeq (dBm)
W	0	2 to 500	15	30	-153.4	-157.3	-152.3	16.8	28.3
W	0	100 to 1000	15	30	-153.4	-157.3	-152.3	16.8	28.3
W	0	500 to 2500	15	30	-152.2	-157.0	-151.0	17.0	27.1
W	0	1000 to 4000	12	30	-152.2	-157.0	-151.0	14.5	24.1
W	15	2 to 500	10	30	-138.4	-142.3	-137.3	16.8	29.3
W	15	100 to 1000	10	30	-138.4	-142.3	-137.3	16.8	29.3
W	15	500 to 2500	10	30	-138.2	-142.0	-137.0	16.7	28.7
W	15	1000 to 4000	6	30	-137.2	-141.0	-136.0	14.5	25.7
N	0	2 to 100	17	29	-154.0	-158.0	-153.0	18.3	28.1
N	0	100 to 500	17	29	-154.0	-158.0	-153.0	18.3	28.1
N	0	900 to 2250	17	30	-152.1	-156.0	-151.0	19.8	27.1
N	0	2000 to 3400	12	28	-154.9	-159.0	-154.0	13.6	23.6
N	15	2 to 100	13	29	-139.0	-143.0	-138.0	18.3	32.5
N	15	100 to 500	13	29	-139.0	-143.0	-138.0	18.3	32.5
N	15	900 to 2250	13	30	-137.1	-141.0	-136.0	19.8	31.4
N	15	2000 to 3400	8	28	-139.9	-144.0	-139.0	13.6	27.0
I	0	2 to 100	30	43	-139.4	-143.0	-138.0	36.7	32.5
I	0	100 to 500	30	43	-139.1	-143.0	-138.0	36.7	32.5
I	0	900 to 2250	29	43	-139.4	-143.0	-138.0	36.7	31.1
I	0	2000 to 3400	22	43	-139.4	-143.0	-138.0	36.7	24.8

* At 0 dB Optical Loss. Spec values are worst case over temperature and frequency.

Table A-1. Noise and Linearity constants for *DiLink* series Fiber Optic Link pairs.

LINEAR PHOTONICS, LLC
Bringing Performance to Light!

3 Nami Lane, Suite 7C
Hamilton, NJ 08619
Tel. 609*584*5747
Fax. 609*631*0177
email: linfo@linphotonics.com

www.linphotonics.com