State of the Art in Analog Fiber-Optic Link Technology

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ABSTRACT

In this paper we present the principle figures of merit that quantify the performance of analog fiber-optic links. We list the main applications of analog links and speculate on what level of performance from a single link would satisfy the requirements of all these applications. We discuss the extent to which present device technology precludes the achievement of this level of performance, and specify the technology advancements required to close this performance gap.

INTRODUCTION

At the output end of a fiber-optic link there are two methods that can be employed to recover the analog signal from its optical carrier—*direct detection* and *coherent detection.* Coherent detection may eventually yield better performance than direct detection, but so far has been hindered by the substantial degree of optical phase noise from most optical sources. Direct detection also has its limitations, its main drawback being that it is blind to optical frequency or phase modulation. That is, it can only sense and recover a signal that *intensity-modulates* the optical carrier. The analog link models and results presented in this paper apply to intensity-modulation/ direct-detection (IM/DD) links.

At the input end of the link an optical source generates a carrier at the desired wavelength, and a modulator imposes the analog signal on the optical carrier. The optical source and the modulator can be a single device such as a semiconductor laser whose optical output is *directly modulated* by an analog signal applied in conjunction with the dc bias current. Alternatively, the optical carrier from the laser can be *externally modulated* by the analog signal that is applied to a separate device (that is therefore called an "external modulator").

We define the "link" to include the optical source, modulator, fiber, and optical receiver (which, in the direct-detection case, is just a single photodetector such as a p-i-n photodiode), but not any electronic or optical amplifiers. The link has RF input and output ports, and as such can include passive circuits that transform their impedances to match those of the modulation and detection device impedances, respectively.

There are three main figures of merit that quantify the analog performance of a two-port electronic device such as a fiber-optic link. Gain, G, is a measure of efficiency in that it is the ratio of the output RF signal power to the input RF signal power (for small input powers). Noise figure, NF, expresses the extent to which the signal-to-noise ratio degrades between the input and output of the link. Spurious-free dynamic range, $SFDR$, is the maximum range of input signal powers for which the output signal is greater than the output noise but the output distortion products resulting from device nonlinearities are below the output noise.

ANALOG LINK PERFORMANCE GOALS

What constitutes desirable link performance depends on the application into which a link is inserted as a replacement for a coaxial cable or other RF waveguide. Analog fiber-optic links have found widespread use as a means of cable television (CATV) signal distribution. CATV distribution system designers wish to have a single link carry as many channels as possible without significant distortion of any one channel. They use a measurable parameter called "composite triple beat" (CTB) to quantify the level of distortion resulting from a given number of channels. When channels are spaced at equal frequency intervals, a small part of the information transmitted on three of the channels can appear as distortion on a fourth channel transmitted at a frequency that is the sum of two channel frequencies minus the third channel's frequency. Thus CTB, like $SFDR$, is a measure of nonlinearity. To meet the CTB requirements of CATV applications, the link $SFDR$ must exceed 110 dB in a 1 Hz bandwidth [1].

Analog fiber-optic links can also carry cellular telephone calls and personal communication system (PCS) signals between the antenna base stations and the central routing station. The "up-link" (which carries information from the antenna site to the central station) must perform very well to maximize the number of calls that can be conveyed simultaneously. To maximize the area that one antenna station can cover it is important to maximize link sensitivity, which means that low NF is required. Additionally, signals conveyed by the up-link must not undergo significant distortion, which means that high *SFDR* is also required. The design specifications for the "up-link" (carrying information to be transmitted by the antenna to the user) are not nearly so stringent, because the signal can be regenerated at the central routing station after being conveyed there by an up-link. However the down-link signal must not fade significantly in the process of reaching the antenna base station—that is, there needs to be a specification for minimum G [2].

Another application in which analog fiber-optic links might prove extremely useful is the routing of signals to and from antennas remotely located from a radar's signal generating and processing equipment. As in the case of the links for routing cellular and PCS signals, the links for bringing received signals to the central receiver/signal-processor equipment from the remote antennas have more stringent performance requirements than the links that carry transmit signals to the antennas from the signal generators. It has been proposed that a link exhibiting $NF < 6$ dB and $SFDR > 145$ dB in a 1 Hz bandwidth would meet or exceed the performance needs of most receive radar antennas, whereas for transmit applications the most desired performance trait is that G exceed –3 dB [3]. A single link with $G > -3$ dB along with the *NF* and *SFDR* proposed for the receive radar antenna remoting link would meet or exceed the performance desired for any of the applications mentioned so far. In the remainder of this paper we examine the extent to which present device technology precludes the achievement of this level of performance, and specify what technology advancements are needed to close this performance gap.

GAIN

In a direct-modulation/direct-detection fiber-optic link, G is proportional to the square of the product of the small-signal "slope" efficiencies of the optical source/modulator (usually a semiconductor diode laser biased above threshold) and the detector (usually a reverse-biased p-i-n photodiode). The laser's slope efficiency S_L expresses the change in its optical output power for a given change in input current, and the detector's slope efficiency S_D is the change in output current resulting from a given change in input optical power. Therefore the product of S_L and S_D is the detector output *current* for a given laser input *current*; G, the output and input signal *power* ratio, is proportional to the square of this product. Theoretically the maximum possible G should be obtained if each electron that comprises the laser's input current generates one photon, and if each photon reached the detector and generates an electron-hole pair; this would correspond to $(S_LS_D)^2=1$, resulting in $G=0$ dB in the case of equal source and load impedances.

In another paper [4] we presented the measured slope efficiencies and 3-dB (electrical) bandwidths that have been reported recently for detectors and directly modulated semiconductor lasers of various types. The highest of those fiber-coupled laser and detector slope efficiencies are plotted along the left-hand vertical axis of Figure 1. For a link consisting of a laser diode resistively matched to the RF source impedance, and an output load impedance (equal to that of the RF source) applied directly across the high reverse-biased detector impedance, G is equal to $(S_LS_D)^2$. We have calculated and plotted on the right-hand vertical axis the maximum G achievable using the two most efficient devices available at a given frequency.

Note that even for frequencies below 3 GHz the link resulting from the combination of the most efficient detector and directly-modulated semiconductor laser would have G equal to –12 dB. It is clear that improvements in device slope efficiency and fiber coupling efficiency are needed to achieve the –3 dB link gain we have established as our goal.

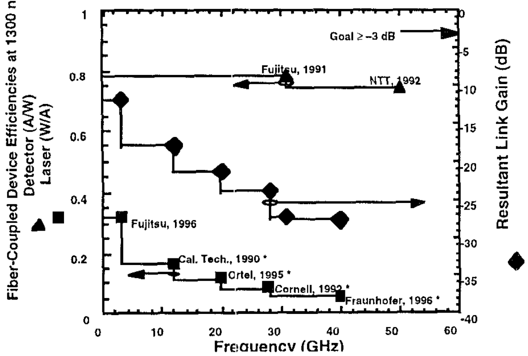


Figure 1 Reported detector and laser slope efficiencies, and the link G calculated vs. frequency by assuming the use of the laser and detector having the highest slope efficiencies at that frequency.

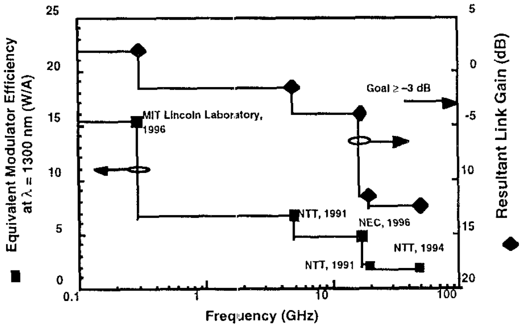


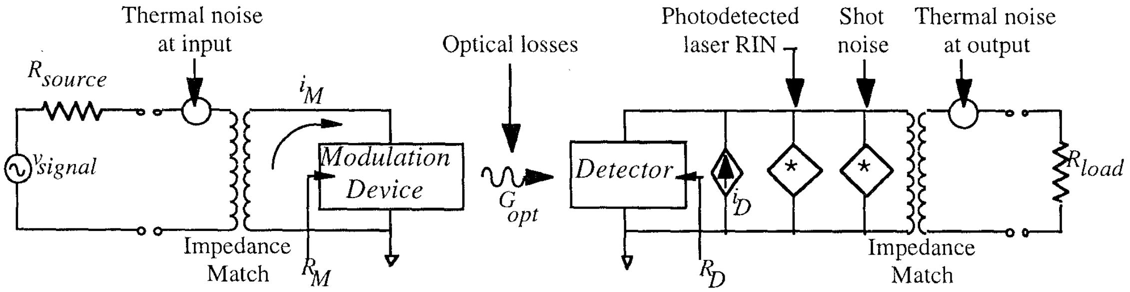
Figure 2 Reported electro-optic modulator efficiencies as a function of frequency, assuming an input optical power of 400 mW, and the link gain calculated vs. frequency by assuming the use of a modulator and detector having the highest slope efficiencies at that frequency.

In an external-modulation fiber-optic link, G is proportional to the square of the product of the small-signal "slope" efficiencies of the external modulator (usually an MZ interferometer manufactured in lithium niobate) and the detector (usually a reverse-biased p-i-n photodiode). The modulator's slope efficiency S_M is the change in its optical output power for a given change in input voltage; it is proportional to the CW optical power fed to the modulator (P_I) and inversely proportional to the voltage necessary to extinguish light at the modulator output (V_π). Theoretically one can increase the modulator slope efficiency indefinitely by endlessly increasing P_I. Practical considerations such as the cost of high-power lasers and the damage threshold of the modulator and detector preclude this, of course, but P_I values as high as 400 mW at λ=1300 nm have been successfully fed through an MZ modulator [5]. To increase S_M even further would require that V_π be reduced—a goal that modulator designers continue to pursue.

We previously [4] summarized the slope efficiencies and bandwidths that have been reported for MZ external modulators. On the left-hand vertical axis of Figure 2 we have plotted the highest slope efficiencies reported for MZ modulators vs. their 3 dB bandwidths. For a link consisting of a modulator with a 50 Ω electrode impedance connected directly to a 50 Ω RF source impedance, and an output load impedance (also 50 Ω) applied directly across the high reverse-biased detector impedance, G is equal to $(S_M S_D)^2$. We have calculated and plotted on the right-hand axis of Figure 2 the maximum G achievable using the most efficient modulator available at a given frequency, together with a 50 GHz detector demonstrated by researchers at UCLA, JPL, and Lucent Technologies [6]. Using this detector even at lower frequencies where some detectors have greater efficiency always yields the best link gain because it can always withstand the optical power that illuminates it when the modulator input optical power is 400 mW. Note that for frequencies below 5 GHz the link resulting from the combination of the 50 GHz detector and the most efficient external modulator fed by a 400 mW of CW optical power would have a gain G in excess of the –3 dB goal. Above this frequency it is clear that improvements in modulator slope efficiency are needed to achieve the gain goal of –3 dB or greater.

NOISE FIGURE

Next we discuss link noise figure NF and the device characteristics that affect it. The fiber-optic link's equivalent circuit model shown in Figure 3 helps to illustrate how various device parameters affect the magnitude of each term in the NF expression (also shown in the Figure).



$$G = \left(S_M G_{opt} S_D\right)^2 \frac{R_D}{R_M} \quad \text{if} \quad R_{load} = R_{source}$$

$$NF \equiv 10\log\left[\frac{\left(S/N\right)_{in}}{\left(S/N\right)_{out}}\right] \quad \text{for } \bar{N}_{in} = kT_0 \text{ and } T_0 = 290\text{K} \qquad = 10\log\left[\frac{\bar{N}_{out}}{kT_0\,G}\right]$$

$$\text{Therefore, } NF = 10\log\left[\overset{\text{Thermal noise from source}}{1} + \overset{\text{Thermal noise from modulation device}}{\ldots} + \overset{\text{Photodetected laser RIN}}{\frac{I_D^2\,RIN\,R_D}{kT_0\,G}} + \overset{\text{Shot noise}}{\frac{2qI_D R_D}{kT_0\,G}} + \overset{\text{Thermal noise at output}}{\frac{1}{G}}\right]$$

Figure 3 Equivalent circuit of an IM/DD link, and expressions for the gain and noise figure.

As in any two-port electronic device, thermal noise arises from the input source impedance. When transmitted through the fiber-optic link along with the input signal, the input thermal noise undergoes the same gain or loss as the signal does. The equations on this chart show how this dictates that the minimum *NF* for any two-port electronic device is 10•log(1), or 0 dB. The resistive portion of the modulation device (the external modulator or directly-modulated semiconductor laser) and any RF loss in the input impedance matching circuit can also contribute to the total thermal noise that will modulate the optical carrier. Depending on the type of modulator and method of impedance-matching, this either will or will not result in an additional input thermal noise term [7].

Two sources of noise have proven to be particularly problematic for analog fiber-optic link designers. The noisy nature of the optical source is quantified by a term called its *relative intensity noise* (*RIN*). This noise is detected along with the signal, so it is shown in Figure 3 as a noise current in parallel with the photodetected signal current i_D. Additionally, the detection process itself results in shot noise, which is also shown as a noise current source. These sources of noise result in two terms in the *NF* equation that are inversely proportional to *G*. The shot noise term is proportional to the average photocurrent I_D. The *RIN* term is proportional to the square of I_D. In an external modulation link the modulator slope efficiency is proportional to the average CW optical power, and therefore the link *G* is proportional to the square of I_D. This makes the *RIN* term independent of I_D and the shot noise term inversely proportional to I_D. Therefore, using a high-power, low-*RIN* optical source such as a solid-state laser should enable low *NF*s for external modulation links.

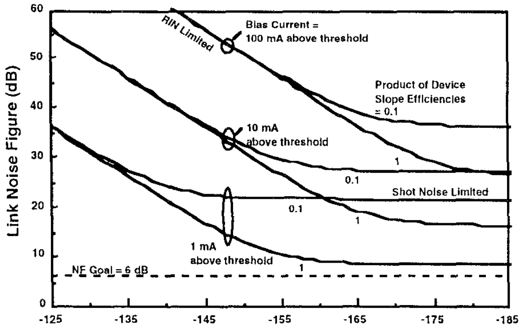


Figure 4 **Direct modulation link noise figure's dependence on the semiconductor laser's RIN, the laser bias current above threshold, and the product of the fiber-coupled laser and detector slope efficiencies.**

Finally, thermal noise from the resistive portion of the detector circuit will have a spectral density equal to kT_0 at the link output, resulting in a contribution of a $1/G$ term to the *NF* expression.

In a direct modulation link the *NF* is usually dominated by either the photodetected laser *RIN* or by the shot noise. Figure 4 shows the effect of laser *RIN* on the direct modulation link's *NF*. Curves are shown for a semiconductor laser at three different DC bias currents, and with two different sets of laser and detector slope efficiencies. Starting with the case where the laser is biased at only 1 mA above its threshold current, notice how as the laser *RIN* is decreased, the *NF* decreases up to a point, then is invariant as the *RIN* is decreased further. The *RIN*-invariant performance occurs when the laser *RIN* is low enough to cause shot noise to dominate the noise figure.

Note also that in the shot-noise limited regime, *NF* is much lower when the fiber-coupled laser and detector slope efficiencies are high. The best theoretically attainable case is when the product of these efficiencies is 1. However the other curve, corresponding to a product of slope efficiencies equal to 0.1, better represents typical device performance.

It is also more typical for the laser to be biased at least 10 mA (rather than only 1 mA) above its threshold current. This is due to the fact that efficient direct modulation of a semiconductor laser cannot occur above its relaxation oscillation frequency, which is typically low at threshold but increases as the square root of the bias current above threshold [8]. For efficient modulation of a DFB at 10 GHz, for instance, it is often necessary to apply a bias that is 40-60 mA above threshold [9].

Figure 4 shows what device characteristics must be achieved to minimize direct modulation link *NF*: first, both the laser and detector must have high fiber-coupled slope efficiency; second, the laser's high slope efficiency must be achieved over a broad frequency range under low bias current; third, the laser must exhibit low *RIN* under low bias current. Note, however, that even achieving the theoretically ideal device efficiencies and infinitely low *RIN* for a laser bias of only 1 mA above threshold will not enable a direct modulation link's *NF* to reach the goal of ≤ 6 dB we have set.

For reasons already stated it is possible to achieve high *G* and low *NF* when designing an external modulation link. If a low-*RIN* solid-state laser is used, then performance improves as the optical carrier's average power is increased.

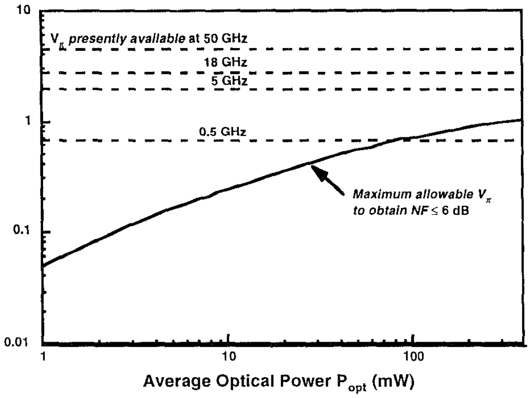


Figure 5 Maximum external modulator halfwave voltage V_π allowable for a given available CW optical power P_I in order to achieve a link noise figure of less than 6 dB.

Figure 5 shows how an external modulation link's NF depends on the CW optical power fed to the modulator and on the modulator's V_π. The solid curve shows for a given amount of CW optical power how small the modulator's V_π must be in order to achieve a link NF of 6 dB or less. It makes sense that as the optical power increases, V_π doesn't need to be as low in order to yield the same link NF. The curve begins to level off as optical power continues to increase, because at some point the input thermal noise rather than the shot noise becomes the dominant contribution to the link NF (at which point NF becomes invariant with both the average detector current and G).

SPURIOUS-FREE DYNAMIC RANGE

Finally we discuss link spurious-free dynamic range ($SFDR$) and the device characteristics that affect it. Recall that the goal we have set for our hypothetical "ideal" link is $SFDR$ > 145 dB in a 1 Hz receiver bandwidth.

If two fundamental tones are fed to the input of a two-port device, nonlinearities in the device transfer function will result in the generation of harmonic and intermodulation distortion. Second-order intermod spurs are the strongest distortion products, but occur at frequencies far from the closely-spaced fundamental tones themselves. Therefore in a link that operates across an RF frequency band less than one octave wide, the third-order intermodulation products will be the strongest and cannot be filtered out.

There are many methods that can be, and in some cases have been, employed in order to "linearize" the modulation device's transfer function to extend the link's $SFDR$. One set of techniques, which have been employed to linearize other types of two-port electronic devices, involves the deliberate introduction of additional nonlinearity before or after the modulation device in such a way that the combined transfer function is more linear. The names of the specific techniques (*i.e.*, predistortion, feedback distortion and feed-forward distortion) are derived from the point in the link at which the additional nonlinearity is introduced. Each of these has the disadvantage that the nonlinearity for which the compensation is added must not change as the environmental conditions vary.

Obviously, a modulation device with a higher degree of linearity will improve a link's $SFDR$. There is no known fundamental limit to how linear one can make the above-threshold portion of a semiconductor laser's transfer function. A standard MZ modulator, however, always has a sinusoidal transfer function arising from the interferometry. Another, less maturely developed, type of modulator that does not rely on interferometry to modulate the optical intensity is the electro-absorption (EA) modulator. As the name implies, in this device the RF signal modulates the degree to which an optical carrier is absorbed. As for the directly-modulated laser, there is no known limit to how linear the transfer function of an EA modulator can be. To date, however, most EA modulators are quite nonlinear and cannot withstand large optical power levels; therefore they do not achieve low link NF in conjunction with high $SFDR$.

Standard MZ modulators can be configured in novel optical combinations that yield improved linearity, as several authors have shown [10-15]. These "linearized" MZ modulators can exhibit very large $SFDR$; however maintaining on several electrodes the correct electrical signal balance required for linearization gets progressively more difficult as the RF frequency and/or percentage bandwidth of operation are increased.

Direct optical frequency modulation using a semiconductor laser can be performed with high linearity. Optical phase modulation in an electro-optic material like lithium niobate is also a highly linear process. Retrieving either of these types of optical modulation requires coherent optical detection, and therefore a more complex optical receiver than is needed for direct detection. Initial studies suggest that the highest $SFDR$ is possible using optical FM with coherent detection, but only if methods can be developed for reducing or counteracting the optical phase noise output of most lasers [16].

SUMMARY AND RECOMMENDATIONS

We have reviewed the state of the art in analog optical links, concentrating primarily on links employing intensity modulation and direct detection of the optical carrier. In doing so, we discussed advances in some of the most commonly used link components, including optical detectors, semiconductor laser diodes, and external modulators. Techniques for improving the noise figure and extending the dynamic range performance of these links were reviewed. Specifically, IM/DD link applications would benefit greatly from the following device technology developments (some of which we have not discussed in this paper):

- Photodetectors that can handle high optical power with high slope efficiency at high frequency
- Diode lasers with modulation bandwidths above 30 GHz (up to 100 GHz, for example)
- Diode lasers with higher fiber-coupled slope efficiency, and with better linearity
- Wideband linearization, *i.e.*, linearization of both second- and third-order distortion, that does not sacrifice the noise figure
- Polarization independent modulators
- A modulator material that is more compatible with semiconductor processing
- High-power CW lasers with wide intermodal spacing
- Lower cost components

We also believe that optical FM/coherent-detection link technology should be further developed. It is expected that if the optical phase noise from FM-modulatable optical sources can be reduced, optical FM links can achieve the *SFDR* goal more readily than IM/DD links.

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