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What Do We Need to Get Great Link Performance?

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SUMMARY

It is well known that the RF performance of optical fiber links falls short of what is desired, and often required. These seem to be the facts of life: links using commercially available components have at least 20 dB of RF loss, their noise figures are even greater than their loss, and their dynamic ranges are marginal to acceptable [1]. Further, all three of these performance parameters degrade significantly with increasing frequency. This state of affairs is in stark contrast with the fundamental limits of link performance [2], which have shown that low loss, low noise figure, high linearity links should be possible, even up to fairly high frequencies. So why have we not been able to realize links with such performance? We will pursue the answer to this question by hypothesizing a set of link requirements and seeing what level of device performance would be required to meet it.

Assume that we desire a link with an RF-to-RF gain (G_l) of -3 dB over a bandwidth of less than one octave, a noise figure (NF) of 6 dB, and an intermodulation-free dynamic range (IMFDR) of 145 dB in a 1 Hz bandwidth. For the purposes of this discussion we will also limit consideration to amplifierless links using intensity modulation with direct detection (IMDD) and with passive impedance matching at the input and output ends of the link.

Link Gain

To get an estimate of the link gains we can expect, we have surveyed the device literature for values of the parameters we use in our link models (as described in [3]). Figures 1 and 2 show, respectively, the calculated direct and external modulation link gains vs. frequency, based on these device data and assuming that details like having a common wavelength have been resolved. Thus even the devices in development fall short of our hypothetical goals.

Let us now turn the tables and ask: what level of device performance would be required to achieve the hypothetical link goals listed above? The expression for IMDD link gain g_l is simply the product of the square of the fiber-coupled slope efficiencies for the modulation device and the photodetector [6]. Since we want $G_l = 10 \log (g_l) = -3$ dB, this corresponds to $g_l = 0.5$. Photodetectors are commercially available with fiber-coupled responsivities of 0.9 A/W, which is very close to the theoretical maximum value at $\lambda = 1.3$ µm of 1.05 W/A. To achieve a -3 dB link gain using this photodetector, we need a fiber-coupled laser slope efficiency of 0.78 W/A. This is a little more than double the current state-of-the-art fiber-coupled laser slope efficiency of 0.32 W/A [4], slightly above the best demonstrated slope efficiency of bare diode lasers, but well below the maximum theoretical efficiency at $\lambda = 1.3$ µm of 0.95 W/A. Consequently to improve the gain of direct modulation links it appears likely we will require not only more efficient fiber coupling, but also higher slope efficiency diode laser chips as well.

In external modulation links, gains as high as 31 dB have already been achieved, albeit at low frequencies [5]. However there are two issues that keep us from stating that the external modulation link gain problem is completely solved. One is the high average optical power needed to achieve these record results; at present these power levels require a relatively large—and

expensive—solid-state laser. The other issue is that the modulator sensitivity tends to decrease as the frequency increases (due to increased loss in the traveling-wave electrodes), thereby decreasing the link gain at higher frequencies. Note from Figure 2 that only at frequencies below about 5 GHz have traveling-wave modulators come close to exhibiting the modulation efficiency needed to achieve the hypothetical link gain goal of -3 dB.

Link Noise Figure

The noise figure of direct modulation links is usually dominated by the diode laser relative intensity noise (RIN). Consequently for direct modulation links to meet the hypothetical link noise figure goal will require decreasing the RIN of diode lasers, together with high slope efficiency. Generally even laser slope efficiencies that are sufficiently high for gain purposes fall short of yielding a desirable noise figure. For instance, assuming the laser and detector slope efficiencies give a -3 dB link gain, the noise figure of 6 dB we proposed above cannot be met even when RIN is negligible; shot noise is sufficient to preclude low direct modulation link noise figure unless low RIN can be achieved at a very small amount of bias current above threshold, as Figure 3 conveys.

External modulation link noise figures are dominated by shot noise if a low-RIN solid-state laser is used as the CW optical source. At low frequencies, 150 MHz, external modulation links have been demonstrated with a noise figure of 4.5 dB [5]. To meet the hypothetical link noise figure goal at higher frequencies will require increased modulator sensitivity at high frequencies and photodetectors with increased sensitivity and capable of handling high optical powers.

Link Intermodulation-free Dynamic Range

Given the hypothetical noise figure 6 dB, this dictates that if the dominant order of distortion (nonlinearity) in the link is three (as it is in suboctave links with no linearization) then an input third-order intercept power of 49.5 dBm must be achieved if the dynamic range goal of 145 dB proposed above is to be achieved. If the application of linearization techniques will increase the slope of the distortion products by canceling out lower-order nonlinearities, and we assume for the moment that this will affect only the slope and not the intercept point, then it is possible to take the dynamic range goal and work backwards to find the dominant order of distortion required, as has been done in Figure 4.

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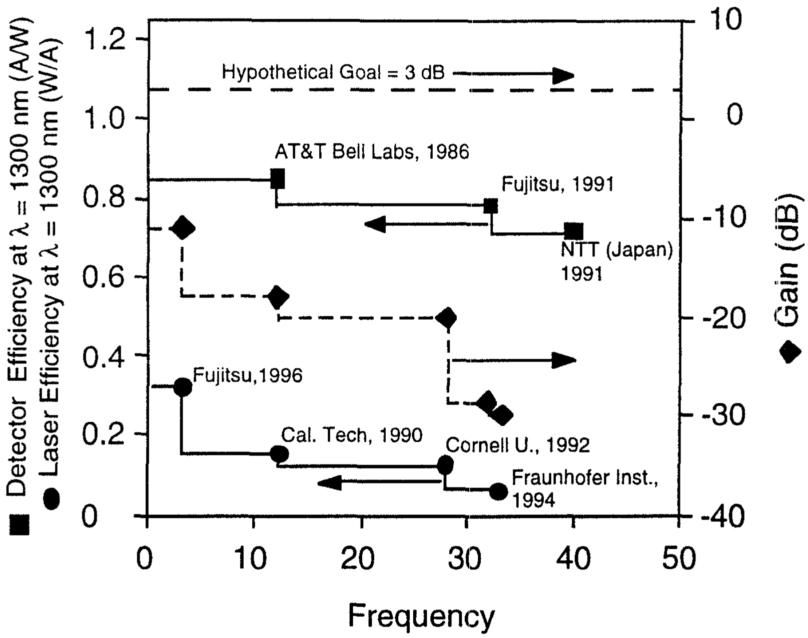

Figure 1:

Reported detector and laser slope efficiencies as a function of frequency, and the link gain calculated vs. frequency by assuming use of the laser and detector having the highest slope efficiencies at that frequency.

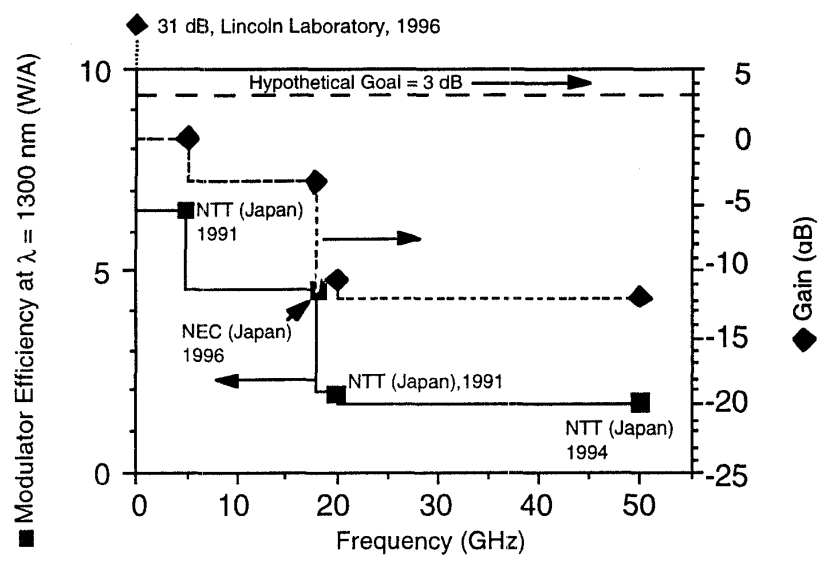

Figure 2:

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 use of the modulator having the highest slope efficiency at that frequency and a photodetector capable of handling the high optical power.

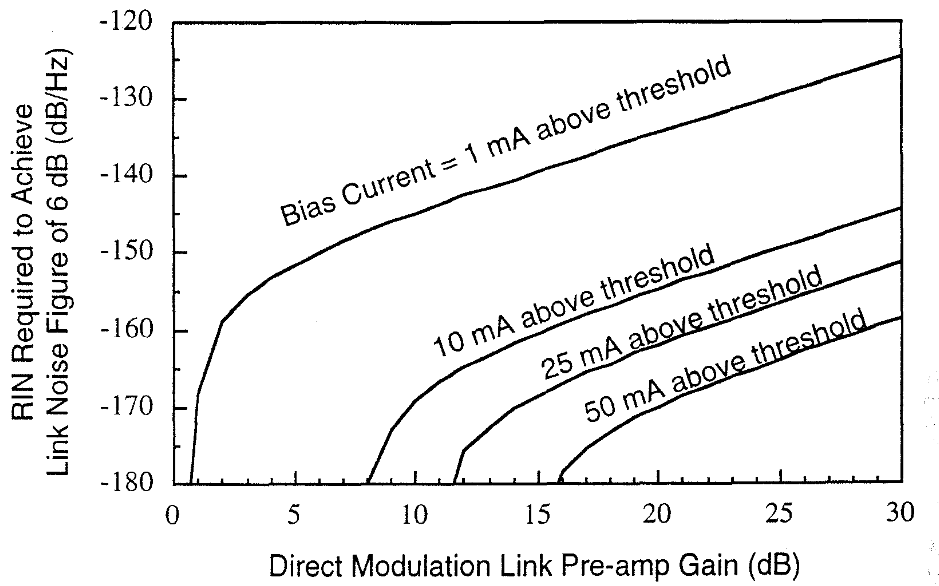

Figure 3: Directly modulated laser RIN required to achieve 6 dB link noise figure, as a function of laser DC bias current and pre-amp gain (assuming pre-amp noise figure of 2 dB and unamplified link gain of 3 dB).

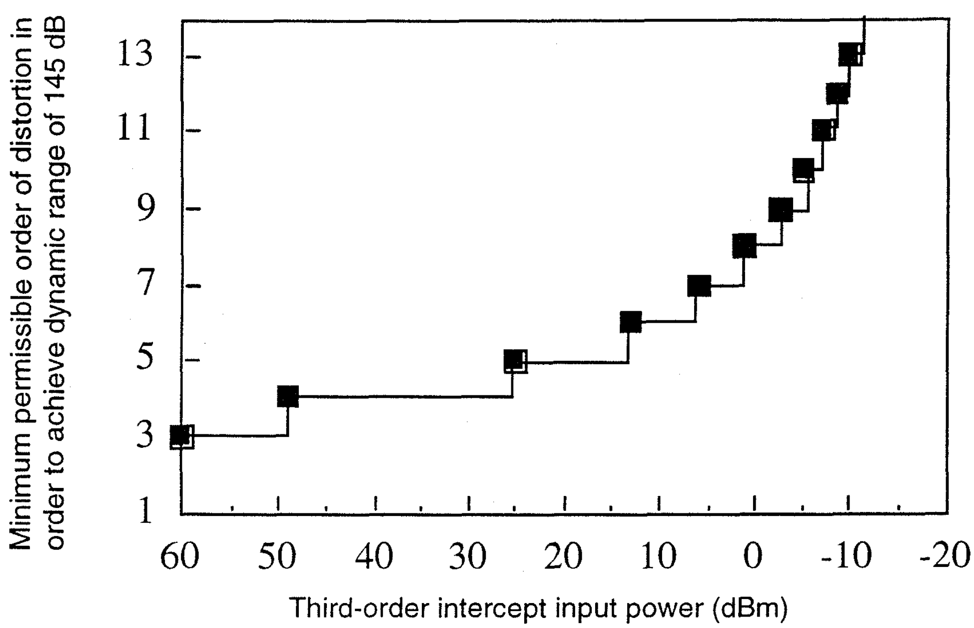

Figure 4: Minimum order of nonlinearity required to achieve hypothetical dynamic range goal of 145 dB, given a third-order intercept input power (assuming this is not dependent on the order of linearization).