AM FIBER OPTIC TRUNKS - A NOISE AND DISTORTION ANALYSIS

David Grubb III
Yudhi Trisno, PhD.

Jerrold - Applied Media Lab

ABSTRACT

Nonlinear optical effects in single mode fiber can limit the amount of power that can be coupled into a fiber. The threshold powers for these effects are calculated. The maximum practical optical modulation depth is limited by clipping. This clipping occurs when the peaks of the RF signal drive the laser below threshold. The maximum modulation depth is determined for both standard and HRC systems. The results are used to project system carrier to noise performance.

INTRODUCTION

There are two major issues in distributed feedback laser performance (DFB) for AM-VSB systems. These are output power and linearity. The use of DFB lasers for analog applications is a relatively new idea, having been taken seriously by optoelectronic device manufacturers for only the last year or so. Development of DFB lasers for analog applications is continuing rapidly and there is no indication that the pace is slowing. The question which this paper will attempt to answer is: what are the limits on link carrier to noise performance if highly linear DFB lasers can be developed? In order to answer this question this paper will address the following issues:

1) Output power - Assuming that the output power of laser diode chips will continue to increase over time, what then are the limitations on laser coupled output power due to nonlinear optical effects in single mode fiber.

2) Optical modulation depth - Assuming a perfectly linear laser could be developed, what would be the limitations on optical modulation depth as a function of channel loading. The limitation is due to distortion introduced when the peaks of the signal drive the laser below threshold. This will be examined for both standard and HRC systems.

The power and modulation depth limitations will be used to project realizable system performance as a function of channel loading.

OUTPUT POWER LIMITATIONS

Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) is a nonlinear optical phenomenon which can limit the amount of power coupled into an optical fiber. When the SBS threshold is reached the energy in the forward wave (signal) couples to a wave at a slightly longer wavelength traveling in the opposite direction in the fiber. The result is that the forward wave is severely attenuated. The threshold depends strongly on the source linewidth because the spontaneous Brillouin bandwidth is less than 100 MHz.[1] As the source linewidth increases beyond 100 MHz, the SBS threshold will increase. For narrow linewidth (<100 MHz) sources the SBS threshold can be calculated using the following equations.[2]

$$P_{TH} = \frac{21 \cdot A_e \cdot K}{g_B \cdot L_e} \qquad (1)$$

$$L_e = \frac{1 - e^{-\alpha L}}{\alpha} \qquad (2)$$

A_e = effective core area of the fiber
K = polarization factor $(1 \le K \le 2)$
g_B = peak Brillouin gain coefficient (4.6E-11 m/W)
L_e = effective interaction length (m)
α = fiber loss (m^{-1})
L = fiber length (m)

Figure 1 shows the SBS threshold for single mode fiber as a function of fiber length for two different attenuation rates corresponding to 1310 nm and 1550 nm operation. It is assumed that the effective core diameter is 11.5 μm and that K = 2 (complete polarization scrambling). This shows that for long links the maximum input power at 1310 nm is about 10 mW.

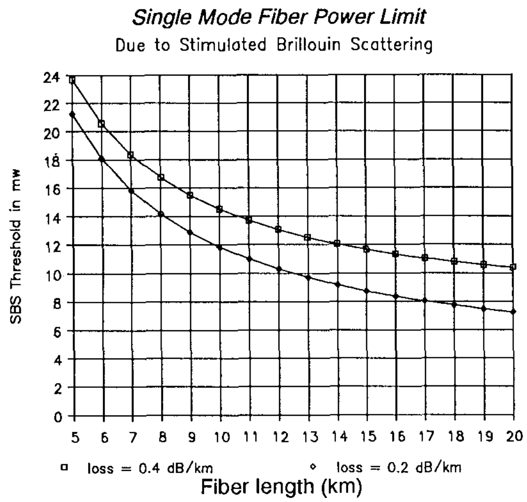


Figure 1

The actual SBS threshold for an AM-VSB system depends on the type of laser that is used and on the method of generating the optical signal. There are two methods commonly used to generate optical signals in AM-VSB systems. They are direct modulation and external modulation (see Figure 2). In direct modulation systems the source laser is usually a distributed feedback (DFB) laser. The linewidth of DFB lasers is typically less than 100 MHz with no modulation applied.[3] However, when the laser is intensity modulated the carrier densities in the active region are modulated. This causes the refractive index of the material to vary which in turn causes the laser output frequency (or wavelength) to vary. This phenomena is referred to as chirp. The amount of chirp a laser exhibits is a function of chip design but it is typically more than 5 GHz.[4,5] This effectively increases the source linewidth to many GHz when the laser is modulated. This means that for systems employing direct modulation the SBS threshold will be considerably higher than that shown in Figure 1.

In systems that use external modulators light is coupled from the laser source to an external electro-optic modulator. The modulating signal is applied to the external modulator. The laser is operated in a CW mode which means the source linewidth can be narrower than the spontaneous Brillouin bandwidth depending on the type of source chosen. This means that the SBS threshold could be as low as the levels shown in Figure 1.

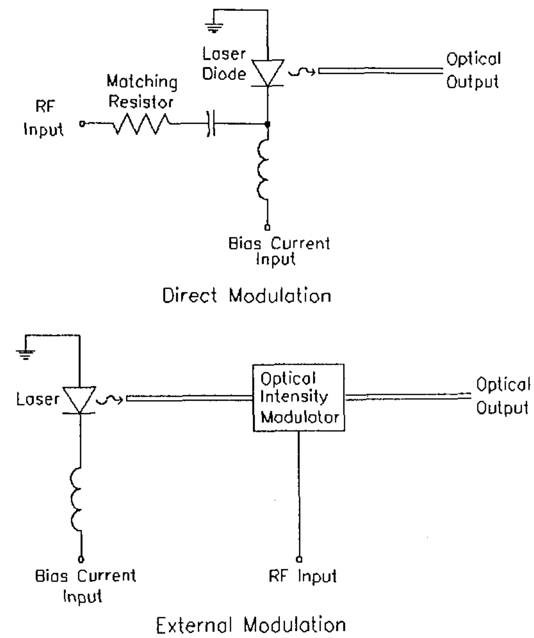


Figure 2

Stimulated Raman Scattering

Raman scattering can be thought of as the modulation of light by molecular vibration. The process generates Stokes light at wavelengths both shorter and longer than the pump wavelength. The Stokes light travels in both the forward and reverse directions. In long optical fibers the signal wave will act as the pump source for the Raman gain. In glass fibers the Raman gain-bandwidth is very wide so laser chirp should not affect the threshold. As with stimulated Brillouin scattering, when the stimulated Raman scattering threshold is reached it causes the fiber attenuation to become nonlinear. The SRS threshold can be computed using the following equation.[6,7]

$$P_{Th} = \frac{16 \cdot A_e \cdot K}{G_R \cdot L_e} \qquad (3)$$

A_e, K and L_e are as defined above

G_R = peak Raman gain coefficient (1.38E-13 m/W at 1.3μm)

Using this equation the SRS threshold is on the order of 8 Watts at 1310 nm for long fibers. From this result it is apparent that stimulated Raman scattering will not be a practical limitation on AM fiber systems.

OPTICAL MODULATION DEPTH LIMITATIONS

Optical modulation depth directly affects both carrier to noise and distortion performance. Generally, higher modulation depths will improve C/N and degrade distortion performance. The exact relationship between modulation depth and distortion depends on the characteristics of the particular laser. There is, however, an upper limit on optical modulation depth for even perfectly linear lasers. This upper limit on modulation depth per carrier depends on the number of carriers and the frequency plan that is being used. In order to mathematically determine the maximum useful modulation depth it is important to understand the characteristics of the composite RF signal. The most important characteristic of the signal is whether the individual carriers are correlated with each other. In a standard system with free running carriers, the carriers are uncorrelated. In an HRC system the carriers are all phase locked to a common reference, which means they are correlated.

In the case where the carriers are uncorrelated the characteristics of the composite CATV signal can be determined using statistical methods.

Let each carrier be represented by:

$$x_i(t) = m_i(t) \cdot \cos(w_i t + \theta_i) \qquad (4)$$

where:
w_i is the carrier frequency
θ_i is the carrier phase
$m_i(t)$ is the modulating signal

The composite signal which modulates the laser can be represented by:

$$y(t) = \sum_i x_i(t) \qquad (5)$$

The laser drive current is given by:

$$I(T) = I_{th} + I_{bias} \cdot [1 + y(t)] \qquad (6)$$

Where I_{th} is the laser threshold current and I_{bias} is the nominal bias current above threshold. When the signal, $y(t)$, exceeds the value -1 the laser is driven below threshold. The result of this is that the signal is clipped, causing distortion.

It is useful to examine the statistical distribution of the composite signal. In order to simplify the analysis, let $m_i(t)$ = constant (unmodulated carriers). Define a random variable X_i, formed by sampling the signal $x_i(t)$ at time T as follows:

$$X_i = x_i(T) \qquad (7)$$

$$X_i = m_i \cdot \cos(w_i T + \theta_i) \qquad (8)$$

where θ_i is uniformly distributed over the interval $-\pi$ to π.

The probability density function (pdf) of X_i is:[8]

$$p_{Xi}(x) = \begin{cases} \dfrac{1}{m_i \cdot \pi \cdot \sqrt{(1-(x/m_i)^2)}} & , |x| < m_i \\ 0 & , \text{otherwise} \end{cases} \qquad (9)$$

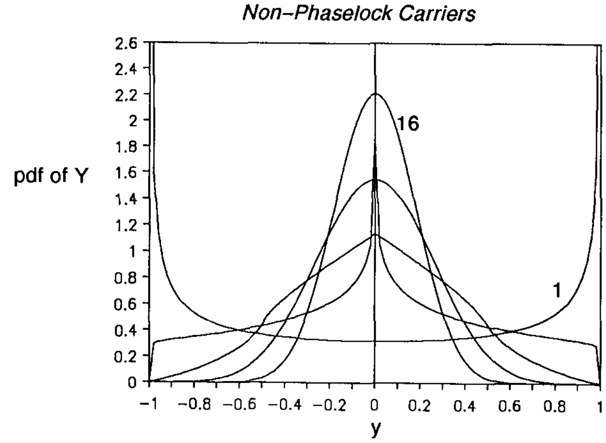
Define a random variable Y, formed by sampling the signal y(t) at time T. Assuming the random variables θ_i are statistically independent, the pdf of Y can be determined by convolving the pdf's of each individual signal.[9] So for N channels the pdf of Y can be determined as follows:

$$p_Y(y) = p_{X1}(y) * p_{X2}(y) * \ldots * p_{XN}(y) \qquad (10)$$

Figure 3 shows the function $p_Y(y)$ for different numbers of channels. The channel amplitudes, m_i, are normalized to $m_i = 1/N$ in each case. The function approaches a Gaussian distribution as the number of channels increases. For N>8, $p_Y(y)$ can be approxiamated by a zero mean Gaussian distribution variance given by equation 11.

$$\sigma = m_i \cdot \sqrt{(N/2)} \qquad (11)$$

Statistical Distribution of Sums of Non-Phaselock Carriers



1, 2, 4, 8, and 16 carriers

Figure 3

This result can be used to estimate practical values of modulation depth as a function of the number of channels. Assuming a perfectly linear laser, the only source of distortion in the laser's optical output is due to clipping when the signal drives the laser below threshold. For values of m_i less than 1/N this never occurs. As the modulation index is increased past some threshold, distortion due to clipping increases rapidly. Based on experimental results this threshold seems to be between 5% and 6% per carrier for a 40 channel system and between 7% and 8% per carrier for a 20 channel system. Assuming $m_i = 0.055$, then for 40 channels $\sigma = 0.055\sqrt{20} = 0.246$. The probability of the signal driving the laser below threshold at any given time is equal to the probability of a zero mean Gaussian random variable with $\sigma=0.246$ exceeding -1. This probability can be evaluated using the Q function[10] and it is roughly 2.5E-5. This probability is quite small but it seems to be significant in terms of measured distortion performance. This result can be used to project the practical modulation depth as a function of channel loading based on the assumption that the maximum practical value of σ is 0.246 regardless of the number of channels.

$$\sigma = m_i \cdot \sqrt{(N/2)} = 0.246 \qquad (12)$$

$$m_i = \frac{0.246}{\sqrt{(N/2)}} = \frac{0.348}{\sqrt{N}} \qquad (13)$$

In HRC systems the statistical distribution of the signal depends on the phase relationships between the channels. It is possible to choose the channel phases in such a way as to minimize the peak amplitude of the composite signal. It has been suggested by other authors that this could have an effect on system performance[11] but the extent of the possible improvement was not explored for AM fiber systems. In a 40 channel system with $m_i=1$ the peak signal level could be as high as 40. With proper selection of carrier phasing it is possible to reduce the peak signal level to less than 9.1. Figure 4 shows the pdf's of a 40 channel standard signal and a 40 channel optimally phased HRC signal. In both cases the carriers are unmodulated with $m_i=1/40$. The pdf of the HRC signal was determined by computer simulation of the signal. In general, we have determined that the peak signal level with optimally phased unmodulated HRC carriers can be determined using the following equation.

$$\text{Peak} \le 1.5 \cdot m_i \cdot \sqrt{N} \qquad (14)$$

pdf of Phase Optimized HRC Carriers
Compared to Non-Phaselock Carriers

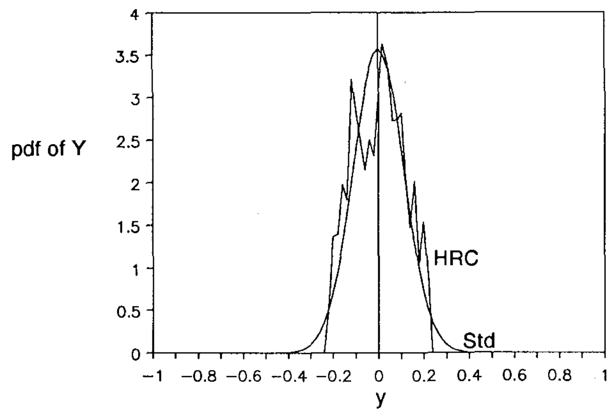


Figure 4

When the carriers are modulated with video information the peak signal level may increase somewhat. The extent of this increase has to be determined experimentally.

This expression for peak signal level can be used to determine the theoretical maximum useable modulation depth for HRC systems. The theoretical maximum is a modulation depth which results in a peak signal level just equal to one.

$$\text{Peak} = 1$$

$$1.5 \cdot m_i \cdot \sqrt{N} = 1$$

$$m_i = \frac{1}{1.5 \cdot \sqrt{N}} = \frac{0.67}{\sqrt{N}} \qquad (15)$$

Table 1 shows the calculated modulation index as a function of channel loading using equations 13 and 15.

Table 1

N	m_i (per carrier) Std	HRC
10	0.11	0.21
20	0.078	0.15
40	0.055	0.11
60	0.045	0.086
80	0.039	0.075

This result shows that it is at least theoretically possible to use modulation depths in HRC systems that are twice as large as the modulation depths that are practical in non-phaselock systems. This translates to a possible improvement in link carrier to noise ratio of up to 6 dB. The extent to which this improvement is realizable has to be determined by extensive laboratory testing.

SYSTEM PERFORMANCE

The carrier to noise ratio at the output of the link can be calculated using equation 16.[12]

The C/N is calculated in terms of mean squared currents at the input of the receiver amplifier. The numerator represents the mean squared signal current of each video carrier. The terms in the denominator are due to quantum noise, laser noise and receiver thermal noise (transimpedance receiver) respectively.

Figure 5 shows the AM link C/N versus laser coupled power for a 40 channel system with a 10 dB loss budget. The three curves were calculated based on the assumptions summarized in Table 2.

The quantum limit represents the upper limit on C/N performance due to quantum noise. The modulation depth per carrier was calculated using equation 15 because this represents the maximum achievable optical modulation depth. The two practical limits curves assume a state of the art optical receiver employing a high responsivity pin diode (0.9 A/W at 1310 nm). In order to simplify the analysis the laser RIN was assumed to be -160 dB/Hz. In reality the laser RIN is a function of the laser's output power, with the best DFB lasers consistently exhibiting RIN levels in the low -150's today.

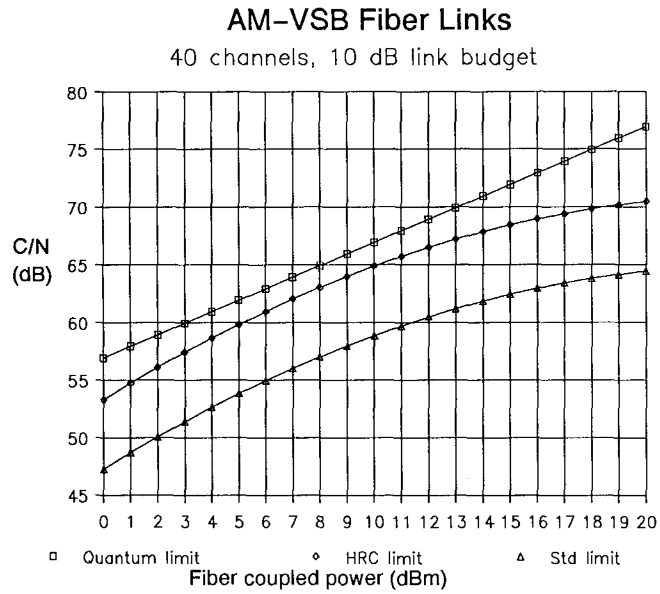


Figure 5

$$C/N = \frac{(m_i \cdot R \cdot Pr)^2}{(2 \cdot e \cdot Bv \cdot R \cdot Pr) + RIN \cdot Bv \cdot (R \cdot Pr)^2 + \frac{4 \cdot k \cdot T \cdot F \cdot Bv}{Rz}} \quad (16)$$

Where:
RIN = laser noise
m_i = optical modulation index
Pr = received optical power
Bv = video bandwidth
e = charge of an electron
k = Boltzmann's constant
R = photodiode responsivity
Rz = receiver preamp transimpedance
F = noise factor of preamp
T = receiver temperature

Table 2

	Quantum limit	Practical limit (HRC)	Practical limit (Std)
m_i	0.11	0.11	0.05
Photodiode quantum efficiency	100%	86%	86%
Laser RIN (dB/Hz)	No laser noise	-160	-160
Amplifier transimpedance (Ω)	No thermal noise	1200	1200
Amplifier noise factor	NA	2	2

CONCLUSIONS

These results show that for standard systems 40 channel link C/N performance of 55 dB is achievable with laser output power of 6 dBm (4 mW). This power level is well below the stimulated Brillouin scattering threshold of 10 mW for narrow linewidth sources. In systems using direct modulation or external modulation with broad source linewidths considerably higher power levels are theorectically possible. This could lead to higher C/N performance or longer link budgets. In optimally phased HRC systems the link C/N performance could be as much as 6 dB better than in standard systems. The actual amount of realizable performance improvement has to be determined by extensive lab testing.

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