PERFORMANCE OF AM MULTI-CHANNEL FIBER OPTIC LINKS

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ABSTRACT

This paper is a presentation of how the characteristics and specifications of the basic components of an AM fiber optic link are interrelated to determine system performance. A simple theory and basic equations for calculating link performance is developed. Of particular emphasis is the calculation of carrier-to-noise ratio for a fiber optic link. Factors determining system distortions are discussed, and trade-offs indicated. Performance data for a current state-of-the-art AM system is presented.

INTRODUCTION

Since the beginning of lightwave communications, fiber optic systems have been designed for digital transmission. For digital communications, the intensity of the optical source is modulated on and off (referred to as on-off keying, or OOK) in response to logic levels "zero" and "one". Because the modulation is digital, modulation linearity is not an issue. For analog modulation, however, modulation linearity is a basic system parameter and a key factor in some systems. Also, laser noise requirements are much more stringent with AM modulation. Subcarrier FM has been used to advantage in multi-channel CATV systems since it is less affected by modulation nonlinearities than AM systems and requires a carrier-to-noise ratio of only 16 dB or so. However, since the cable distribution system to the home must carry signals in the AM format, AM technology is the preferred technology in cases where system objectives can be met with AM.

This paper first discusses direct laser modulation, laser noise, and the effects of optical reflections on noise. Expressions for CNR (carrier-to-noise ratio) due to laser noise are given and CNR expressions are derived for the optical receiver. Laser distortion is discussed and relationships between distortions and channel loading are given. Data for a CATV prototype system are presented.

INTENSITY MODULATION OF OPTICAL SOURCE

Light is generated in a semiconductor laser by forward biasing the semiconductor junction with a dc current. The relationship of light intensity to input current is given by the L versus I curve. An example of a distributed feedback (DFB) laser L-I curve is given in Fig. 1. As indicated in Fig. 1, lasing begins at a bias current referred to as the threshold current, I_{th}, and increases nearly linearly for bias currents greater than threshold. The light intensity, L, is commonly given in milliwatts or dBm. The efficiency of the electrical-to-optical conversion is given by the slope efficiency SE of the laser, which is defined as the slope of the L-I curve at the operating point I_b:

Eq. 1 $$SE = \frac{\Delta L}{\Delta I} \qquad \mathrm{mW/mA}$$

Slope efficiency is also referred to as differential quantum efficiency. For the laser of Fig. 1, the slope efficiency is 8.5 percent. Note that efficiency is not dimensionless since the laser produces watts of output in response to amperes of input current.

To amplitude modulate a laser by a multi-channel AM CATV source, the broadband RF signal is added to the laser dc bias current. The amount of intensity modulation produced by the broadband RF signal is given by the modulation index. Modulation index is normally defined on a per-channel basis and is equal to the peak change in optical intensity divided by the average optical intensity. In this paper, it is assumed that all carriers are of equal amplitude. Modulation index m is defined as

Eq. 2 $$m = \frac{\Delta L_p}{L_o}$$

where ΔL_p is the peak change in optical power caused by a single RF carrier and L_o is the average optical power. The term optical modulation depth, OMD, is also used to define the amount of modulation and is identical to modulation index m.

Typically, for a 40 channel AM system, m ranges from .035 to .05.

Linearity of laser modulation is an important parameter in analog fiber optic systems. Laser linearity is measured by some manufacturers as the percent change in slope efficiency over the operating range normalized to the slope efficiency at the bias point, i.e.,

$$\text{Eq. 3} \qquad \text{LINEARITY} = \frac{\Delta SE}{SE_o}$$

where ΔSE is the change in slope efficiency and SE_o is the slope efficiency at the bias point. A plot of normalized slope efficiency as a function of current is given in Fig. 2. In this example, laser linearity is 8.5 percent for an optical modulation depth of 1.0.

Laser linearity is also specified by the amount of harmonic distortion generated by the laser, and by two-tone second- and third-order distortion. Distortion is discussed in later sections in this paper.

LASER OPTICAL NOISE

In analog lightwave systems, noise from the optical source contributes to the optical link CNR and is an extremely important factor in practical system applications. Laser diodes produce fluctuations in light output, or intensity noise. This intrinsic intensity noise is caused by the statistical nature of the carrier re-combination process. Laser noise is defined by RIN (relative intensity noise) as

$$\text{Eq. 4} \qquad \text{RIN} = \frac{\langle L_n^2 \rangle}{L_o^2}$$

where $\langle L_n^2 \rangle$ is the mean-square spectral intensity of light output noise. Noise power is referred to a 1 Hz bandwidth and RIN is dimensionless. RIN is normally expressed in dB/Hz and is equal to 10log(RIN).

Theoretical analyses [1] show that intrinsic laser noise is maximum for laser threshold current and decreases as the bias current increases as follows:

$$\text{Eq. 5} \qquad \text{RIN} \propto \left(\frac{I_b}{I_{th}} - 1 \right)^{-3}$$

Generally, for commercially available lasers, laser types with a lower threshold attain better noise performance than those with a higher threshold for the same output power [1]. Intrinsic noise is essentially independent of modulation frequency at low frequencies and increases to a resonance peak corresponding to the relaxation-oscillation frequency of the laser. The overall shape of the RIN response curve has the same general characteristic shape as the modulation frequency response [2].

Knowing RIN and the modulation index, one can calculate the carrier/noise ratio in a 1 Hz bandwidth (C/No) and CNR for a 4 MHz bandwidth according to CATV practices. The equivalent input noise current $\langle I_n^2 \rangle$ that would produce optical noise equal to that produced by the laser is, from (1) and (4), given by

$$\text{Eq. 6} \qquad \langle I_n^2 \rangle = \text{RIN}\left(\frac{L_o}{SEo} \right)^2 \quad \text{A}^2/\text{Hz}$$

Likewise, for optical modulation depth of m, the peak input signal current is mL_o/SE_o. The mean-square signal current I_s^2 is

$$\text{Eq. 7} \qquad I_s^2 = \frac{1}{2}\left(\frac{mL_o}{SE_o} \right)^2 \quad \text{A}^2$$

From (6) and (7), the carrier-to-noise ratio for a 1 Hz bandwidth is

$$\text{Eq. 8} \qquad \text{C/No} = \frac{m^2}{2\text{RIN}}$$

Of particular interest is the carrier-to-noise ratio in a 4 MHz bandwidth due to laser noise:

$$\text{Eq. 9} \qquad \text{CNRrin} = \frac{m^2}{8 \cdot 10^6 \text{RIN}}$$

Expressed in dB,

$$\text{Eq. 10} \qquad \text{CNRrin(dB)} = -69 + 20\log(m) - \text{RIN(dB)}$$

Note that CNRrin due to laser noise is independent of laser power. The effect of link loss and the contribution of optical receiver noise on the link CNR is given in later sections.

As an example, if RIN = -153 dB and m = .04 (typical for 40 AM channels), CNRrin due to laser noise is 56 dB. Commercial DFB lasers with integral optical isolators are available with RIN better than -150 dB/Hz. These lasers are capable of meeting current objectives for AM applications.

Intrinsic laser noise can be altered considerably due to the interaction of the laser and optical fiber. Laser diode noise increases significantly when light is reflected into the laser by discontinuities in the optical path [1]. Near-end reflections, less than ~10 cm, interact with the laser cavity and cause mainly low-frequency noise in the kilohertz range. Reflections from ~10 cm to ~100 m cause periodic noise peaks in the RF spectrum, and reflections from greater than ~100 m cause noise with an almost flat noise spectrum in the HF and VHF range [1]. In [1], the quantitative evaluation of reflection effects on laser noise characteristics was reported. It was found for the three types of lasers investigated that the maximum laser-coupled reflected power should be -65 to -73 dB to limit the increase in induced noise to within a few dB of the intrinsic laser noise level.

To prevent excess reflection-induced laser noise in practical AM systems, lasers with internal optical isolators should be used. These devices are commercially available with 30 dB of optical isolation. Furthermore, because of the high isolation required, fusion splices are recommended to ensure optimum system performance.

PHOTODETECTION OF OPTICAL SIGNAL

An optical receiver must be employed to convert the intensity-modulated optical signal to an RF signal for distribution in the CATV feeder network. For AM CATV systems, PIN photodiode detectors are usually employed. FM and digitally modulated systems operate at lower signal-to-noise ratios than AM systems and thus the received optical power is usually lower. For those systems, an avalanche photodiode (APD) is often used. An APD functions similarly to a PIN photodiode except that the APD can provide current gain whereas the PIN is limited to unity gain. However, the APD generates more noise in the optical/electrical conversion and is therefore at a disadvantage where the received optical power is large. Therefore, this discussion will be limited to PIN photodiode detectors only.

A photodiode emits electrons in response to incident photons. Quantum efficiency η is defined as

Eq. 11 $$\eta = \frac{\textit{number of photoelectrons}}{\textit{number of photons}}$$

and is equal to (reflection loss)·(absorption loss)·(absorption efficiency). Typically, quantum efficiency for a PIN photodiode is approximately 80 percent at 1.3-1.5 µm, but an efficiency of approximately 95 percent can be realized.

Responsitivity R is the measure of detected current due to incident optical power. Responsitivity is given by

Eq. 12 $$R = \frac{\textit{detected photocurrent}}{\textit{incident optical power}} \quad \text{A/W}$$
$$= \eta\frac{q\lambda}{hc}$$

where q is electron charge ($1.6\cdot10^{-19}$), h is Planck's constant ($6.63\cdot10^{-34}$), c is light velocity, and λ is optical wavelength. In the ideal case, η = 100 percent and responsitivity is

R = 0.684 A/W at = .85 µm
= 1.046 A/W at = 1.3 µm
= 1.248 A/W at = 1.5 µm

PHOTODIODE SHOT NOISE

A photodiode detector also generates a noise current called shot noise. Shot noise is caused by the discrete nature of electrons. In a photodiode, discrete charge carriers are generated by the incident optical signal and each contributes a pulse of current to the total dc current. These pulses are emitted randomly in time and thus produce a noise current referred to as shot noise.

For a PIN photodiode, shot noise $<I_{sn}^2>$ is equal to

Eq. 13 $$<I_{sn}^2> = 2qI_o \quad \text{A}^2\text{/Hz}$$
$$= 2qRP$$

where I_o is the dc current that flows in response to the incident optical power P. This shot noise limits the signal-to-noise ratio that can be achieved by the photodiode detector for a given optical input signal power. This limit is referred to as the quantum limit. If shot noise dominates in system operation, the system is said to be quantum limited.

Consider the signal current that flows in response to an incident optical signal. If the power incident on the photodiode is P watts, then from (2), the peak signal power is mP. The resulting peak signal current is mRP, and the mean-square signal current I_s^2 is

Eq. 14 $$I_s^2 = \frac{1}{2}(mRP)^2 \quad \text{A}^2$$

From (13) and (14), the signal-to-noise ratio in a 1 Hz bandwidth is

Eq. 15 $$\text{C/No} = \frac{m^2RP}{4q}$$

Thus, the quantum-limited CNR for 4 MHz bandwidth is

Eq. 16 $$\text{CNRsn} = 3.906\cdot10^{11}m^2RP$$

Expressed in dB,

Eq. 17 $$\text{CNRsn} = 85.9 + 20\log(m) + 10\log(R) + P(\text{dBm})$$

For example, if $m = .04$ (typical for 40 channels) and $R = .85$ A/W, the quantum limited CNRsn is 57.2 dB for $P = 0$ dBm. CNR decreases 1 dB per dB decrease in received optical power.

DETECTOR AMPLIFIER NOISE

Consider now the noise added by the amplifier that amplifies the output current of the photodiode. Even in an ideal case in which the amplifier contributes no excess noise, thermal noise is added by the load resistor that terminates the photodiode. Thermal noise current $\langle I_n^2 \rangle$ in resistor R_l at temperature T is

Eq. 18 $$\langle I_n^2 \rangle = \frac{4kT}{R_l} \quad \mathrm{A^2/Hz}$$

where k is Boltzmann's constant ($1.38 \cdot 10^{-23}$) and T is °Kelvin. If the amplifier noise factor is F, the equivalent input-current spectral density $\langle I_{an}^2 \rangle$ is

Eq. 19 $$\langle I_{an}^2 \rangle = \frac{4kTF}{R_l} \quad \mathrm{A^2/Hz}$$

Note that the noise factor of an amplifier is a function of the source impedance, which, in the case of interest herein, is a current source shunted by a small capacitance in the range of 1 pF. Thus, the amplifier noise figure in situ is likely quite different from that measured in a characteristic impedance of 50-75 ohms, as is generally the practice. Equivalent input noise current is better suited for the transimpedance amplifier concept than the more common noise figure specification.

As indicated in (19), it is desirable to increase the photodetector load resistance in order to decrease the amount of amplifier noise. FET amplifiers are designed for that purpose. However, the impedance level that can be achieved practically is limited by the inherent circuit capacitance and the bandwidth required. Practical values for AM CATV applications range from approximately 500 to 2000 ohms. The design value is, in general, a function of the received signal power and sensitivity required.

The signal-to-noise ratio due to amplifier noise only can be determined in a manner similar to that for the quantum limited case. The signal current is given by (15). The signal-to-noise ratio for a 1 Hz bandwidth due to amplifier noise is

Eq. 20 $$\mathrm{C/No} = \frac{(mRP)^2 R_l}{8kTF}$$

The amplifier-limited CNRan (for 4 MHz bandwidth) is

Eq. 21 $$\mathrm{CNRan} = 7.81 \cdot 10^{12} (mRP)^2 \frac{R_l}{F}$$

Expressed in dB, CNRan is

Eq. 22 $$\begin{aligned}\mathrm{CNRan(dB)} &= 68.9 + 20\log(m) \\ &\quad + 20\log(R) + 10\log(R_l) \\ &\quad - F(\mathrm{dB}) + 2P(\mathrm{dBm})\end{aligned}$$

For example, if the received power $P = 0$ dBm, and if $m = .04$, $R = .85$ A/W, $R_l = 1000$ ohms, and $F = 3$ dB, then CNRan due to amplifier noise is 66.5 dB. Note that CNRan due to amplifier noise decreases 2 dB per dB decrease in received optical power.

LINK CNR

The CNR for the fiber optic link can be obtained from the individual CNRs defined above in a manner similar to that used in computing the cascade CNR in a CATV system. Specifically,

Eq. 23 $$\mathrm{CNR} = \frac{1}{\frac{1}{\mathrm{CNRrin}} + \frac{1}{\mathrm{CNRsn}} + \frac{1}{\mathrm{CNRan}}}$$

If the CNR's are expressed in dB,

Eq. 24 $$\mathrm{CNR(dB)} = -10\log\left[10^{\frac{-\mathrm{CNRrin}}{10}} + 10^{\frac{-\mathrm{CNRsn}}{10}} + 10^{\frac{-\mathrm{CNRan}}{10}}\right]$$

For the preceding examples, $\mathrm{CNR_{rin}} = 56$ dB, $\mathrm{CNR_{sn}} = 57.2$ dB, $\mathrm{CNR_{an}} = 66.5$ dB, and, from (24), the total CNR is 53.3 dB. If the received power is decreased to -5 dBm, the system CNR is 49.9 dB.

Fig. 3 is an example of a plot of link CNR and CNR due to RIN, photodiode shot noise, and receiver amplifier noise. The laser output power is 2 mW and other parameters are the same as in the previous examples. Also, link distance is shown assuming the link loss budget is 0.5 dB/km.

INTERMODULATION DISTORTION

The main source of nonlinear distortion in a well designed fiber optic system is the laser itself. Other sources of distortion include interaction of the fiber with the laser and reflections and discontinuities in the fiber system. Laser linearity can be degraded by the reflection of light into the laser cavity [3], but with the laser optically isolated, as it should be to prevent reflection-induced excess noise, this effect should not be a problem. In addition to nonlinear distortions from reflected light, connectors and splices can generate additional distortion because the loss of connectors and splices is a function of optical frequency [4]. Nonlinear distortions occur since direct modulation of a semiconductor laser not only modulates the light intensity but also the wavelength. The photodiode and receiver should not add significant distortion. In [5], the nonlinearity of photodiodes was measured and it was concluded that photodiode distortion is negligible.

Intermodulation distortion studies have provided a theoretical basis for determining distortion in a laser as a function of physical parameters of the device [6][7]. In [7], expressions for second- and third- harmonic distortions and two-tone third order distortion are given. It was also concluded that those expressions are valid for a variety of lasers, including DFB and Fabry-Perot devices at wavelengths of 1.3 and 1.5 μm. In theory, only the small-signal response characteristics of the laser are required to predict distortion levels. In [8], experimental tests are reported which show that measured data at microwave frequencies agree well with theoretical calculations, including triple-beat distortion of the form F1 + F2 - F3.

In CATV and other systems, distortion is often calculated assuming the nonlinear device is without memory (nonlinearity is independent of frequency) and the transfer function of the device can be expressed by a power series. Although this is not a rigorous approach, the results can be reasonably valid and a meaningful relationship between system variables can be derived. This method has been used [9] to accurately describe laser nonlinearity and predict intermodulation products. Also, since in CATV applications the maximum modulating frequency is low compared to the resonant frequency of the laser, the simple model should be useful [10].

The development that follows is patterned after [9]. First, neglecting distortion, for a single carrier of modulation index m, the optical output $L_{(t)}$ of a laser is given by

Eq. 25 $$L_{(t)} = L_o(1 + m\cos\omega_m t)$$

A laser with nonlinearity is represented by the series

Eq. 26 $$L_{(t)} = L_o(1 + m\cos\omega_m t + C_2(m\cos\omega_m t)^2 + C_3(m\cos\omega_m t)^3)$$

where C_2 and C_3 are second-order and third-order distortion coefficients. The ratio of the second harmonic to the fundamental is $mC_2/2$, and the ratio of the third harmonic to the fundamental is $m^2C_3/4$. From this, it is evident that second-harmonic distortion, relative to the fundamental, increases in proportion to the per-channel modulation index. Third-harmonic distortion, relative to the fundamental, is proportional to m^2.

By applying two or more carriers, each with modulation index m, the results can be extended to the other second-order and third-order beats. Table 1 gives the relationship of the various beats and crossmodulation. It also shows the familiar principle that all second-order distortions, relative to the fundamental, increase in proportion to m, or at a 1 dB/dB rate. Likewise, the relative change in third-order distortion, including crossmodulation, is proportional to m^2 and changes at a 2 dB/dB rate. Note that the ratios in Table 1 are amplitude ratios; the factor 20log is used to convert to dB.

TABLE 1

ORDER	FREQ. TERMS	DISTORTION RELATIVE TO FUNDAMENTAL	RELATIVE VALUE (dB)
2	2F1	$\frac{mC_2}{2}$	0
2	F1 + F2	mC_2	6
3	3F1	$\frac{m^2C_3}{4}$	0
3	2F1 + F2	$\frac{3m^2C_3}{4}$	9.5
3	2F1 + F2 + F3	$\frac{3m^2C_3}{2}$	15.6
3	F1 (XMOD)	$\frac{3m^2C_3}{2}$	15.6

Composite triple beat (CTB) distortion and composite second order (CSO) distortion are the results of power addition of all second-order or third-order beats at the nominal frequency of interest. In systems not harmonically related and phase locked, frequency and phase uncertainties cause each beat to be distinct. The composite distortion is, therefore, given by the power addition of all beats at the nominal frequency. Distortion is calculated by counting the number of beats of a given type that fall at specific frequencies, and dividing the carrier/distortion ratio for a single beat of that type by the number of beats.

Crossmodulation is a third-order distortion and can be calculated based on parameters in Table 1 and the number of TV channels. Crossmodulation is measured according to CATV practices with all interfering carriers synchronously modulated. Therefore, as measured, crossmodulation distortion adds on a voltage basis. For N channels there are N-1 interfering channels to produce crossmodulation. The composite crossmodulation ratio is the ratio given in Table 1 (a power ratio) for one interfering channel multiplied by $(N-1)^2$. However, it has been the authors' experience that laser crossmodulation is not always predictable, due perhaps to the nature of synchronously modulating the laser at 15 kHz with a high modulation index. In addition, the laser semiconductor is thermally modulated causing the emission to be wavelength modulated. But, based on other perceptibility tests [11], crossmodulation is not expected to be a major factor with laser video modulation.

Figs. 4 and 5 present the distribution of beat counts as a function of channel loading. This data can be used to calculate CTB and CSO from knowledge of harmonic, two-frequency, or three-frequency distortion. For these figures, beat counts are calculated for the standard frequency plan (excluding channels A-2 and A-1). Fig. 4 presents beat counts for determining CSO distortion. Curve (a) is the beat count (in dB) for the top channel ($F_1 + F_2$ beats plus second harmonics); channel 2 is the bottom channel. Curve (b) is the beat count (in dB) for channel 2 ($F_1 - F_2$ beats).

Fig. 5 presents beat count data for determing CTB. Curve (a) is the equivalent triple-beat count for the worst channel in N channels. All channels start with channel 2. In some systems, it is advantageous to split the total number of channels into two or more bands on one fiber, with each band modulating a laser, in order to reduce CSO and achieve better performance. For those applications, curve (b) shows the beat count data for a contiguous band of N channels starting at any channel above A-2. These beats are triple beats of the form $F_1 + F_2 - F_3$ and two-frequency beats of the form $2F_1 - F_2$. The relative value of the latter is 6 dB less than that of the triple-beat and is weighted accordingly (1/4 the power) when determining the equivalent triple-beat count.

For the simple model of the static *L-I* characteristic described by Eq. 26, linearity as given by Eq. 3 can be related to the distortion coefficients C_2 and C_3 and, by means of Table 1, the various distortions. For a single carrier with optical modulation depth = 1, second-harmonic distortion is $C_2/2$, and linearity due to parabolic curvature of the *L-I* characteristic is $4C_2$. Thus, C_2 = (linearity)/4, and the relative amplitude of the second-harmonic component = (linearity)/8. On this basis, for 40 channels with $m = .04$ and linearity = 4 percent, calculated CSO at channel 2 is 53.7 dB.

An example will illustrate how CTB and CSO can be predicted from knowledge of harmonic, two-frequency, or three-frequency distortion. Assume that the specified second harmonic distortion is -55 dBc for a modulation depth of 0.25. Calculate CSO for 20 channels assuming the per-channel modulation index is .06.

First, the harmonic distortion is calculated for the change in modulation index. Table 1 shows that the relative amplitude of second-order distortion is proportional to m. Therefore, the improvement in second-order distortion for a modulation index of .06 is 20log(.25/.06), or 12.4 dB. Thus, the carrier/second-harmonic distortion ratio at m = .06 is 55 dB + 12.4 dB = 67.4 dB.

Next, the difference in a two-frequency beat and a second harmonic is accounted for. From Table 1, $F_1 \pm F_2$ distortion is 6 dB greater than second-harmonic distortion, so the carrier/($F_1 \pm F_2$) distortion is 67.4 dB - 6 dB = 61.4 dB. (The preponderance of second order beats are of the type $F_1 \pm F_2$; only one harmonic component at most can be included in CSO beats).

Finally, a correction is made to account for the number of beats on a particular channel. From Fig. 3, a factor of 8.5 dB is added to account for 7 beats at channel 2 for 20 channel loading. Thus, the calculated CSO is 61.4 dB - 8.5 dB = 52.9 dB.

SYSTEM PERFORMANCE

Laser technology for CATV applications is currently progressing rapidly as more effort is expended in laser development for this market. With this changing technology, there is presently much variance in performance and yields from laser sources, particularly with regard to distortion specifications. For awhile it may be desirable for manufacturers to select and grade lasers to meet specific system requirements. Lasers that do not meet CSO objectives but are satisfactory otherwise could be used where the bandwidth is less than an octave or so. As the technology improves, yields and variances are expected to improve.

The system data in Table 2 was taken with one of the better lasers of those available at the time from different manufacturers. This system performance cannot be guaranred at this time in a standard product. Processes and specifications for this laser are being improved by the manufacturer, which should make this device suitable for production systems. This laser exhibits good linearity which enables a high modulation index to be used and still achieve very low distortion. Data was taken on a production prototype developed for the CATV market. Some of the system parameters are:

laser type- DFB
laser wavelength- 1330 nm
output output power- 2.6 mW
link distance- 15 km
link loss- 5.6 dB
channel loading- 40
bandwidth- 330 mHz (channels 2-EE)

TABLE 2
SYSTEM PERFORMANCE

FREQ. (MHz)	CNR (dB)	CTB (dB)	CSO (dB)	XMOD (dB)
55.25	54	69.7	69	57
83.25	53.7	74	71	57
121.25	54.1	67.7	>	56
145.25	53.8	66.9	69.8	
175.25	54.3	67.6	70	58
205.25	54.3	66.9	70	58
241.25	53.8	66.6	69	58
265.25	54.3	66.9	66.5	57
295.25	54.3	67.5	65	59
325.25	54.1	67.5	62.0	60

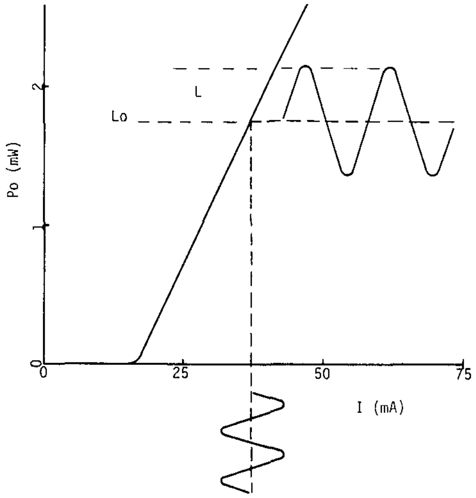

Fig. 1. Laser light intensity vs bias current. Laser bias is in mA and optical output is in mW. The response to a sinusoidal modulation current is shown.

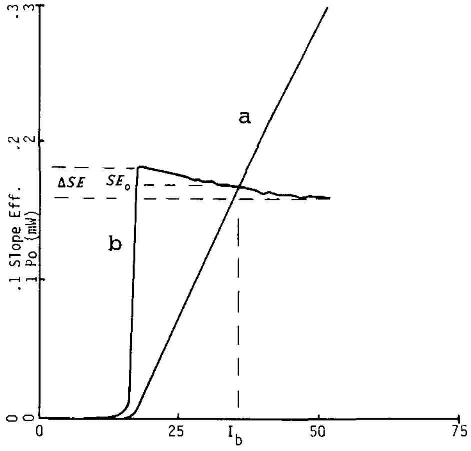

Fig. 2. Laser L-I curve (a), and slope efficiency SE (b).

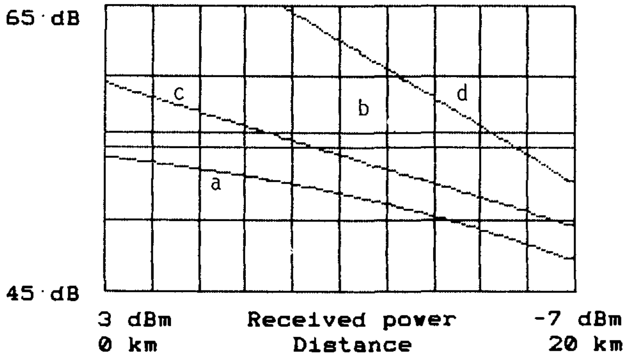

Fig. 3. (a): Link CNR. (b) through (d) are CNR due to: (b); laser intrinsic noise, RIN = -153 dB/Hz, (c); photodiode quantum noise, responsitivity = .85 A/W, (d); amplifier noise, R_1 = 1000 ohms, F = 3dB. Laser output is 2 mW and modulation index is .04/channel. Fiber loss budget is assumed to be .5 dB/km.

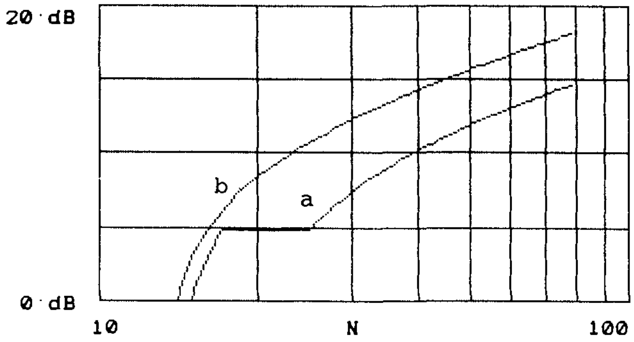

Fig. 4. Number of discrete second-order beats (in dB) that comprise CSO as a function of the number of channels, N, in the standard frequency plan. (a) is for highest channel; (b) is for channel 2.

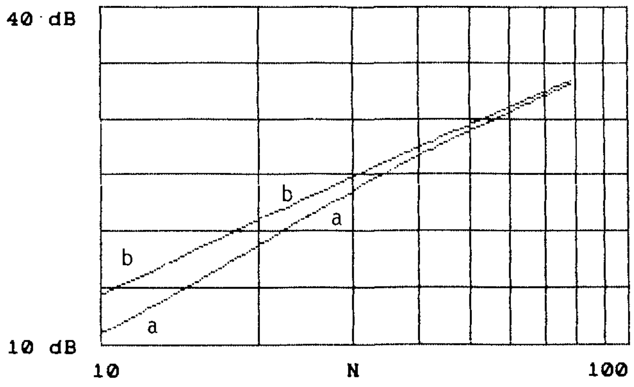

Fig. 5. Maximum number of discrete third-order beats that comprise CTB as a function of the number of channels. (a) is for channel assignments starting at channel 2, and (b) is for the contigious channels starting at A-2 and above. N is the number of channels in the standard frequency plan. Ordinate is 10log(number of channels).

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