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ANALOG SIGNALS TRANSMISSION OVER OPTICAL FIBER SYSTEMS

M. Ramadan

Rockwell International
1200 N. Alma Road
Richardson, Texas 75080

ABSTRACT

A theoretical and experimental investigation is made to determine the feasibility of transmitting analog video signal over fiber at 1.3 μm. Effects of LED current and optical modulation index on various parameters such as second and third order intermodulation, and differential gain (DG) and differential phase (DP) were evaluated. Preemphasis effects on signal-to-noise ratio (S/N) and DG and DP were also presented. Experimental results were in close agreement with theory.

I. INTRODUCTION

The past few years have seen tremendous progress in optical-fiber technology. With the promise of optical fiber to every home, several efforts are underway to provide video and data services, in addition to phone services, over a single fiber [1] through [4].

The primary emphasis is on a low-cost system with an acceptable level of video quality. Hence, direct intensity modulation of an LED with the analog video signal is considered. The two conflicting requirements in any analog transmission system are that the received signal should be at a sufficiently high level with respect to noise, yet the transmitter must be operated at a low level to reduce nonlinearity effects to an acceptable level. These conflicting requirements set an upper limit for measured video quality in terms of S/N, DG, and DP.

This paper deals with a theoretical analysis of an analog method of transmission of video on an optical fiber. The results of the analysis are experimentally verified. Section II presents a derivation of the S/N of the optical detector. Section III deals with the analysis of the LED linearity. Expressions relating LED drive current and optical modulation index to 2-tone intermodulation (IM) and video DG and DP are given. Section IV presents methods for improving linearity. Section V deals with multiple signal modulation; and finally, experimental results confirming the theoretical predictions are presented in section VI.

II. ANALYSIS OF OPTICAL RECEIVER S/N

The receiver typically consists of a high-impedance FET preamplifier and a PIN photodiode detector combination. A simplified model which approximates the receiver is shown in figure 1.

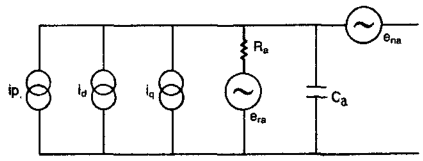

Figure 1. Optical Detector Model.

Where:

$\bar{i}^2_p = R^2P^2$ Mean squared (ms) signal current

$\bar{i}^2_d = 2qI_d$ (ms) dark current noise, A^2/Hz

$\bar{i}^2_q = 2qRP$ (ms) quantum current noise, A^2/Hz

$\bar{e}^2_{ra} = 4kTR_a$ (ms) thermal noise voltage, V^2/Hz

$\bar{e}^2_{na} = \frac{2.8\ kT}{g_m}$ (ms) amplifier noise voltage, V^2/Hz

C_a = Total capacitance, P = Incident power, R = Responsitivity = 0.6, R_a = FET bias resistance, k = Boltzman's constant, T = Temperature in degree Kelvin, q = Electron charge, g_m = Input FET conductance = 0.02 s

The total mean squared noise voltage in V^2/Hz is:

$$\overline{V_n^2} = \frac{(2qI_d + 2qRP)R_a^2}{1 + \omega^2 C_a^2 R_a^2} + \frac{4kTR_a}{1 + \omega^2 C_a^2 R_a^2} + \frac{2.8\ kT}{g_m} \quad (1)$$

The mean squared P-P signal voltage is:

$$\overline{V_{pp}^2} = \frac{4R^2P^2m^2R_a^2}{(1 + \omega^2 C_a^2 R_a^2)} \quad (2)$$

$$(S/N)_{PP/rms} = 10 \log (\bar{V}^2_{pp} / \bar{V}^2_n) \quad (3)$$

The weighted P-P signal to rms noise ratio is calculated as a function of received optical power for:

i_d = 50 Na, R_a = 500 kΩ, R = 0.6, m = 0.7, e_{na} = 2 to 10 nanovolts, and f = 20 MHz

Figure 2 shows the result. It can be seen that at -27-dBm received optical power the weighted video S/N for 2 nanovolts of amplifier noise is 56 dB. The required S/N for subscriber loop applications is 45 dB. Therefore, the calculated S/N is more than adequate for this case and, thus, lower receive optical power can be used.

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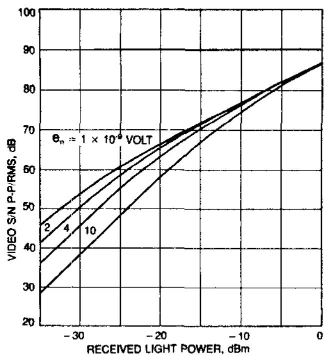

Figure 2. Video S/N Versus Received Light Power.

III. EFFECT OF NONLINEARITIES

The video signal contains a chromatic signal superimposed on a luminance signal. The chromatic signal consists of a subcarrier modulated both in amplitude and phase, which determines the saturation and hue of the transmitted color. DG and DP are defined as the difference between maxima and minima of amplitude and phase, respectively, of the chromatic signal as a function of the luminance signal amplitude. They should be less than 1% and 1°, respectively, in a short-haul system, and 8% and 4°, respectively, in subscriber-loop applications. If amplitude or phase nonlinear distortions occur in the VSB video transmission system, the saturation or hue of the transmitted color is affected, and thus both DG and DP degrade.

A. Two-Tone Analysis of LED

It is a common practice to express the linearity of most devices in terms of 2-tone, second and third order IM levels. Therefore, it is convenient to relate DG and DP to the levels of these IM products.

In order to evaluate the IM output of LED analytically, the input/output relationship must be known. However, there is no closed form expression for LED and therefore one could derive a power series expression which would fit the manufacturer's published input/output characteristic. Such a series was evaluated for Fujitsu LED type FED 131S. Thus,

$$P = 1.4533 \times 10^{-2}\, i - 5.6 \times 10^{-5}\, i^2 + 1.067 \times 10^{-7}\, i^3 \quad (4)$$

The effects of operating current, i_o can be found by expressing equation (4) in a Taylor series around the operating current i_o. Thus,

$$P = a_o + a_1 (i - i_o) + a_2 (i - i_o)^2 + a_3 (i - i_o)^3 \quad (5)$$

For 2-tone input

$$i = i_o [1 + m (\cos \omega_1 t + \cos \omega_2 t)], \quad (6)$$

Where m is the optical modulation index, $m = I/i_o$.

Substituting equation (6) into equation (5), the relative level of the products L_2 at $(f_1 \pm f_2)$ and L_3 at $(2f_2 \pm f_1)$ are calculated as a function of i_o and m as shown in figures 3 and 4 respectively.

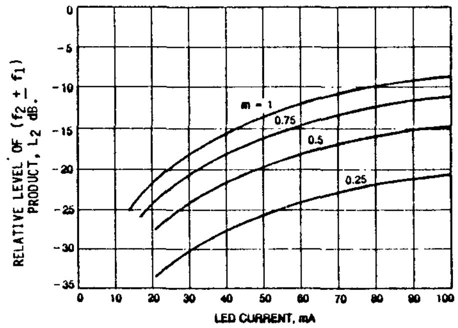

Figure 3. L_2 Versus LED Current.

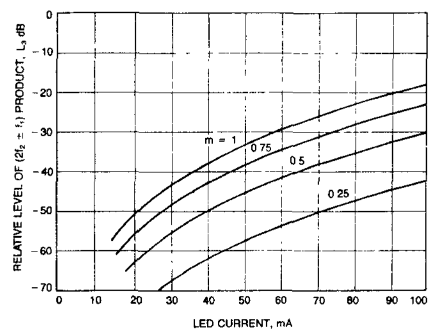

Figure 4. L_3 Versus LED Current.

It can be seen that the second order component is quite high even at low LED current and small optical modulation index.

B. Evaluation of Differential Gain and Differential Phase

Differential gain resulting from LED nonlinearities can be evaluated using the 2-tone signal given in equation (7) in conjunction with the P-I characteristics of the LED as given by equation (5).

$$i_{in} = i_o + I_v \cos \omega_v t + I_w \cos \omega_w t \quad (7)$$

Where f_w is the chrominance signal frequency = 3.58 MHz and f_v is the luminance signal frequency = 80 Hz and $I_v >> I_w$.

Thus, DG due to second order nonlinearity is derived as:

$$DG_2 = 2\frac{a_2}{a_1} I_v \times 100, = 200\sqrt{2} \times 10^{(L_2/20)}, \% \quad (8)$$

Similarly, the differential gain resulting from third order nonlinearity is:

$$DG_3 = 300\, I_v^2\, a_3/a_1, = 800 \times 10^{(L_3/20)}, \% \quad (9)$$

Differential phase is the result of amplitude-dependent phase of the LED or simply AM/PM conversion. Thus, if we include an amplitude-dependent phase function in the input/output expression of the LED and follow similar analysis to that used to evaluate DG, we obtain:

$$DP = (28 \times 10^{(L_3/20)}) \times 20 \log [1 + 2\sqrt{2} \times 10^{(L_2/20)}], \text{ degrees} \quad (10)$$

A plot of equations (8) and (9) is shown in figure 5, and a plot of equation (10) is shown in figure 6.

It can be seen that in order to obtain DG that meets subscriber-loop requirements, the third order IM must be less than 40 dB and the second order IM must be less than 30 dB. The DP will be more than adequate if the requirements for DG are met. Referring to figures 3 and 4, it can be seen that the LED current must be less than 30 mA and the optical modulation index must be less than 0.5 to meet the desired 8% DG. This requirement is in conflict with the S/N requirement. Therefore, some linearization scheme must be used to improve the linearity and reduce DG to the desired level.

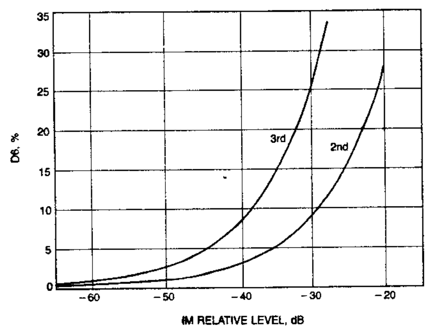

Figure 5. DG Versus L_2, L_3.

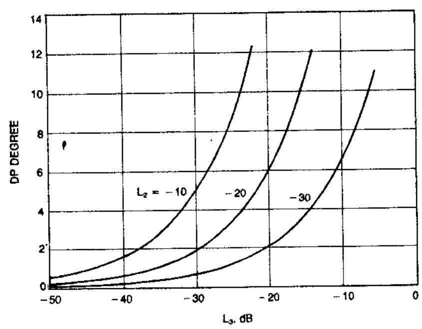

Figure 6. DP Versus L_3 for Various L_2.

IV. METHODS OF IMPROVING LINEARITY

Most linearization schemes require additional complexity and cost. Simple techniques for improving linearity are highly desirable. The schemes to be discussed here are preemphasis and LED predistortion.

A. Preemphasis

If a preemphasis network having a response that attenuates the low-frequency components of the luminance signal is placed prior to the LED and a deemphasis network that performs the opposite function is placed after detection, the IM component levels and DG will be reduced as can be seen from equations (8) and (9).

Thus, with 10-dB preemphasis, DG_2 and DG_3 will be reduced to one-third and one-tenth the initial values respectively.

There is, however, a slight S/N penalty with preemphasis. To evaluate this penalty, let $G_1(\omega)$ be a preemphasis network which reduces the level of the low-frequency components or the luminance signal of the transmitted video signal and $G_2(\omega)$ be a deemphasis network which deemphasizes the high frequency or the chrominance signal, such that:

$$G_1(\omega)\, G_2(\omega) = 1$$

The received signal power assuming an ideal receive filter is:

$$S = \int_0^{\omega_b} G_1^2(\omega)\, G_2^2(\omega)\, S^2(\omega)\, d\omega = \int_0^{\omega_b} S^2(\omega)\, d\omega \qquad (11)$$

Which is the same as the case with no preemphasis and deemphasis. The received noise power is:

$$N = \int_0^{\omega_b} N^2(\omega)\, G_2^2(\omega)\, d\omega \qquad (12)$$

If we assume for simplicity that $N^2(\omega) = N_0$, is flat Gaussian noise, then the change of noise power with deemphasis is:

$$\Delta N = \frac{1}{\omega b}\int_0^{\omega_b} G_2^2(\omega)\, d\omega \qquad (13)$$

Let us assume further that the deemphasis network is a 2-element RC low-pass filter with gain such that

$$G_2^2(\omega) = \frac{K^2\,\omega_c^2}{\omega^2 + \omega_c^2} \qquad f \le f_1$$
$$= 1 \qquad f \ge f_1 \qquad (14)$$

and $f_c = \frac{f_1}{K^2-1}$

The change of noise is:

$$\Delta N = \frac{1}{\omega_b}\left[\int^{\omega_1} \frac{K^2\,\omega 2}{\omega^2 + \omega 2}\, d\omega + \int_{\omega_1}^{\omega_b} d\omega\right] \qquad (15)$$
$$= K^2\, \frac{\omega_c}{\omega_b} \tan^{-1} \frac{\omega 1}{\omega_c} + (\omega_b - \omega_1)/\omega b$$

If f_b = 6 MHz, f_1 = 3.58 MHz and preemphasis = 10 dB, ΔN is calculated to be 1.4 dB.

Thus, the degradation in S/N with 10-dB preemphasis is 1.4 dB.

B. Predistortion

In order to linearize the LED, the predistortion circuit must have second and third order nonlinearities of opposite polarity to those of the LED. However, since second order distortion is predominant, only second order predistortion is required. Figure 7 shows an FET circuit having second order nonlinearity in the V-I characteristics. The magnitude and sign of the nonlinearity can be adjusted to cancel that of the LED by varying the feedback between the drain and the gate using resistance R.

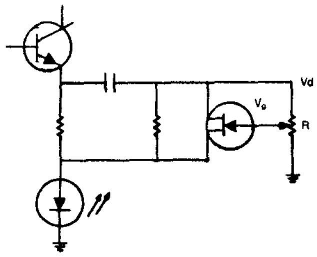

Figure 7. Second Order Predistorter.

V. MULTIPLE SIGNAL MODULATION

In most practical cases, several signals must be transmitted on the same fiber; therefore, these signals must first be frequency-division-multiplexed (FDM) before being used to intensity-modulate the LED. Two cases of interest are discussed here, namely, multiple video and FDM voice channel transmission.

A. Multiple Video Transmission

When several VSB video channels are used to intensity-modulate the LED, the nonlinearity of the LED will affect the individual channels as discussed before. In addition, there will be intermodulation between the channels causing the IM product to occupy a wide band. If these products fall on the transmitted channels, additional degradation will be encountered, the severity of which will depend on the level and on the transmitted frequency plan. Furthermore, the presence of third order nonlinearity gives rise to cross modulation between channels or intelligible crosstalk. That is, the AM modulation from one signal will be transferred to the other regardless of the frequency format of the composite multichannel signal. The level of the cross-modulation component is proportional to the level of the $(2f_2 \pm f_1)$ component.

The level of the IM components can be obtained from figures 3 and 4.

Thus, to avoid cross-product falling on individual channels, the frequency spectrum of the composite transmitted signal must be chosen to avoid the effects of the predominant second order nonlinearity. Furthermore, since the LED frequency response is typically about 45 MHz, the number of video channels that could be practically transmitted is limited.

B. FDM Voice Channels Transmission

The performance, in this case is measured by the noise power ratio (NPR) in each of the individual 3-kHz channels.

The NPR may be evaluated by the usual technique of simulating the FDM signal by flat Gaussian noise. Thus, it can be shown that the NPR due to second order nonlinearity, a_2 is

$$NPR_2 = -10 \log P_c \, (2-f/f_b) \left(\frac{a2}{a_1}\right)^2, \quad f \leq 2f_b \qquad (16)$$

where P_c is the composite power of the FDM signal and f_b is the highest channel frequency. Equation (16) can be expressed in terms of the 2-tone IM level, assuming that multichannel composite power is equal to the 2-tone power, thus

$$NPR_2 = -L_2 - 10 \log (2-f/f_b), \quad f \leq 2f_b \qquad (17)$$

Similarly, the NPR due third order nonlinearity is

$$NPR_3 = -L_3 - 10 \log \frac{8}{3} (3-f^2/f_b^2), \quad f \leq f_b \qquad (18)$$

It can be seen from figures 3 and 4 that the NPR is limited by the second order distortion. Assuming, as discussed before, that the second order nonlinearity is equalized using predistortion, the NPR in the worst channel with LED current of 50 mA and m = 0.7, is 31 dB.

VI. EXPERIMENTAL RESULTS

An analog fiber-optic system was set up. The system consisted of a driver amplifier, a 1.3-μm wavelength LED with its biasing circuit, an optical attenuator simulating path loss, PIN-FET detector, and a gain amplifier. The system parameters were i_0 = 50 mA, P = -20 dBm, m = 0.7, path loss = 10 dB, and receive optical power = -30 dBm. The measured weighted video S/N (P-P/rms) was 52 dB. DG and DP without preemphasis and without predistortion were 36% and 1°, respectively. When 10-dB preemphasis and deemphasis were used, the DG was reduced to 14% and DP was not affected. Finally, the addition of predistortion resulted in a DG of less than 1% and DP of 2°.

The performance of two video channels was also evaluated. The two channels used were on 7-MHz and 13-MHz carrier frequencies because modems were available at those frequencies. The measured weighted S/N for both channels with LED predistortion was better than 48 dB and DG and DP were less than 10% and 1° respectively.

Finally, a 960-channel noise load test was performed with i_0 = 50 mA and m = 0.7. The NPR in the lowest slot was 31/35 dB with predistortion.

VII. CONCLUSION

A low-cost fiber-optic system for the transmission of video signal was analyzed theoretically. Expressions were obtained for key system parameters. An experimental setup confirmed the theoretical predictions. Satisfactory performance was achieved for subscriber-loop applications.

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