Analysis of Fundamental Nonlinear Distortions in Optical Source and the Effect on SCM Optical Networks

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Abstract

We analyze the 2nd and 3rd order distortions of the laser diodes. It shows that the fundamental nonlinearity of laser diode is caused by the nonlinear energy exchange between the photons and carriers in its active layer. The relaxation oscillation frequency of the laser diode determines the performance of the laser diode in SCM optical system. Based on these results, we obtain the CSO and CTB for the system. We show that for a 60-channel SCM system, under the requirement of CSO and CTB=60 dBc, the modulation index is about 5% for one channel and the corresponding k_{11} k_{111} are about 10^{-2} and $3.3 \cdot 10^{-3}$ respectively.

1 Introduction

In recent years, subcarrier multiplexing (SCM) techniques have been proven to be very attractive for the CATV systems over optical distribution networks [1,2]. SCM takes the advantage of the large modulation bandwidth of semiconductor lasers and the availability of microwave components which provides a convenient way for multi-channel video transmission in the passive or active optical networks. But there are two problems which limit the performance of SCM system. One is the intermodulation products in the transmission bandwidth when the number of subcarriers is large. This effect is mainly due to the fundamental nonlinearlity of the laser diodes. The other is that for AM-VSB SCM systems, the requirement of CNR (carrier-to-noise ratio) is very high. In order to overcome these problems, a laser diode (LD) with high linearity and large output optical power is needed.

In this paper, the 2nd and 3rd order distortions of DFB laser diodes are calculated. It shows that the fundamental nonlinearity of laser diodes is caused by the nonlinear energy exchange between the photons and carriers in its active layer. The relaxation oscillation frequency of the laser diodes determines the performance of the LD in SCM optical systems. Based on these results, we obtain the CSO and CTB for the system. It is shown that for a 60-channel SCM system, under the requirement of CSO and CTB=60 dBc, the modulation index is about 5% for one channel and the corresponding k_{11} k_{111} are about 10^{-2} and $3.3 \cdot 10^{-3}$.

2 Fundamental Nonlinear Distortions of Laser Diode

The single longitudinal mode rate equation for the LD is:

$$\frac{dP}{dt} = (G - \gamma)P + R_{sp} \tag{1}$$

$$\frac{dN}{dt} = \frac{J}{q} - \gamma_e N - GP \tag{2}$$

where G is the stimulated-emission rate, γ is the photon decay rate, J is the current density in the active region. P and N are photon and carrier density in the active layer. Assume the input signals are N channels of AM-CATV subcarriers and they have the same amplitudes and intital phases, then

$$j(t) = J_0 + j_m \sum_{i=1}^{N} e^{j\omega_i t} + c.c. \tag{3}$$

By using perturbation analysis on Eqt. (1) and (2), it is found that the fundamental nonlinearity of the LD is due to the nonlinear energy exchange between photons (p) and carriers (n) in the active layer of LD. In optical SCM transmission systems, only 2nd and 3rd order distortions are deteriorative. Thus, $p(t)$ and $n(t)$ can be expressed as:

$$p(t) = P_0 + \sum_{i=1}^{M} p_{1i} e^{j\omega_i t} + \sum_i \sum_j p_{i\pm j} e^{j\omega_{i\pm j} t} + \sum_i \sum_j \sum_k p_{i\pm j\pm k} e^{j\omega_{i\pm j\pm k} t} + c.c.$$

$$n(t) = N_0 + \sum_{i=1}^{M} n_{1i} e^{j\omega_i t} + \sum_i \sum_j n_{i\pm j} e^{j\omega_{i\pm j} t} + \sum_i \sum_j \sum_k n_{i\pm j\pm k} e^{j\omega_{i\pm j\pm k} t} + c.c.$$

where p_{1i} and n_{1i} are the linear terms, $p_{i\pm j}, n_{i\pm j}, p_{i\pm j\pm k}$ and $n_{i\pm j\pm k}$ are the 2nd and 3rd order distrotion terms respectively. By solving the rate equation, the linear, 2nd and 3rd order terms are:

$$p_{1i} = \frac{G_N}{\eta q} \frac{m P_0^2}{\omega_R^2 + (\Gamma_R + j\omega_i)^2}, \qquad n_{1i} = (\frac{j\omega_i + \Gamma_p}{G_N P_0}) p_{1i}$$

$$n_{i\pm j} = \frac{(j\omega_{i\pm j} + \Gamma_p)p_{i\pm j} - G_N p_{1i} n_{1j} - G_P p_{1i} p_{1j}}{G_N P_0}$$

$$p_{i\pm j} = \frac{((j\omega_{i\pm j} + \Gamma_N)p_{1i}/P_0(n_{1j} + \frac{G_p}{G_N}p_{1j}) - (G_p n_{1i} p_{1j} + G_N n_{1i} n_{1j}))G_N P_0}{(j\omega_{i\pm j} + \Gamma_N)(j\omega_{i\pm j} + \Gamma_p) + GG_N P_0}$$

$$p_{i\pm j\pm k} = \frac{G_N((j\omega_{i\pm j\pm k} + \Gamma_N)(p_{i\pm j} n_{1k} + p_{1i} n_{j\pm k} P_0) - G_p(n_{i\pm j} p_{1k} + n_{1i} p_{j\pm k}))}{(j\omega_{i\pm j\pm k} + \Gamma_p)(j\omega_{i\pm j\pm k} + \Gamma_N) + GG_N P_0}$$

Simulation result is shown in Fig. (1). The parameters of the LD is shown in Ref. [3] with modulation index m=5% and output optical power for LD is 10 mW. It shows that when f_R (relaxation oscillation frequency) is low, the 2nd and 3rd order intermodulation seriously affect the performance of the SCM system. When the f_R is high enough, the difference of $p_{1i}, p_{i\pm j}$ and $p_{i\pm j\pm k}$ will remain for 35 dB respectively within the transmission bandwidth of VSB-AM CATV system. Thus, the laser diode which is employed in SCM system should have a high relaxation oscillation frequency to minimize the nonlinearity of LD.

By making certain apporximations and adding the nonlinearity of P-I curve for the LD, the total linear and distortion terms can be simply expressed as:

$$P_{1i} = (A_0 + I_0 \frac{dP}{dI})m = C_1 m$$

$$P_{i\pm j} = (A_{11} + \frac{I_0^2}{4}\frac{d^2P}{dI^2})m^2 = C_{11}m^2$$

$$P_{i\pm j\pm k} = (A_{111} + \frac{I_0^3}{24}\frac{d^3P}{dI^3})m^3 = C_{111}m^3$$

where A_0, A_{11} and A_{111} are derived from the above rate equation, I_0 is the bias current, C_1, C_{11} and C_{111} are the linear, second and third order distortion parameters.

For N-channel analog TV transmission system, the RF power of linear, second and third order intermodulation in a specific channel i are:

$$C = \frac{1}{2}(C_1 RM)^2 m^2 \quad (4)$$

$$D_{11} = \frac{1}{2}(C_{11} RM)^2 I m^4 \quad (5)$$

$$D_{111} = \frac{1}{2}(C_{111} RM)^2 J m^6 \quad (6)$$

where R and M are the responsivity and gain of photon detector, I and J are the number of 2nd and 3rd order intermodulation terms falling in the channel i. If we ignore the distortion caused by optical fiber and assume that the optical receiver is a linear amplifier, the CSO and CTB for a specific channel are:

$$CSO = \frac{C}{D_{11}} = \frac{1}{m^2 I k_{11}^2} \quad (7)$$

$$CTB = \frac{C}{D_{111}} = \frac{1}{m^4 J k_{111}^2} \quad (8)$$

where $k_{11} = D_{11}/C_1$ and $k_{111} = D_{111}/C_1$ are the intrinsic distortion coefficents (independent of m and the number of carriers) of 2nd and 3rd order intermodulation.

For a 60 channels VSB-AM CATV, the maximum number of intermodulation terms for 2nd ($f_i \pm f_j$) and 3rd ($f_i + f_j - f_k$) are about 50 and 1,260 in two different channels [4]. Thus, the CSO and CTB in the worst case is shown in Fig. (2a), it is obviously that for the requirement of CSO and CTB= 60 dBc, modulation index is around 5-6% per channel. Fig. (2b) shows k_{11} and k_{111} versus the modulation index under the condition of CSO and CTB=60 dBc. From this curve we know that for multichannel CATV system, the larger the modulation index and the smaller the k_{11} and k_{111}, the higher the linearity the LD should be. If modulation index is too large, clipping distortion will occur [5].

3 Conclusions

In conclusion, we have analyzed the 2nd and 3rd order distortions of the laser diodes. It has shown that the fundamental nonlinearity of laser diodes is caused by the nonlinear energy exchange between the photons and carriers in its active layer. The relaxation oscillation frequency of the laser diodes determines the performance of laser diodes in SCM optical systems. Based on these results, we have obtained the CSO and CTB for the system. We have also shown that for a 60-channel SCM system, under the requirement of CSO and CTB=60 dBc, the modulation index is about 5% for one channel and the corresponding k_{11} k_{111} are about 10^{-2} and $3.3 \cdot 10^{-3}$ respectively.

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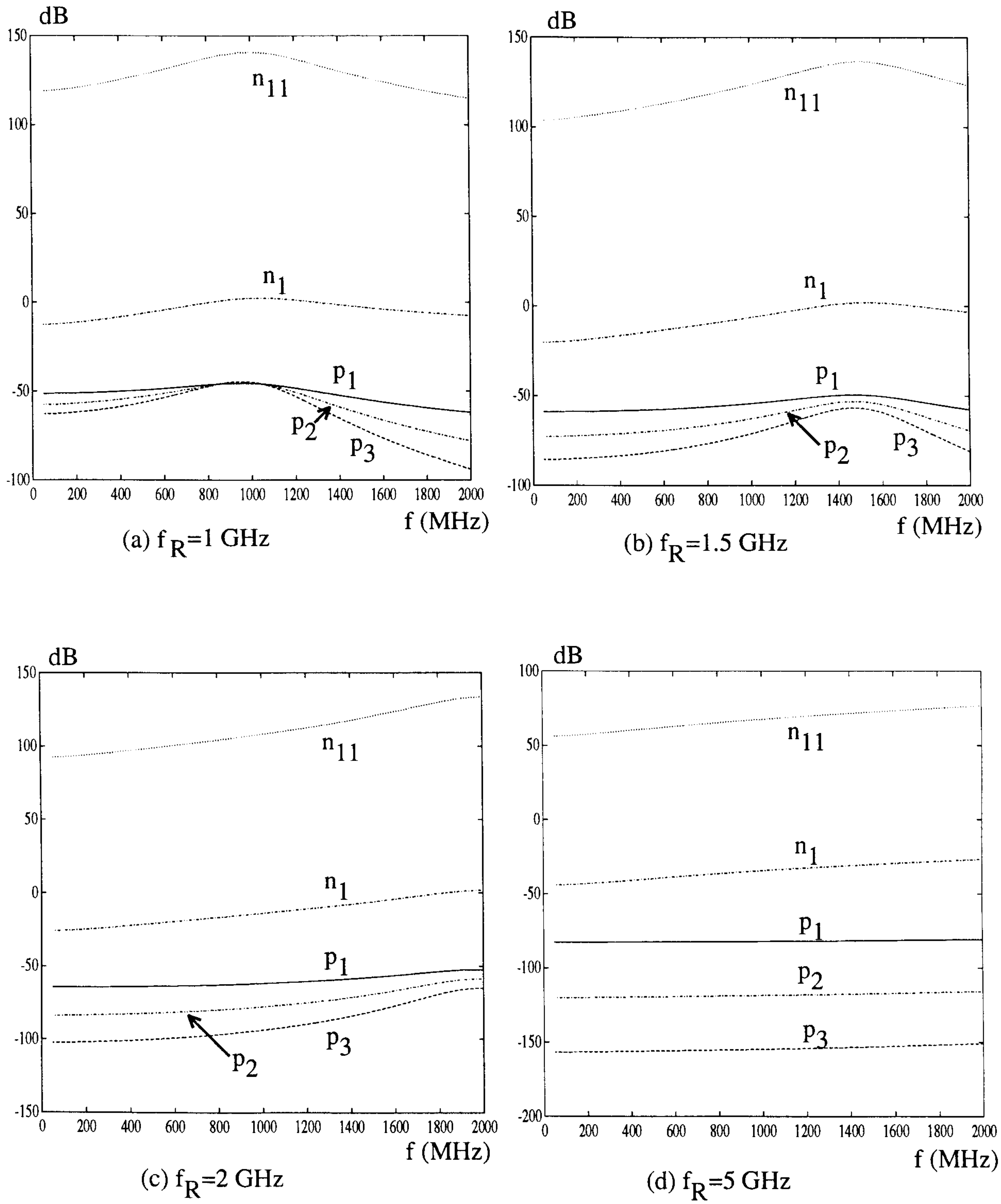
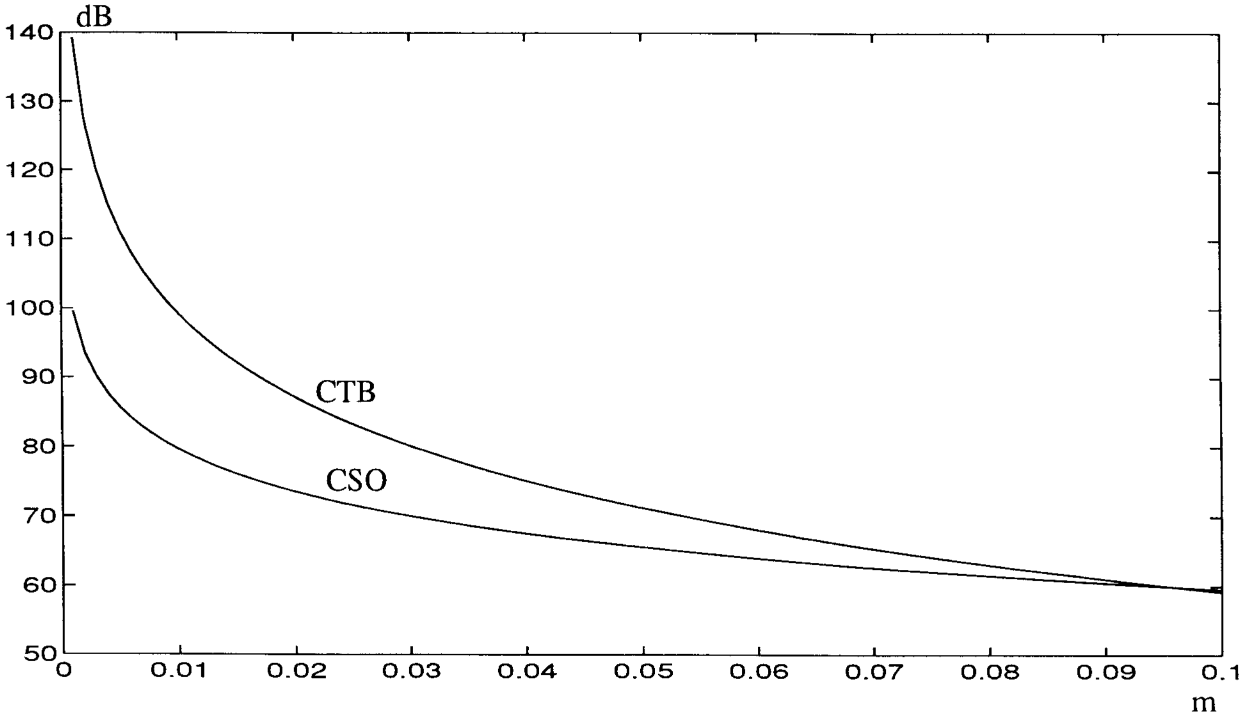
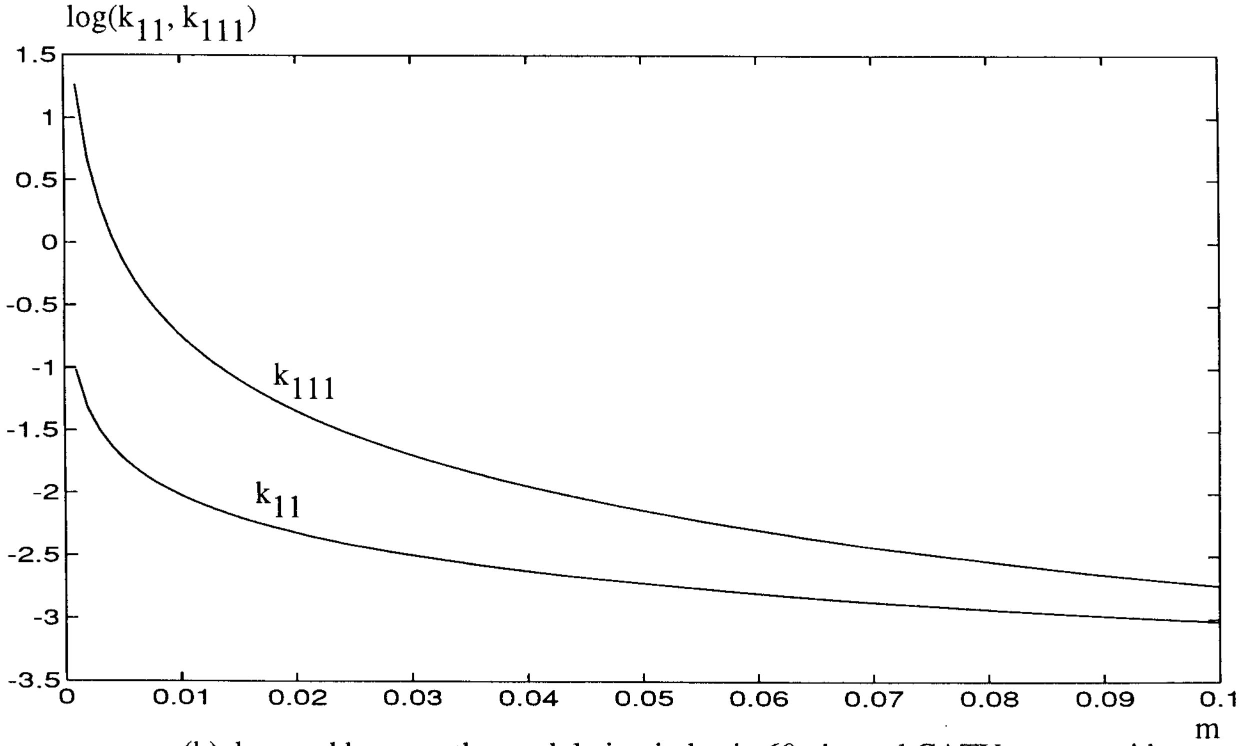


Fig. 1. The frequency spectrum of linear, 2nd and 3rd terms for single mode LD. The modulation index is 5% and optical power is 10 mW. f_R is the relaxation oscillation frequency of LD.



(a) CTB and CSO vs the modulation index in 60-channel optical CATV system.



(b) k_{11} and k_{111} vs the modulation index in 60-channel CATV system with CTB and CSO are 60 dBc

Fig. 2. Nonlinearity effects on the performance of 60 channels SCM CATV system.