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Nonlinear distortion evaluation in a directly modulated distributed feedback laser diode-based fiber-optic cable television transport system

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Abstract. This study evaluated a directly modulated distributed feedback (DFB) laser diode (LD) for cable TV systems with respect to carrier-to-nonlinear distortion of LDs. The second-order distortion-to-carrier ratio is found to be proportional to that of the second-order coefficient-to-first-order coefficient of the DFB laser diode driving current and to the optical modulation index (OMI). Furthermore, the third-order distortion-to-carrier ratio is proportional to that of the third-order coefficient-to-first-order coefficient of the DFB laser diode driving current, and to the OMI^2. [DOI: 10.1117/1.OE.54.12.126112]

Keywords: distributed feedback laser diode; fiber-optic cable television transport systems; optical modulation index.

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1 Introduction

With the popularity of optical fiber networks and the demand for high-quality videos, the development of changing TV signals from traditional cables to optic fibers has been promoted globally; thus, fiber-optic cable television (CATV) has been widely discussed.[1–5] Therefore, the transmission quality of such a system has been defined and regulated, which basically determines the signal-receiving quality of the system based on the following three parameters: carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB).[6] Both noise and nonlinear effects in the fiber-optic CATV transmission system are mostly caused by active components but rarely by passive components. Such noise severely affects both system performance and transmission distance; thus, CNR is usually adopted in the parameter measurement of CATV systems to analyze the characteristics of the transmission signal quality of the system. Given that CNR is proportional to the optical modulation index (OMI), a higher CNR could be obtained by increasing the OMI. However, an extremely high OMI could worsen the nonlinear distortion of the system, causing the system to generate second and third harmonic distortions, as well as second and third intermodulation distortions. These nonlinear distortions result from the accumulation of signals that fall on other channels, which decreases both CSO and CTB of the system. Under ordinary conditions, designing a CATV system to obtain high CNR, CSO, and CTB values altogether is impossible, but an optimum balance range between noise and the systematic nonlinear effect could be determined. Such a nonlinear effect has become an important research topic to directly modulate distributed feedback (DFB) laser diode (LD) in fiber-optic CATV systems.[7–10] The present study theoretically deduces the relationship among the direct modulation, driving current, OMI, harmonic distortion, and intermodulation distortion of DFB LD, as proven through experiments.

2 Experimental Setup

Figures 1(a) and 1(b) show the fiber-optic CATV transmission system by directly modulating DFB LDs 1 and 2, respectively. In Fig. 1(a), a multiple carrier generator (Matrix SX-16) is used to generate signals from channels 2 to 78 (55.25 to 547.25 MHz), which are directly modulated on DFB LD 1, whose driving current is set to 90 mA and output optical power to 10 mW (10 dBm). The signals are expected to reach an optical receiver after a certain fiber transmission distance. In this case, the optical power received by the optical receiver is expected to be 0 dBm, which generates a 10-dB fiber link loss with 25 km total transmission distance. Concurrently, the OMI of each channel changes from 8.5% to 13%, and an HP-8591C CATV analyzer is used to record variations in the CSO and CTB values. Similarly, Fig. 1(b) uses a multiple carrier generator (Matrix SX-16) to generate signals from channels 2 to 78 (55.25 to 547.25 MHz), which are directly modulated on DFB LD 2, whose driving current is set to 275 mA and output optical power to 40 mW (16 dBm). The optical link loss was expected to be 16 dB with ~40 km total transmission distance. Additionally, the OMI of each channel changes from 8.5% to 13%, and an HP-8591C CATV analyzer is used to record variations in the CNR, CSO, and CTB values.

In a fiber CATV system, CNR, CSO, and CTB exhibit a complementary relationship. CNR and OMI are positively correlated, whereas CSO, CTB, and OMI are negatively correlated. A higher OMI means a higher CNR value of signal reception, which would distort transmission signals and worsen both CSO and CTB values. By contrast, a lower OMI generates higher CSO and CTB values, and a lower CNR value. A compromise is required between these two conditions. Therefore, harmonic and intermodulation distortions in a fiber CATV system are evaluated through a Taylor series expansion of optical power P_o in terms of DC bias current

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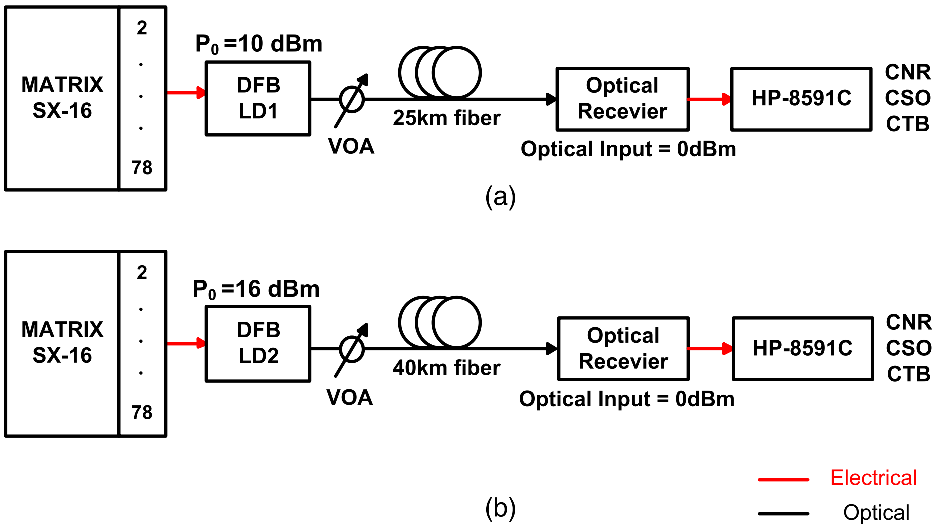

Fig. 1 Experimental setup of proposed directly modulated fiber optic cable television system using (a) distributed feedback laser diode (DFB LD) 1 and (b) DFB LD 2.

I_{op} and modulating driving current $i(t)$ within the source bias point.[11] Under general conditions, optical output power $P_o(t)$ of DFB LD could be represented as

$$P_o(t) = a \cdot I_{op} + b \cdot i(t) + c \cdot i^2(t) + d \cdot i^3(t), \tag{1}$$

where the series higher than the third term is truncated. As a modulation driving current, $i(t) = \sum_{i=1}^{n} \mathrm{A_i} \cos(\omega_i t + \varphi_i)$ flows through the DFB LD, where n denotes the total number of transmission channels, and the system reaches 550 and 750 MHz if $n = 80$ or 110. In addition, A_i, ω_i, and φ represent the amplitude, angular frequency, and phase of the i'th channel, respectively. By introducing $i(t)$ into Eq. (1), we can derive all types of nonlinear effects and outputs of the optical power of DFB LD as follows:

i. Second-order harmonic-to-carrier ratio (2HD/C):

$$2\mathrm{HD/C} = \frac{P_o(2\omega_x)}{P_o(\omega_x)} = \frac{c \cdot A_x}{2b}, \tag{2}$$

ii. Second-order intermodulation distortion-to-carrier ratio ($\mathrm{IMD_2/C}$):

$$\mathrm{IMD_2/C} = \frac{P_o(\omega_x + \omega_i)}{P_o(\omega_i)} = \frac{c \cdot A_x}{b}, \tag{3}$$

iii. Third-order harmonic-to-carrier ratio (3HD/C):

$$3\mathrm{HD/C} = \frac{P_o(3\omega_x)}{P_o(\omega_x)} = \frac{d \cdot A_x^2}{4b}, \tag{4}$$

iv. Third-order intermodulation distortion-to-carrier ratio ($\mathrm{IMD_3/C}$):

$$\mathrm{IMD_3/C} = \frac{P_o(2\omega_x + \omega_i)}{P_o(\omega_x)} = \frac{3d \cdot A_x \cdot A_i}{4b}, \tag{5}$$

or

$$\mathrm{IMD_3/C} = \frac{P_o(\omega_x + \omega_i + \omega_k)}{P_o(\omega_x)} = \frac{3d \cdot A_i \cdot A_k}{2b}, \tag{6}$$

where ω_x and A_x are the angular frequency and amplitude of the x'th channel, respectively.

Given that amplitude A_x is a function of the OMI, $A_x = \mathrm{OMI} + K$, where K is a constant. By introducing A_x into Eqs. (2)–(6), we can derive the following results:

$$\mathrm{CSO} = K_1 \cdot (c/b)(\mathrm{OMI}) + K_2, \tag{7}$$

$$\mathrm{CTB} = K_3 \cdot (d/b)(\mathrm{OMI})^2 - K_4(d/b)(\mathrm{OMI}) - K_5, \tag{8}$$

where K_m ($m = 1, 2, 3, 4, 5$) is a constant.

3 Experimental Results and Discussion

The experimental structure is shown in Fig. 1. Two DFB LDs available in the market with different driving currents and output optical powers are utilized. The DFB LD 1 used is manufactured by Mitsubishi with model number FU-68SDF-22, which outputs an optical power of 6 to 10 mW, according to a driving current of 55 to 90 mA. The DFB LD 2 used is manufactured by JDS Uniphase with model number CQF938/400, which outputs an optical power of 30 to 40 mW, according to a driving current of 200 to 275 mA. The relative intensity noises are −155 dB/Hz and −160 dB/Hz for DFB LDs 1 and 2, respectively. The characteristic of the driving current of DFB LD to the corresponding output optical power of this laser diode is shown in Fig. 2. Through curve fitting, the characteristic P_o-$i(t)$ of DFB LD1 and DFB LD2 could be represented as

$$P_o(\mathrm{DFB\ LD1}) = 869 - 60.5 \cdot i(t) + 1.63 \cdot i^2(t) - 0.0207 \cdot i^3(t) + 0.000108 \cdot i^4(t) - 1.35e - 9 \cdot i^6(t), \tag{9}$$

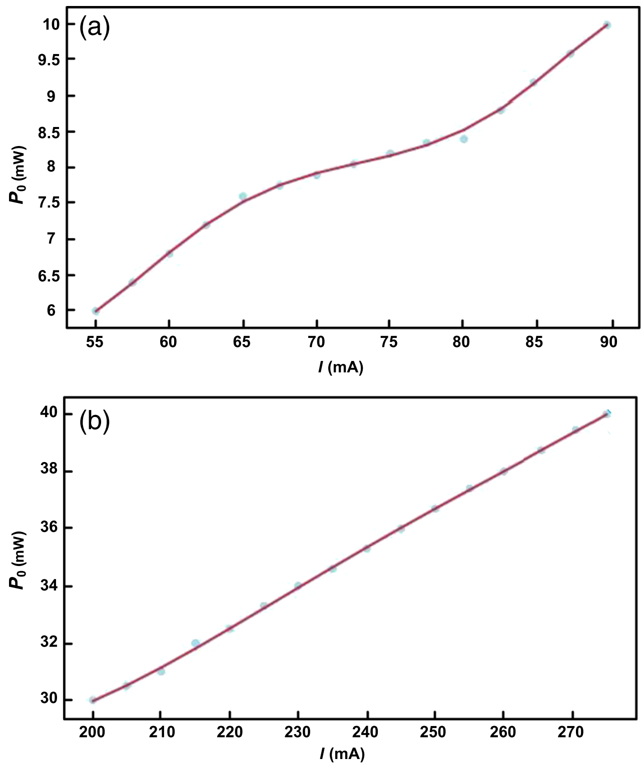

Fig. 2 Optical output power versus driving current characteristic for (a) DFB LD 1 and (b) DFB LD 2.

$$P_o(\text{DFB LD2}) = 572 - 9.38 \cdot i(t) + 0.0593 \cdot i^2(t) - 0.000164 \cdot i^3(t) + 1.68e - 7 \cdot i^4(t). \tag{10}$$

According to the P_o-$i(t)$ characteristic of DFB LD 1 in Eq. (7), $c/b = 1.63/60.5 = 0.027$ and $d/b = 0.0207/60.5 = 0.00034$ can be obtained. Similarly, based on the P_o-$i(t)$ characteristic of DFB LD 2, $c/b = 0.0593/9.38 = 0.0063$ and $d/b = 0.000164/9.38 = 0.0000175$ can be obtained. Given that both c/b and d/b for DFB LD 1 are larger than those of DFB LD 2, the latter linearly performs better than the former.

Figure 3 shows the measured CNR values using DFB LDs 1 and 2, respectively, to directly modulate channels 2 to 78. The simultaneous change of OMI corresponds to the x-axis in the chart while the y-axis shows the CNR value of different OMI reacting on the CATV parameter. Such CNR value is the mean of all CNR values measured by the HP-8591C CATV analyzer at the system's reception side regarding all 2 to 78 channels. The theoretical expression for CNR is

$$\text{CNR} = \frac{\text{OMI}^2 I^2}{2BN}, \tag{11}$$

where I is the optical power incident on the receiver that generates photocurrent. OMI and I indicate the carrier level while B corresponds to the bandwidth in which the noise is measured. N is the grand total of all noise, which includes thermal and shot noise that are associated with the receiver, laser noise results from the intrinsic laser RIN, and phase noise and multipath interference noise result from interactions between the light and the fiber. From Eq. (11), we derive the relationship of CNR and OMI as $\text{CNR} \propto \text{OMI}^2$, that is, CNR is proportional to OMI squared.

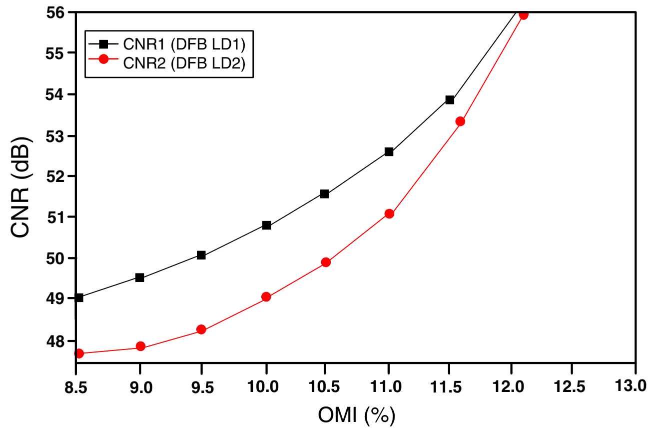

Fig. 3 Measured carrier-to-noise ratio values for distributed feedback laser diodes 1 and 2 for different optical modulation indices (OMIs) per channel.

Figures 4 and 5 show the measured CSO and CTB values using DFB LDs 1 and 2, respectively, to directly modulate channels 2 to 78. Similar to the CNR measurement method, we used the HP-8591C CATV analyzer to measure the CSO/CTB values from channels 2 to 78 and by averaging the CSO/CTB values of all channels, we derived the CSO/CTB value corresponding to the concerned OMI. By altering OMI and repeating the above measurement, the changes of CSO/CTB were recorded. The result clearly shows that the measured CSO and CTB values have differences of 2–3.8 dB and 0–7 dB in the system when DFB LD 1 is used compared with using DFB LD 2. Evidently, the ratio of the second- and third-order coefficients generates such a result, and the first-order coefficient of the DFB LD 1 driving current is larger than that of DFB LD 2. According to the measurement results in Figs. 4 and 5, both CSO and CTB can be degraded in proportion to OMI and OMI^2, respectively, regardless of whether the degradation is for DFB LD 1 or 2. When the OMI of each channel increases from 8.5% to 13%, the measured CSO and CTB values of DFB LDs 1 and 2 could be represented as follows via curve fitting:

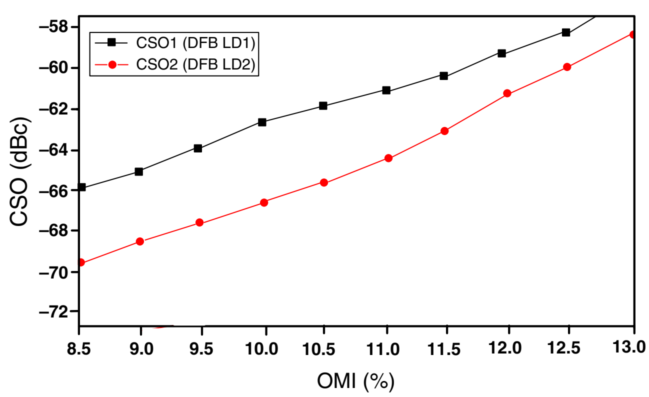

Fig. 4 Measured composite second-order values for distributed feedback laser diodes 1 and 2 for different OMIs per channel.

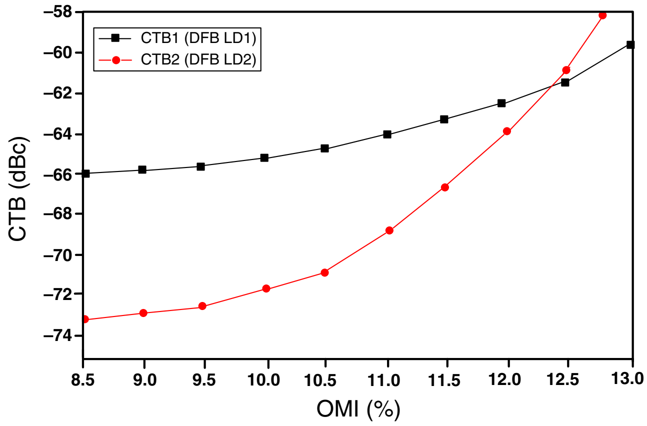

Fig. 5 Measured composite triple-beat values for distributed feedback laser diodes 1 and 2 for different OMIs per channel.

$$\mathrm{CSO(DFB\ LD1)} = 1.86(\mathrm{OMI}) - 81.5\,(\mathrm{dBc}), \tag{12}$$

$$\mathrm{CTB(DFB\ LD1)} = 0.261(\mathrm{OMI})^2 - 4.28(\mathrm{OMI}) - 48.6\,(\mathrm{dBc}), \tag{13}$$

$$\mathrm{CSO(DFB\ LD2)} = 2.41(\mathrm{OMI}) - 90.2\,(\mathrm{dBc}), \text{and} \tag{14}$$

$$\mathrm{CTB(DFB\ LD2)} = 0.99(\mathrm{OMI})^2 - 17.7(\mathrm{OMI}) + 6.04\,(\mathrm{dBc}). \tag{15}$$

According to Eqs. (11)–(14), different nonlinear distortion degradations of CSO and CTB values occur in various laser diodes. The results of Eqs. (12)–(15) are obviously derived from Eqs. (7) and (8). When the strength of the light signal becomes 0 dBm (1 mW) at the light receiver, the CNR/CSO/CTB values at the optical node should be ≥ 50 dB/ ≤ -60 dBc/ ≤ -60 dBc. According to the measurement result of OMI to CNR, CSO, and CTB parameters (as shown in Figs. 3–5), the OMI of DFB LD1 shall be within 9.5% to 11.7% and the OMI of DFB LD2 shall be within 10.5% to 12.6% for the system to satisfy the required CNR/CSO/CTB performance, which would verify the positive relationship between OMI and CNR as well as the negative relationship between CSO/CTB. Therefore, the system shall attain a balance in between in order to satisfy the CNR/CSO/CTB values simultaneously.

4 Conclusion

Based on deduction theory and experimental measurements, the second-order distortion-to-carrier ratio is proportional to that of the second-order coefficient-to-first-order coefficient of the DFB LD driving current and to the OMI. Additionally, the third-order distortion-to-carrier ratio is proportional to that of the third-order coefficient-to-first-order coefficient of the DFB LD driving current, and to the OMI^2. By introducing the derived CSO and CTB degradation equations, we can deduce the transmission characteristics of the system from the optical receiver node of an optical CATV transmission system.

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