Frequency-dependent and Frequency-independent Nonlinear Characteristics of a High-speed Laser Diode

W.I. Way

Bell Communications Research
Red Bank, NJ 07701

1. ABSTRACT

This paper experimentally demonstrates if a laser diode can be treated as a memoryless nonlinear device. It was found that for an operating condition with modulation depth below about 60%, the relative time delay (which ranges from zero to several hundred pico-seconds) caused by increased modulation depth has strong effect on the frequency-dependent intermodulation products. In this case, the RF bandwidth over which the laser diode can be considered to be effectively memoryless has to be smaller than the inverse of the measured time delay by two orders of magnitude. Increased optical reflections from fiber connectors were observed to cause significant fluctuations of the measured time delay as a function of frequency, and thus cause more pronounced frequency-dependent nonlinear behavior.

2. INTRODUCTION

Since 1986, high speed semiconductor laser diodes (LDs) have been extensively employed for directly transporting wideband multicarrier signals such as downlink satellite signals [1,2], video distribution networks [3], or local area cable television [4]. One of the fundamental limitations of those fiber-optic systems was caused by the nonlinearity of the high speed LDs. It is therefore important for a system designer to be able to predict the nonlinear distortions caused by LDs under different operating conditions, especially for wideband transmission systems. Reviewing the nonlinearity modeling approaches for conventional microwave devices such as traveling-wave tube amplifiers, solid-state amplifiers, etc., we can see that the most convenient method which gives close prediction of intermodulation (IM) or harmonics levels is the single-frequency AM-AM (gain compression) and AM-PM (amplitude modulation induced phase variation) measurement technique [5]. This technique is what most theoretical work was based on [6-11] and has been applied to a relatively large bandwidth of 500 MHz such as satellite communication systems. This technique, if applicable, is preferred for analog fiber-optic systems because of the its simplicity and versatility. It is also preferrable to methods using rate equations [13,15], since the latter needs tedious work to extract laser intrinsic parameters, especially for wide-band and large signal modulations. However, a simple AM-AM/AM-PM model is valid only when the device "memory" is much smaller than the reciprocal of the input signal bandwidth [11], i.e., it is valid for essentially memoryless devices (this model was used to predict third-order intermodulation products of a laser diode under narrowband two-tone modulations [12]). The "memory" of a device is defined as the amplitude- and frequency-dependent time delay, $\tau(R,\omega_0)$, between the transmitted and received RF signal, where R and ω_0 are the envelope and the center frequency of the input narrowband signal, respectively. This paper illustrates how to experimentally determine if a LD is memoryless or with significant memory , and to estimate the frequency range over which the simple AM-AM/AM-PM method can be used. The results reveal the basic nonlinear behavior differences between a laser diode and a conventional microwave device.

3. MEASUREMENT

A high speed InGaAsP LD with a threshold current (I_{th}) of 15 mA and a 3-dB bandwidth of 6 GHz was used in the experiment. An optical attenuator was inserted between the LD and a high-speed p-i-n diode to prevent the p-i-n diode from being operated in a nonlinear region. The input RF signal power to the LD supplied from a HP8510 network analyzer (port 1) was varied among -15 (modulation depth MD=9%), -2 (MD=42%), and +5 dBm (MD=93%). The LD was biased at 27 mA. The output of the p-i-n diode was amplified and fed back to port 2 of the HP8510. The measured phase and gain differences for modulating RF power of -2 and -15 dBm over a frequency range of 0.5 to 7 GHz are shown in Fig.1(a) (curve (i)) and 1(b), respectively. The phase difference ranges from about 1° at 0.5 GHz, to about 30° at 2.75 GHz. Gain compression caused by the additional 13 dB driving power is negligible except near the resonance region, where a maximum of about 2.5 dB compression is observed. The periodic variations (with a period of 40-50 MHz) in the curves are due to the weak optical reflections from the fiber connectors. The power ratio of the fundamental carrier and third-order intermodulation products (C/IM_3) versus modulation frequency, at an RF modulation power of -2 dBm, is shown in curve (ii) of Fig.1(a). It can be easily seen that the frequency dependency of C/IM_3 is controlled by the slope of the AM-PM vs. frequency characteristics. The slope of the AM-PM vs. frequency characteristics, calculated from curve (i) of Fig.1(a) and plotted in Fig.2, is the "memory" of the LD, i.e., $\tau(R,\omega_1) = -\Delta[\phi_1(R,\omega_1)-\phi_2(R,\omega_2)] / \Delta\omega$, where ϕ_1 and ϕ_2 are the phase lag (or lead) caused by the modulating signal power of -2 and -15 dBm, respectively, and $\Delta\omega = \omega_1-\omega_2$. In Fig.2, the periodic fluctuations were again caused by the inevitable optical reflection noise, and were superimposed on the actual (intrinsic) time delay, $\tau(R,\omega)$. Comparing Fig.1(a) and Fig.2, we see that in the low frequency range below 0.8 GHz where the LD has intrinsic $\tau_0(R,\omega_0)\approx 45ps$, the C/IM_3 changes at a rate of 40 dB/decade (this rate can also be calculated from small signal analysis of the rate equations [13]); when the intrinsic delay is close to zero, the C/IM_3 remains essentially constant; and the rise and fall rate of C/IM_3 vs. frequency in all other frequency regions can be approximately estimated from the ratio of $\tau(R,\omega_0)/\tau_0(R,\omega_0)$ multiplied by 40 dB/decade. Note that beyond the resonance region, C/IM_3 is dominated by the AM-AM rather than by the AM-PM characteristics, and a third-order nonlinear behavior is observed (C/IM_3 falls at a rate of 120 dB/decade as the normal frequency response falls at a rate of 40 dB/decade). Note also that in measuring C/IM_3 , tone separation has been carefully chosen to be 4 MHz to avoid fluctuations in the measured values due to optical reflections [14].

The RF driving power was then increased to +5 dBm (MD=93%). The measured phase and gain differences for RF power of +5 and -15 dBm over 0.5 to 7 GHz are shown in Fig.3(a) and 3(b) (curve (i)), respectively. The corresponding C/IM_3 vs. frequency characteristics is shown in curve (ii) of Fig.3(b). Despite the significant increase of phase differences shown in Fig.3(a), the C/IM_3 vs. frequency characteristics under this operating condition is essentially dominated by the gain compression (AM-AM), as is clearly shown in Fig.3(b). The RF gain compression varies from 1 dB at lower frequency region to 6 dB near the resonance region. From many similar measurements, it was found that if the MD is higher than about 75%, the corresponding C/IM_3 vs. frequency characteristics is essentially flat below about half of the resonance frequency, and is dominated by only the AM-AM characteristics. This implies that single-frequency AM-AM measurements can be used to predict the LD nonlinearity performance over a wide frequency range. However, when MD is less than about 60%, AM-PM nonlinearity dominates, and the C/IM_3 vs. frequency characteristics can be estimated from the measurement of the LD "memory".

As an additional example, when the LD was biased at a higher level, say 2.33 I_{th} (35 mA), the measured phase and gain differences for modulating RF power of +5 and -15 dBm over 0.5 to 7 GHz are shown in Fig.4(a) (curve (i)) and 4(b), respectively. The MD is about 56% at +5 dBm driving power. Again, it is seen that the corresponding C/IM_3 vs. frequency characteristics as shown in curve (ii) of Fig.4(a) is controlled only by AM-PM characteristics except beyond the resonance region.

For an operating condition with MD smaller than about 60%, AM-AM/AM-PM method is valid for narrowband RF signals only. From the measured results given in curve (ii) of Fig.1 and Fig.2, it is found that the input signal bandwidth has to be smaller than the inverse of intrinsic LD memory, $\tau(R,\omega)$, by about two orders of magnitude, in order to obtain a maximum of 3 dB deviation between the predicted and the measured C/IM_3 over the entire bandwidth. Same conclusion can be drawn by examining curve (i) and (ii) in Fig.4(a).

4. EFFECT OF OPTICAL REFLECTIONS

The small periodic variations in the frequency-dependent AM-AM and AM-PM curves of Fig.1 ,3 and 4 can be significantly enlarged if there is stronger optical reflections from fiber connectors. Fig.5(a) and 5(b) (corresponding to Fig.4(a) and 4(b)) illustrate the AM-AM and AM-PM characteristics under strong optical reflections. The large phase and gain variations (especially near the resonance region) caused by the 20 dB driving power difference are maily due to changes in the LD light coherent property under different levels of RF modulation power [14]. For +5 dBm modulation, the optical reflections from fiber connectors are essentially incoherent to the field in the LD active region, and consequently the received RF signal has a linearer phase and flatter amplitude vs. frequency response (if the modulation power was kept increasing, the nonlinear behavior would again be amplified). On the other hand, for -15 dBm modulation, the LD maintains its high coherent property and is sensitive to optical reflections, therefore the phase and amplitude of the received signal undergo fluctuations with a period proportional to the inverse of the reflection round-trip traveling time.

Comparing Fig.4(a) and Fig.5(a), we can see that large periodic variations in Fig.5(a) imply larger time delay $\tau(R,\omega)$ or larger memory (since the slope of the AM-PM vs. frequency curve shows large fluctuations). The larger delay reduces the frequency range over which AM-AM/AM-PM measurement method can be applied.

5. CONCLUSION

In this paper, the relative frequency-dependant time delay or the memory caused by increased modulation depth of a LD (with weak and strong optical reflections) was measured and its effect on the LD nonlinearity was investigated. In the case of the high speed InGaAsP LD used in the experiment with weak optical reflections, and for modulation depths below 60%, the RF bandwidth over which the LD can be considered to be effectively memoryless is generally very narrow, in fact it is smaller than the inverse of the measured memory by about two orders of magnitude. For modulation depths above about 75%, the nonlinearity of the LD is controlled only by the AM-AM characteristics and the effect of the LD memory is insignificant, and then with a single-frequency AM-AM measurement, one can predict the levels of intermodulation products [12] over a fairly wide bandwidth.

If the LD suffers strong optical reflections from fiber-optic connectors and a modulating signal cannot reduce the LD's coherent property so as reduce the reflection effect, then the phenomenon of frequency-dependent nonlinearity will become even more pronounced, as was illustrated in Fig.5. In this case, the LD has to be treated as a nonlinear device with memory. In order to predict the nonlinear distortion for wide band signal transmission, in which the AM-AM/AM-PM method is not applicable, one has to find alternatives such as circuit modeling [15], Runge-Kutta method, or Volterra series expansion.

References

[1] W.I. Way, R.S. Wolff, and M. Krain, "A 35 km 1.3 μm fiber optic microwave multicarrier transmission system for satellite earth stations," J. of Lightwave Technology, LT-5, December 1987.

[2] J.E. Bowers et al., "Direct fiber optic transmission of entire microwave satellite antenna signals," Electron. Lett., pp.185-187, 23, 1987.

[3] R. Olshansky, "RF multiplexing techniques applied to video distribution local networks," Conference Digest, paper THO2, OFC 1988.

[4] K. Fujito et al,"Low noise and wideband analog optical link using distributed-feedback laser diode," Conference Digest, paper THO3 , OFC 1988.

[5] G.L Heiter, "Characterization of nonlinearities in microwave devices and systems," IEEE Trans. on Microwave Theory and Technology, vol.MTT-21, pp.797-805, December 1973.

[6] O. Shimbo, "Effects of intermodulation, AM/PM conversion and additive noise in multicarrier TWT systems," Proc. IEEE, vol.59, pp.230-238, Feb. 1971.

[7] J.C. Fuenzalida et al,"Time domain analysis of intermodulation effects caused by nonlinear amplifiers," Comsat Tec. Rev., vol.3, Spring 1973.

[8] J. Minkoff, "The role of AM/PM conversion in memoryless nonlinear systems," IEEE MTT Symposium, paper 15.2, 1983.

[9] O. Shimbo et al,"Modulation-transfer noise effects among FM and digital signals in memoryless nonlinear devices," Proc. IEEE, vol.74, pp.580-599, April 1986.

[10] J.A. Albuquerque et al, "Modulation-transfer and other impairments in multicarrier QPSK transmission through a memoryless nonlinear device," Conference Digest, ICC 1984.

[11] J. Minkoff,"Intermodulation noise in solid-state power amplifiers for wideband signal transmission," Tech. Digest, IEEE Int. Microwave Symposium, pp.304-313, 1982.

[12] W.I. Way and A. Afrashteh, "Linearity characterization of connectorized laser diodes under microwave intensity modulation by AM/AM and AM/PM measurements," IEEE Intl. Microwave Symposium, paper Z-3, 1986.

[13] K.Y. Lau and A. Yariv," Intermodulation distortion in directly modulated semiconductor laser," Appl. Phys. Lett., vol.45, pp.1034-1037, 1984.

[14] W.I. Way and M.M. Choy,"Optical feedback effect on linearity performance of 1.3 μm DFB and multimode laser diodes," IEEE J. of Lightwave Tech., accepted for publication.

[15] W.I. Way,"Large signal nonlinear distortion prediction of a single mode laser under microwave intensity modulation," IEEE J. of Lightwave Tech., LT-5, pp.305-315, March 1987.

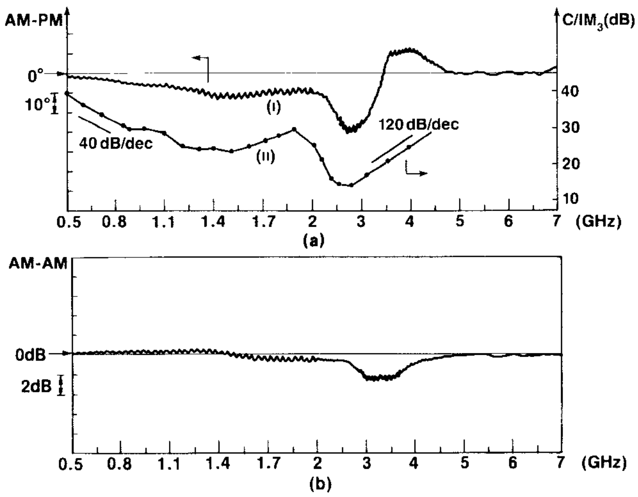

Fig.1 (a) (i) Received signal phase difference (AM-PM), and (b) RF gain difference (AM-AM) for modulating signal power of -2 dBm (MD=42%) relative to -15 dBm (MD=9%). Curve (ii) in (a) is the power ratio of fundamental carrier and third-order intermodulation. The two tones were separated by 4 MHz, and their total power was -2 dBm.

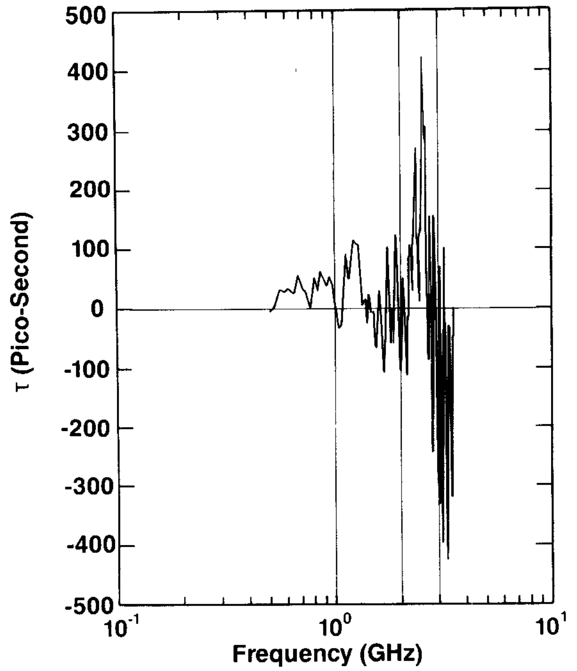

Fig.2 Laser diode memory $\tau(R,\omega)$ versus the frequency of modulating signal at current modulation depth of 43%. The values were obtained from the slope of curve (i) of Fig.1(a).

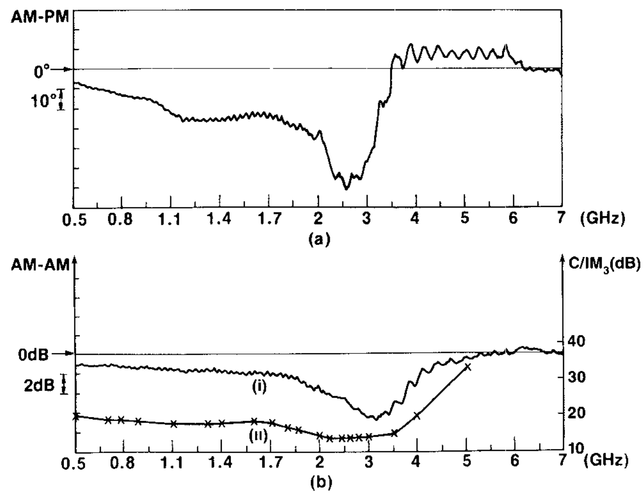

Fig.3 (a) Received signal phase difference (AM-PM), and (b) (i) RF gain difference (AM-AM) for modulating signal power of +5 dBm (MD=93%) relative to -15 dBm (MD=9%). Curve (ii) in (b) is the $ C/ IM sub 3 $. The two tones were seperated by 4 MHz, and their total power was +5 dBm.

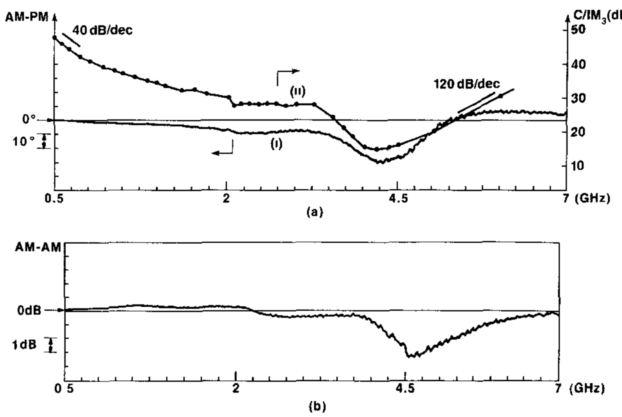

Fig.4 All conditions were similar to Fig.3, except the laser bias was increased from 27 mA to 35 mA, and MD became 56% for +5 dBm modulation.

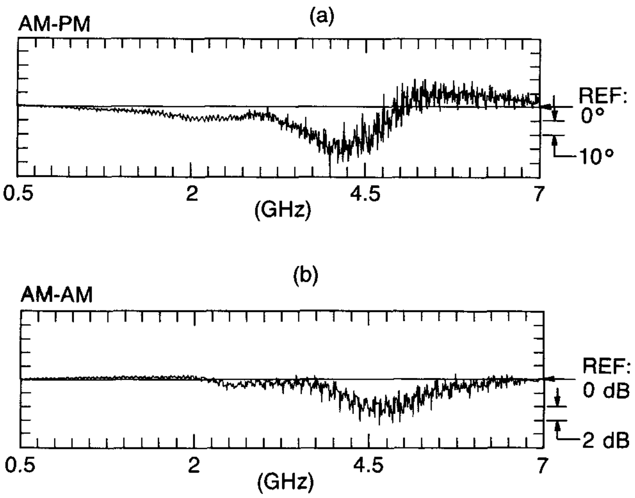

Fig.5 All conditions were similar to Fig.4, except the optical reflections level were significantly enhanced.