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DISTORTION CHARACTERISTICS IN DIRECTLY MODULATED LASER DIODES BY MICROWAVE SIGNALS

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ABSTRACT

A simple method for harmonic and intermodulation distortion determination of a laser diode under direct modulation by microwave analog signals is presented and experimentally verified. The method makes use of small-signal perturbation analysis of the rate equations to obtain analytical expressions for laser diode distortion. Experimental verification of the method presented has been done using DFB laser diodes operated at 1.3 and 1.5μm wavelengths with modulation frequencies up to 6 GHz.

INTRODUCTION

The knowledge of the distortion characteristics of laser diodes under direct intensity modulation at microwave frequencies is of particular importance to the multichannel frequency division multiplexed transmission tchnique. It can be shown that the signal-to-noise ratio of a transmission channel is directly proportional to the square of the modulation depth, OMD of the laser diode and inversely proportional to the sum of the squares of the second- and third-order modulation products. Since these terms are also functionally related to the modulation depth and signal frequency, it is essential to determine the second- and third-order modulation components in order to optimize the signal-to-noise ratio of a channel for the best performance.

We have developed the method for the determination of harmonic and intermodulation distortions produced by the laser diode under analog signal modulation conditions. The method is based on the small-signal perturbation analysis of the rate equations [1].[2]. To obtain a quantitative level of distortion from the equation derived and presented in this paper, only the intensity modulation response of the intrinsic laser at the fundamental frequency is required. The schematic representation of a laser diode [4] is shown in Fig 1. From the modulation response, the damping parameter, is found by using the de-embedding procedure. To accomplish that the network analyzer measurements of the extrinsic laser diode input impedance Z_{IN} over a broad frequency range have been employed. In addition to the method presented we have examined a possibility of modeling the laser diode nonlinearities by using higher-order polynomial forms to determine the dynamic range of modulation at any given modulation frequency. We found that this approach enables one to determine the second- and third-order intercept points of the laser diode which are important factors limiting modulation depth of a laser diode, under given dc bias current, I_o. This method makes use of the input/output RF power of modulation signal measurements. The measurement setup, employed is shown in Fig 2. The distortion characteristics discussed in the paper have been investigated for the Distributed Feedback (DFB) laser diodes operated at wavelengths 1.3μm and 1.55μm each with the optical output power of 5mW in the C.W. mode.

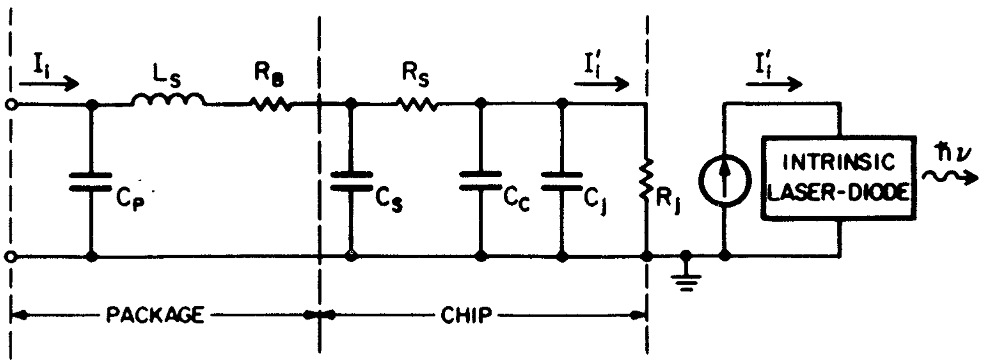

FIG 1 Equivalent Circuit Model of a Laser Diode

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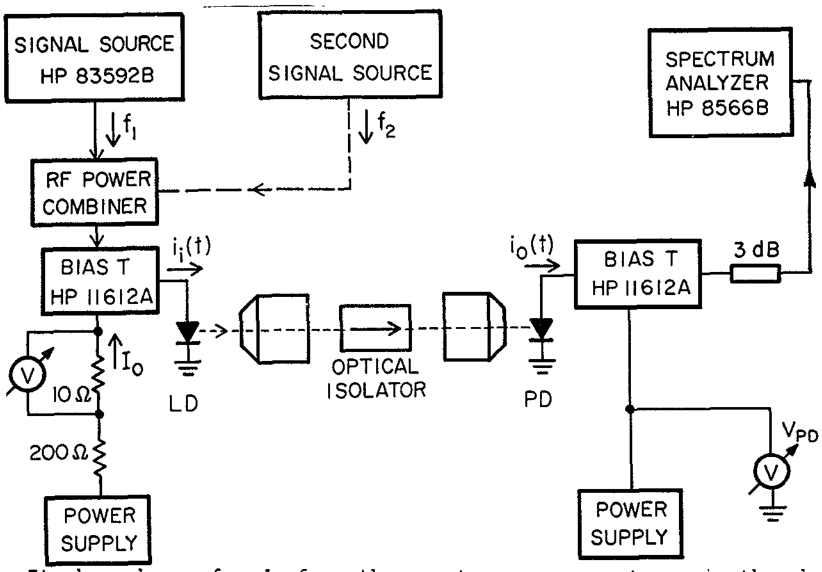

FIG 2 Measurement setup for Harmonic- and IM-Distortion Characterization of Laser Diodes

It has been found from the spectra measurements that each laser diode exhibits almost a single-mode operation with the sidemodes suppression approximately at -32dB. The structure of investigated DFB lasers is similar to that being described in [3]. Although each device has a different threshold current and different quantum efficiency the distortion characteristics of both laser diodes are similar under the same RF modulation signals. This is probably due to very similar optical-gain nonlinearities of both lasers whose among other factors greatly contribute to the frequency dependent distortion characteristics.

Since the distortion characteristics, of both 1.3μm and 1.55μm DFB lasers are similar only the results pertaining to the 1.3μm device are presented in the paper.

ANALYTICAL EXPRESSIONS FOR DISTORTION CHARACTERISTICS

Based on the well-known perturbation analysis of the rate equations for a single-mode laser diode [1] the modulation response at fundamental and harmonic frequencies can be determined. Assuming that the fundamental frequency signal $f > (2\Pi\tau_n)^{-1}$ where τ_n is the carrier lifetime, and also that the spontaneous emission factor is less or equal to 10^{-3} in the laser rate equations the following analytical expressions for distortion characteristics have been derived;

$$T_{2H} = \frac{A(2f)}{A(f)} = OMD.x^2/\sqrt{[(2x)^2-1]^2+B(2x)^2} \quad (1)$$

is the second harmonic amplitude response relative to the signal level at fundamental frequency,

$$T_{3H} = \frac{A(3f)}{A(f)} = 1.5(OMD)^2(x^4+0.5x^2)/\sqrt{\{[(2x)^2-1]^2+B(2x)^2\}\{[(3x)^2-1]^2+B(3x)^2\}} \quad (2)$$

is the harmonic amplitude responses relative to the signal level at the fundamental frequency,

$$T_{IMD} = \frac{A(IMD)}{A(f)} = 0.5(OMD)^2\left|(x^4-0.5x^2)/\sqrt{\{(x^2-1)^2+Bx^2\}\{[(2x)^2-1]^2+B(2x^2)\}}\right| \quad (3)$$

is the IMD products response relative to the carrier level at fundamental frequency, where $x = f/f_o$ is the normalized frequency, and $B = 2\Pi f_o \varepsilon / g_o$ is the damping parameter where ε is the optical gain compression factor, g_o is the optical gain slope, and IMD is $2f_1-f_2$ or $2f_2-f_1$. The optical modulation depth OMD is defined as the half of the peak-to-peak modulated light intensity to the light intensity at a given bias current, I_o [1]. It has been assumed in the derivation of (1) - (3), that $2\Pi f > 1/\tau_n$, and also that $2\Pi f_o << 1/\tau_p$ is the photon lifetime which is typically on the order of 1 ps. Equation (1) implies that there is a single-valued maximum of the second harmonic which occurs at the normalized frequency determined by

$$x_{2HM} = [2(2-B)]^{-0.5} \quad (4)$$

and is given by

$$\left.\frac{A(2f)}{A(f)}\right|_{max} = 0.5\,OMD[B(4-B)]^{-0.5} \quad (5)$$

It can be seen from Equations (2) and (3) that both third harmonic and IMD exhibit double maxima.

The value and location for each of these maxima are determined by the value of the parameters B and resonant frequency, f_o which is a bias current dependent quantity (ε and g_o are current independent constants as explained in [4]). The damping parameter, B, and frequency, f_o, can be obtained from the intrinsic laser small-signal modulation response by employing the de-embedding technique which enables one to extract the extrinsic laser parasitic elements.

The laser-diode circuit model is assumed in the form of a low-pass ladder network shown in Figure 1. The element values of this ladder are determined from measurements of the device input impedance over a broad frequency range. The input impedance characteristic in turn enables one to find the required values of the elements by using standard optimization techniques for the network with a known and relatively simple configuration. The overall small-signal modulation response of the laser diode is given by

$$T(j\omega) = T_P(j\omega)T_I(j\omega) \quad (6)$$

where $T_P(j\omega)$ is the current transfer function for the chip and package parasitic components, $T_I(j\omega)$ is defined as the ratio of the optical modulated power to the RF modulation current injected into the intrinsic device and it can be expressed as [4]:

$$T_I(j\omega) = \frac{T_o}{1-x^2 + jBx} \quad (7)$$

where $T_o = \eta h\nu/2q$ is the optical power response under the dc conditions, η is the quantum efficiency of the intrinsic laser diode.

Under normal operation conditions the numerical value of the damping parameter B for the bias current in the range of $I_{th} < I_o < 2I_{th}$ is typically less than 1, and for higher bias currents lies usually between 1 and 1.41.

The dynamic range of a laser diode which is typically described by the third-order intercept point can be determined by the extrapolation of a laser diode transfer characteristic; P_{OUT}-P_{IN} in its linear range. This approach is widely used for modeling of microwave nonlinear two port devices [5]. We have found that it sufficies to model the laser nonlinearity at a given frequency by a third-order polynomial.

EXPERIMENTAL RESULTS

The harmonic, intermodulation distortion and dynamic range of a laser diode have been obtained using measurement setup shown in Fig 2. The InGaAs p-i-n photodector (PD) used in the experiment has the 3-dB bandwidth above 15 GHz, which is well in excess of the 3-dB modulation bandwidth of the investigated laser diodes. Two types of InGaAsP-DFB lasers have been used in the distortion characterization; one operated at 1.3μm and the other 1.5μm. It has been found that both devices exhibited comparable levels of distortion under the same modulation conditions.

The comparison of experimental and calculated results for the second- and third- harmonics for the 1.3μm LD is shown in Fig 3. It can be seen that they compare very well. The calculated characteristics have been obtained using Eqs (1) and (2) with the values of B, and f_o; 0.52 and 6GHz, respectively. These B and f_o values have been derived from the small-signal modulation response which is also shown in Fig 3. The de-embedding procedure has been employed in order to obtain the modulation response for the intrinsic laser. It has been assumed that the small-signal equivalent circuit of a laser diode has the form as shown in Fig 1. The following values of the circuit elements have been obtained by using

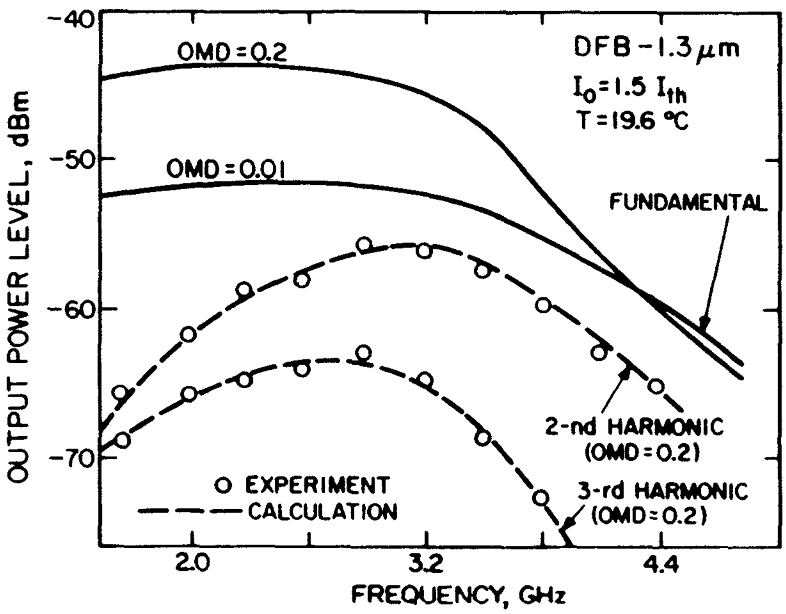

FIG 3 Comparisons of calculated and measured Distortion Levels for the 2-nd and 3-rd Harmonics at OMD = 0.2. Also the response at fundamental frequency is shown.

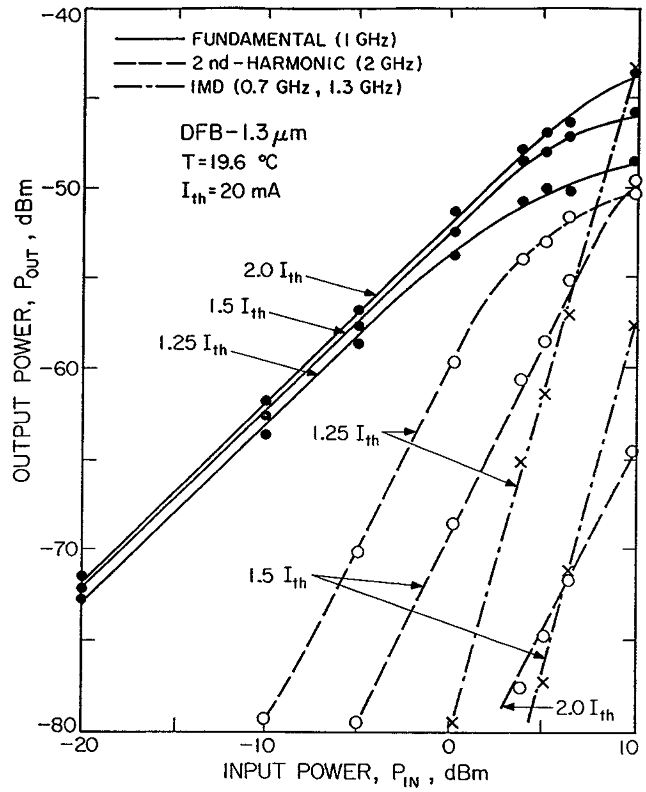

FIG 4 The P_{OUT}-P_{IN} characteristics obtained for 1.3μm DFB LD at Fundamental, 2-nd Harmonic and IMD under various DC bias currents

commercially available software for microwave circuits; R_J = 5Ω, C_J+C_C = 270pF, R_S = 5Ω, C_S = 15.pF, R_B = 2Ω, L_P = 2nH, C_P = 0.25pF. The dynamic characteristics for the 1.3μm DFB LD are shown in Fig 4.

CONCLUSIONS

A simple analytical method for characterization of harmonic and intermodulation distortion from the laser diode under given amplitude modulation and bias conditions has been presented. The equations derived in the paper are based on the small-signal perturbation analysis for the single-mode rate equations developed in [1]. The parameters that are required for the calculation of distortion characteristics are the dampig factor and resonant frequency of the intrinsic laser diode, and they are derivable from the small-signal modulation response of the actual laser using a de-embedding procedure. It can be seen from the comparison made between the experimental and calculated distortion responses that the proposed method offers good accuracy, and therefore it can be used for practical testing of laser diodes in communication applications. In addition, the use of a polynomial approximation to model the laser diode nonlinearity has been examined. Although this approach is applicable to a narrowband charactrization only, it is very useful in the 1-dB response compression and 3-rd order IMD - intercept determinations. These parameters, are of significance to the dynamic range of an analog fiber-optic link which is essentially limited by the distortion level produced by the laser diode nonlinearity.

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