Theoretical and Experimental Study of Second-Order Distortions in CATV DFB Laser Diodes

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***Abstract*— Calculation of linearity performances of a given DFB laser is a well-known problem when working with CATV AM-VSB optical links. In this paper, a nonlinear model of the DFB laser is presented. The bias and frequency dependence of second order intermodulation distortion is analyzed by combining Volterra models of the laser leakage current and rate equations. The prediction of the model is then compared to distortion measurements with a maximum discrepancy of around 1.5 dB.**

I. Introduction

DISTRIBUTED-FEEDBACK (DFB) lasers are commonly used in AM-VSB CATV systems, requiring low noise and particularly high linearity performances. One of the limitations of the DFB laser is its second-order distortion, which is generally caused by the combination of a number of distortion machanisms.

A first solution to analyze the distortion performances of a DFB laser diode could be to use the well-known monomode rate equations [1], [2].

However, the measured second harmonic distortion of a DFB laser as a function of bias current sometimes exhibits a dip at a particular current far from threshold current, especially at low frequencies [3]. This phenomeon can not be theoretically explained just by the rate equations.

A model based on the leakage currents of the laser diode has been described in the literature [4] to explain this particular behavior.

Nevertheless, a large number of DFB lasers can not be characterized using this theory [5].

II. Theory

Starting from these facts, we have conceived a model based on both leakage currents and rate equations.

The nonlinear transfer function from the electrical input current I to the laser output power P is obtained by cascading two nonlinear systems, $\underline{F}$ and $\underline{H}$, describing leakage current and rate equations, respectively.

The magnitude of the second-order two-tone intermodulation (IMD2) response relative to the optical carrier intensity C is given by

$$\frac{IMD2(\omega_1+\omega_2)}{C} = m(I_{a0}-I_{\text{th}})\frac{|\,\underline{K}_2(\omega_1,\omega_2)\,|}{|\,\underline{K}_1(\omega_1+\omega_2)\,|} \quad (1)$$

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where

$$\underline{K}_1(\omega_1+\omega_2) = \underline{F}_1(\omega_1+\omega_2)\cdot\underline{H}_1(\omega_1+\omega_2) \quad (2)$$

$$\underline{K}_2(\omega_1,\omega_2) = \underline{F}_2(\omega_1,\omega_2)\cdot\underline{H}_1(\omega_1+\omega_2) + \underline{F}_1(\omega_1)\cdot\underline{F}_1(\omega_2)\cdot\underline{H}_2(\omega_1,\omega_2) \quad (3)$$

m is the optical modulation depth per channel, I_{a0} is the laser bias current and I_{th} is the laser threshold current.

The singlemode rate equations governing distributed-feedback (DFB) lasers for small-signal analysis [1], [2], neglecting spontaneous emission, are:

$$\frac{d(N_0+\delta N)}{dt} = \frac{(I_{a0}+\delta I_a)}{q} - \frac{(N_0+\delta N)}{\tau_n} - G\cdot(P_0+\delta P) \quad (4)$$

$$\frac{d(P_0+\delta P)}{dt} = G\cdot(P_0+\delta P) - \frac{(P_0+\delta P)}{\tau_p} \quad (5)$$

with

$$G = \Gamma g_0(n_0-n_{tr})(1-\kappa(P_0+\delta P)) = G_0 + G_n\delta N + G_p\delta P \quad (6)$$

where

$N_0+\delta N$	the carrier number,
q	the electronic charge,
$I_{a0}+\delta I_a$	the injected current into the active region,
τ_n	the spontaneous recombination lifetime of the carriers,
$P_0+\delta P$	the photon number,
κ	the gain compression factor,
Γ	the optical confinement factor, given by the ratio of the active region and modal volumes, V_a and V,
g_0	the optical gain coefficient,
n_0 and n_{tr}	the carrier density, and carrier density for transparency, respectively,
τ_p	the photon lifetime.

Around the bias current I_{a0}, it can be written that:

$$0 = \frac{I_{a0}}{q} - \frac{N_0}{\tau_n} - G_0P_0 \quad (7)$$

$$G_0 = \frac{1}{\tau_p} \quad (8)$$

So, derivatives of δP and δN, using the preceding relations, are found to be:

$$\frac{d(\delta P)}{dt} = \delta N G_n P_0 + G_p P_0 \delta P + G_p \delta_p^2 + G_n \delta N \delta P \quad (9)$$

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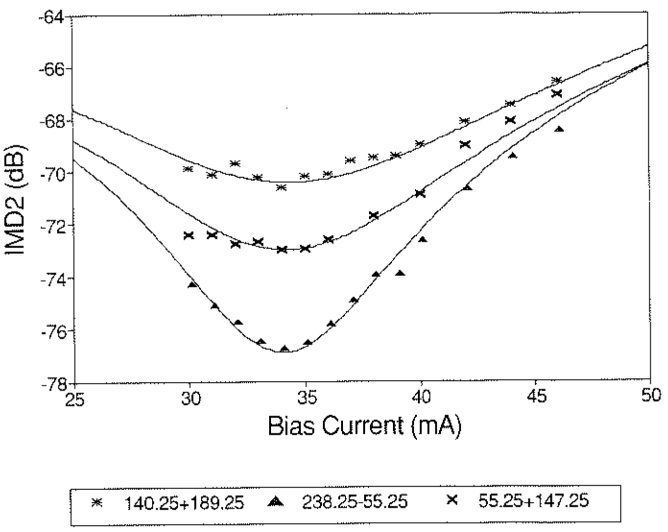

Fig. 1. Theoretical (solid lines) and experimental IMD2 characteristics of an analogue DFB laser at 1300 nm as a function of frequency and bias current.

$$\frac{d(\delta N)}{dt} = \frac{\delta I_a}{q} - \delta N(G_n P_0 + \frac{1}{\tau_n}) - \delta P(G_p P_0 + \frac{1}{\tau_p}) - G_p \delta P^2 - G_p \delta N \delta P \tag{10}$$

Injecting $\delta P = exp(j\omega t)$, where ω denotes pulsation, into relations 9 and 10, it is straightforward to find the Volterra kernels due to the rate equations:

$$\underline{H}_1(\omega) = \frac{1}{A + j\omega B} \tag{11}$$

$$\underline{H}_2(\omega_1, \omega_2) = -\frac{1}{A^3}(2D + (\omega_1 - \omega_2)^2 \cdot K + j(\omega_1 + \omega_2).E) \tag{12}$$

where negligible terms (for operations under 1 GHz) have been omitted.

The different parameters are defined by:

$$A = \frac{q}{\tau_p} \tag{13}$$

$$B = q(1 + \frac{\kappa}{G_n \tau_p} + \frac{1}{G_n P_0 \tau_n}) \tag{14}$$

$$D = \frac{q\kappa}{G_n P_0 \tau_p}(\frac{1}{\tau_n} + G_n P_0) \tag{15}$$

$$E = q(\frac{1}{P_0} + \frac{2\kappa}{G_n P_0 \tau_p}) \tag{16}$$

$$K = -\frac{q}{G_n P_0^2} \tag{17}$$

where

$$G_n = \frac{\Gamma g_0}{V_a} \tag{18}$$

$$P_0 = \frac{(I_{a0} - I_{th})\tau_p}{q} \tag{19}$$

The leakage current model, analytically developed in [4], can be represented by an equivalent electrical circuit as shown in Fig. 4 of [4]. R_l and R_a are resistances in series with the leakage and laser diodes, respectively. This model, adapted for second-order intermodulation distortion, gives the following Volterra kernels:

$$\underline{F}_1(\omega) = 1 + \frac{I_{so}}{I_{a0}}\gamma_0 e^{j\theta/2}(1 - y_0) - y_0' I_{so} \tag{20}$$

$$\underline{F}_2(\omega_1, \omega_2) = -\frac{I_{so}}{I_{a0}}(\gamma_1 y_2' e^{j\theta_1/2} + \gamma_2 y_1' e^{j\theta_2/2}) - y_{12} I_{so} \tag{21}$$

where I_{so} is the leakage current without modulation; γ_0, γ_1, γ_2, θ, θ_1, θ_2, y_0, y_0', y_1', y_2', y_{12} are functions of I_{so}, R_a, R_l, τ which is the lifetime of the minority carriers in the leakage diode, and V_d which is the voltage across the laser diode.

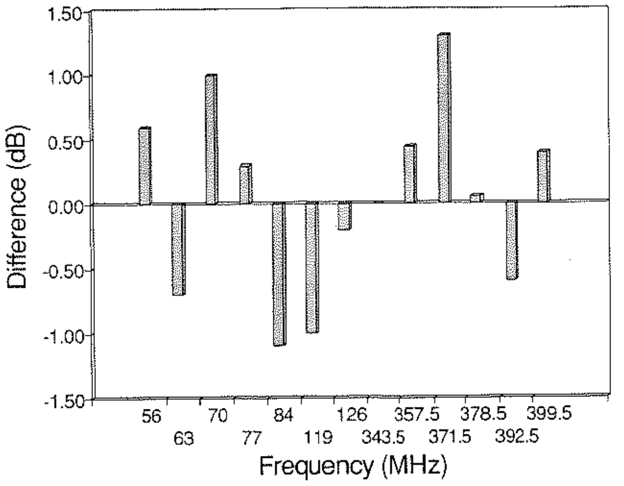

Fig. 2. CSO characteristics of an analogue DFB laser: differences between theoretical and experimental data.

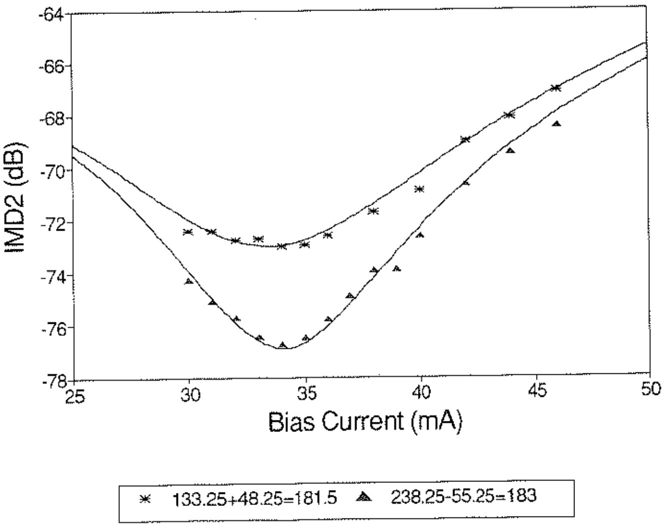

Fig. 3. Theoretical (solid lines) and experimental IMD2 characteristics of an analogue DFB laser in a given channel.

III. Experimental Results

We have experimentally investigated the bias-dependence of IMD2 in the case of a 40-channel AM–VSB transmission.

We use in this experiment a DFB laser emitting at 1310 nm and working with an optical modulation depth of 3.2%.

Regarding the experimental set-up, it can be found that it exists a big interest in maintaining $m(I_{a0} - I_{\rm th})$ constant instead of m constant [6], in order to minimize the influence of optical reflections. On the other hand, when approaching the threshold current, the optical modulation depth has to be kept low enough to avoid clipping effects. In this paper, the results are mathematically corrected to plot the theoretical and experimental data with a constant optical modulation depth.

Fig. 1 shows typical results in the case of a 40 VHF channel AM–VSB optical link. IMD2 curves were measured at bias currents from 25 to 50 mA. Distortions products are presented on this figure for the following frequency arrangements: 140.25 + 189.25, 55.25 + 147.25, 238.25 − 55.25 MHz. The experimental data seem to be in good agreement with theory, even when the resulting frequency is a difference of component frequencies. Up to now, other experiments have been performed, at both 1300 and 1550 nm, and give similar results.

Knowing the frequency plan allocation, the total composite second-order (CSO) distortion can then be calculated with a "$10 \cdot \log$" adding law.

Indeed, as shown on Fig. 2, the maximum CSO discrepancy between experimental and theoretical results is roughly 1.5 dB but is generally better than 1 dB for a wide variety of lasers with wavelengths of 1300 and 1550 nm.

Furthermore, this theory can predict large differences (see Fig. 3) between the IMD2s in a given channel (here around 182.25 MHz).

IV. Conclusions

An analytical nonlinear model of the DFB laser based on Volterra analysis accounting for monomode rate equations and leakage current has been described to calculate the lasers' second-order distortions. Comparisons with experimental data, at both 1300 and 1550 nm, give a maximum discrepancy of around 1.5 dB.

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