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メタデータ	言語: eng
	出版者:
	公開日: 2017-10-03
	キーワード (Ja):
	キーワード (En):
	作成者:
	メールアドレス:
	所属:
URL	http://hdl.handle.net/2297/3728

Dynamic Characterization of Intensity Fluctuations in Semiconductor Lasers under Digital Modulation

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Abstract

We report on modeling of intensity fluctuations in semiconductor lasers subject to low and high speed digital modulation. We examine influence of deciding both decision and sampling times on bit-error-rate (BER). Correlation between BER and relative intensity noise (RIN) is presented.

Keywords: Bit error rate, digital modulation, fluctuation, noise, semiconductor lasers.

1. Introduction

Intensity fluctuations represent an important parameter to criticize performance of semiconductor laser applications. It is common to characterize the noise content of fluctuations in terms of RIN. However, when the laser is utilized as a radiation source in digital systems, intensity fluctuations should be determined in terms of BER. Determination of operating conditions that correspond to minimum levels of fluctuations and BER is very important for both cases of free- and above-threshold biasing [1]. The former is desired to reduce consumption power, while the latter is commonly used for high speed modulation in order to avoid BER degradation due to enhanced intensity fluctuations. Dynamic response of laser in digital systems is qualitatively examined by the visual eye diagram. The BER is examined by sampling intensity fluctuations in both "on" and "off" states over an optional period, and then determining the probabilities *P(on/off)* and *P(off/on)* of incorrect counting of "on" and "off" states, respectively. By scanning this sampling time along the bit slot at definite times, called "decision times", the BER is decided as the minimum average value of *P(on/off)* and *P(off/on)*. Although optimum choices of the sampling and decision times are critical in determining BER, their modeling has received inadequate theoretical consideration. Moreover, it often happens that intensity fluctuations are measured in terms of RIN in digital systems, which perhaps due to rather cheap measuring setups. Therefore correlation between RIN and BER is necessary.

In this paper, we characterize intensity fluctuations of both low and high speed modulated lasers in terms of the eye diagram and BER. We criticize the optimum sampling and decision times. Both cases of biasing-free and above-threshold biasing are considered. We also study influence of nonlinear gain, as an important modulation parameter on BER.

2. Theoretical Model

Laser dynamics are described by the rate equations of the photon number $S(t)$ and injected electron number $N(t)$: [2]

$$\frac{dS}{dt} = \left[A - BS - G_{th} \right] S + \frac{a\xi}{V} N + F_S(t) \quad (1)$$

$$\frac{dN}{dt} = \frac{I}{e} - AS - \frac{N}{\tau_s} + F_N(t) \quad (2)$$

G_{th} is the threshold gain, A and B are coefficients for linear and nonlinear gain, a and ξ are parameters of linear gain, V is volume of active region, τ_s is spontaneous emission lifetime. The injected current I is composed of dc-biasing current I_b and modulation current I_m:

$$I = I_b + I_m * (\text{NRZ - pulse code}) \quad (3)$$

The pulse train is generated by a 2^7-1 virtual random bit-code generator. The terms $F_S(t)$ and $F_N(t)$ are Langevin noise sources that account for intrinsic fluctuations of $S(t)$ and $N(t)$.

Equations (1) and (2) are numerically solved by the fourth-order Runge-Kutta method with a time step of 2ps. Two bit-slots are used with periods T_b=0.5ns (low speed modulation) and 0.1ns (high speed) that correspond to bit frequencies lower and higher than the relaxation frequency, respectively. The noise sources are generated following our model in [2]. The eye diagram is constructed by dividing the stream of $S(t)$ into segments of length $3T_b$ and superposing them. BER is calculated as follows. The photon numbers $S_{on}(t)$ and $S_{off}(t)$ are sampled over different periods $0 \leq T_s \leq T_b$ and at possible decision times $0 \leq T_d \leq T_b$ as shown in Fig. 1(a). For each pair of T_s and T_d, the variances of fluctuations of $S_{on}(t)$ and $S_{off}(t)$ are examined. These variances are then used to calculate the error probabilities *P(on/off)* and *P(off/on)* taking into account shot and circuit noises in the detector end and assuming Gaussian statistics of

the received signal [1]. BER is then calculated as the minimum average of [$P(on/off)$ + $P(off/on)$]/2. RIN is calculated from fluctuations of $S_{on}(t)$ and $S_{off}(t)$ during the optimum times T_s and T_d, as illustrated in [2]. In calculations, we considered AlGaAs lasers with threshold current I_{th}=11.3mA, V=48μm^3, a=2.75x10^{-12}s^{-1}, ξ=0.15 and τ_s=2ns.

3. Results and Discussion

Figs. 1(a) and (b) plot the eye diagrams simulated for bit slots T_s=0.1 and 0.5ns, respectively, when I_b=I_m=2.0I_{th}. The figures indicate that timing jitters are displayed on the eye diagram of the shorter slot case, and the eye is less opened. Fig. 2 plots the BER values associated with the case of T_b=0.1 as functions of T_d and T_s. The figure indicates that minimum values of BER are obtained for longer T_s and intermediate T_d. In the case of T_b=0.5ns, these optimum values change to larger values of both T_s and T_d.
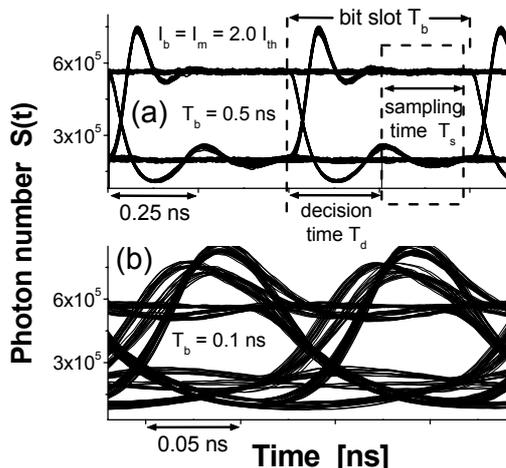

Fig. 1. Eye diagrams simulated for bit slots: (a) T_b=0.1 ns and (b) T_b=0.5 ns, when I_b=I_m=2.0I_{th}.
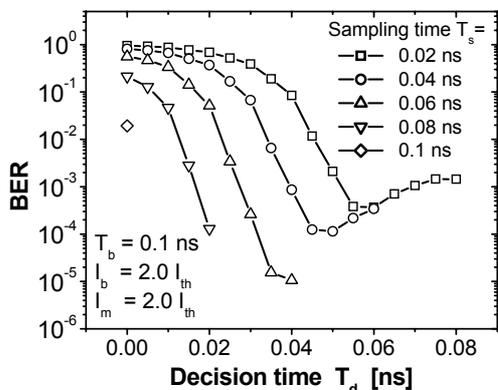

Fig. 2. Influence of deciding T_b and T_s on BER.

Influence of biasing current I_b on BER is illustrated in Fig. 3. The corresponding variation
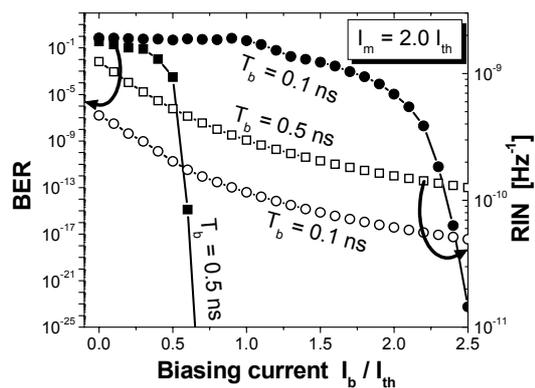

Fig. 3. Influence of I_b on both BER and RIN.

of low-frequency RIN is plotted on the right-hand axis. BER is high for low current I_b and then decreases rapidly when I_b>0.5I_{th} for T_b=0.5ns and when I_b>2.0I_{th} for T_b=0.1ns. RIN, however, decreases smoothly with increase of I_b, and the longer slot case attains higher RIN. Influence of nonlinear gain on BER is illustrated in Fig. 4 as a function of I_d. As shown, nonlinear gain has a little effect on BER when T_b=0.5ns, whereas it enhances BER for current I_b>I_{th} when T_b=0.1ns. This is because nonlinear gain works to suppress the relaxation oscillations that dominate the eye diagram of slot T_b=0.1ns, as shown in Fig. 1.
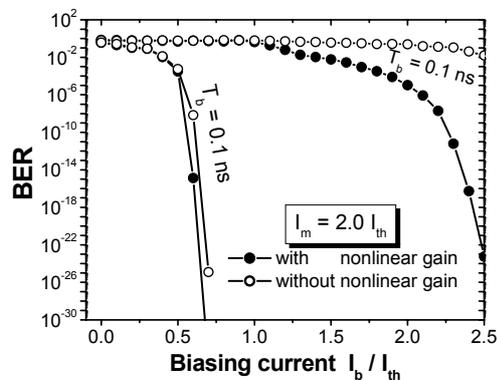

Fig. 4. Influence on nonlinear gain on BER.

References

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