Signal quality in digitally modulated scaled laser diodes

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Abstract

The calculated behavior of Gb/s on-off modulated scaled microlasers exhibit a non-monotonic dependence of timing jitter on spontaneous emission factor, β. Microlasers with $10^{-2} < \beta < 10^{-1}$ give optimal performance for Gb/s on-off modulated applications requiring less than 20 ps jitter and greater than 20 dB optical power contrast ratio.

1. Introduction

Advances in microlaser processing will result in devices with ultra-low threshold current and photon cavity volumes approaching a cubic wavelength. In such microlasers the spontaneous emission factor, β may be tailored to meet the needs of a given application. In this paper we analyze microlaser output signal quality as a function of β. Signal quality is parametrized in terms of timing jitter, σ average turn-on delay, t_d and optical output power contrast ratio, C for below to above laser threshold current (on-off) modulation at 1 Gb/s and in terms of σ and t_d for on-on modulation at 1 Gb/s.

2. Model and simulation

Rate equations with Langevin noise source terms [1] are used to estimate t_d and σ for a scaled laser diode.

$$\frac{dS}{dt} = (G - \kappa)S + \beta R_{sp} + F_{si}(t) \tag{1}$$

and

$$\frac{dN}{dt} = \left(\frac{I}{e}\right) - GS - \frac{N}{\tau_n} + F_{ei}(t) \tag{2}$$

where S and N are total photon and carrier (electron) numbers in the cavity, G (κ) is the optical gain (loss), β is the fraction of the total spontaneous emission that couples into the lasing mode. Variation in β may arise from a change in photon cavity volume and / or from quantum electrodynamic (QED) effects. R_{sp} is the spontaneous emission into all optical modes and F_{si}, F_{ei} are Langevin noise terms [1, 2]. F_{si} and F_{ei} are Gaussian random variables, which in the Markovian approximation have autocorrelation functions,

$$\langle F_{si}(t)F_{si}(t')\rangle = ((G + \kappa)S + \beta R_{sp})\delta(t - t') \tag{3}$$

$$\langle F_{ei}(t)F_{ei}(t')\rangle = (I/e + GS + N/\tau_n)\delta(t - t') \tag{4}$$

We assume no crosscorrelation between the noise terms and the non-Markovian contribution to noise for times shorter than the ~100 fs electron scattering rate is set to zero.

Inset to Figure 1(a) illustrates t_d and σ in laser output relative to deterministic Non-Return-to-

Zero (NRZ) current modulation applied to the laser diode between I_{low} and I_{high}. For on-off modulation $I_{low} < I_{th} < I_{high}$ where I_{th} is the laser threshold current. For on-on modulation $I_{th} < I_{low} < I_{high}$. S_{low} (S_{high}) is the average steady-state number of cavity photons corresponding to an injection current of I_{low} (I_{high}). t_d is the average time to reach a total number of cavity photons which is 50% of the difference in steady-state values such that $S(t = t_d) = (S_{high} + S_{low})/2$. The random nature of spontaneous emission gives rise to a distribution in turn-on delay with standard deviation σ. We assume lasing in a single longitudinal mode, linear optical gain $G = \Gamma g_{slope} v_g (N/V - n_0)$ with $g_{slope} = 4.8X10^{-16}$ cm^2, optical transparency carrier density $n_0 = 1.5X10^{18}$ cm^{-3}, optical mode confinement factor $\Gamma = 0.1$, photon group velocity $v_g = 8.1x10^9$ cm s^{-1}, and active volume $V = 2X10^{-13}$ cm^3. The 10 cm^{-1} internal loss and radiative recombination coefficient $B = 1X10^{-10}$ cm^3 s^{-1} used in our study are typical of InGaAsP lasers [3]. Ignoring QED effects, $R_{sp} = BN^2/V = N/\tau_n$ is assumed.

3. Results

Shown in Figure 1(a) is the dependence of t_d and σ as a function of β for an ultra-low threshold current on-off modulated 1 μm long microlaser photon cavity with 99% mirror reflectivity. The threshold current is $I_{th} = 46$ μA and the electrical input to the laser is modulated between $I_{low} = 8$ μA and $I_{high} = 138$ μA. The continuous decrease in t_d with increasing β shown in Figure 1(a) is due to the accompanying increase in S_{low}. Spontaneous emission is the dominant recombination process below threshold so an increase in β increases S_{low}. Figure 1(a) also shows that timing jitter does not vary monotonically with β. This non-monotonic dependence of jitter on β is due to two competing effects: (i) Enhancement in spontaneous emission noise with increase in β increases σ. (ii) The time for which spontaneous emission influences jitter depends on t_d so an increase in β which decreases t_d reduces σ. As shown in Figure 1(a), effects (i) and (ii) compensate each other so that values of $\beta > 10^{-2}$ do not yield further reduction in σ.

Signal power contrast ratio is $C = S_{high}/S_{low}$. A larger value of C indicates better signal quality. As shown in Figure 1(b), for a fixed I_{high} and I_{low}, C decreases continuously with an increase in β.

When the laser is biased below threshold, spontaneous emission dominates and the total number of cavity photons contributing to S_{low} is strongly dependent on β. Hence, S_{low} increases significantly with an increase in β. Well above threshold, stimulated emission dominates and hence S_{high} shows a very weak dependence on β leading to a small increase in S_{high} with increase in β. To overcome this degradation in C with increase in β, one may increase I_{high} which leads to greater power consumption. Alternately, one may decrease I_{low} which leads to larger t_d and increased electronic delay due to the larger voltage swing across the laser diode that occurs for a given current swing. The latter effect is due to the exponential dependence of the laser diode's current on the voltage across it. Low-cost systems with Gb/s on-off modulation which simultaneously require $C > 20$ dB and $\sigma < 20$ ps will benefit from use of micro-lasers with $10^{-2} < \beta < 10^{-1}$. At present, this is attractive because technologically it is easier to make microlasers with spontaneous emission coupling into ~ 100 modes than microlasers with spontaneous emission coupling into less than 5 modes.

Figure 2 shows the effect of varying β when the device is on-on (above threshold) modulated between $I_{low} = 100\ \mu A$ and $I_{high} = 400\ \mu A$. The turn-on delay increases with an increase in β. This can be understood as follows: t_d of an on-on modulated laser with $\beta \sim 0$ is limited by the ps stimulated emission time while t_d of a laser with $\beta \sim 1$ is affected by the ns carrier lifetime. Hence, t_d increases as β increases. Jitter is insensitive to t_d and is found to be approximately 5 - 6 ps for all values of β. Errors due to the finite number of samples used in our calculations mask subtle variations of σ with β and t_d .

Figure 2 shows that for high-speed (> 10 Gb/s), low-contrast (on-on modulation) systems which are limited by turn-on delay, it is not advantageous to use microlasers with β close to unity. Further, one can see that values of $10^{-2} < \beta < 10^{-1}$ lead to comparatively low turn-on σ and t_d both for on-on and on-off modulation. For on-on modulation one expects negligible dependence of contrast ratio on β.

4. Discussion

In this work, we assume cavity QED effects that occur in micro-lasers do not alter R_{sp} although it has been shown that by suitably designing the cavity R_{sp} can be enhanced or suppressed [4]. Nevertheless, the trends discussed in this work remain valid even for arbitrary changes to β for a given R_{sp}. Another assumption is that gain experienced by a mode is independent of β. In fact, equilibrium modal gain should be linearly dependent on the spontaneous emission coupling into the mode. An enhancement of g_{slope} with an increase in β leads to lower I_{th} and hence, for fixed values of I_{low} and I_{high}, a degradation in C for on-off modulation. This is because, in the limit of I_{th} going below I_{low}, the contrast ratio reduces to that of on-on modulation. The increase in g_{slope} which accompanies an increase in β will tend to decrease even further the turn-on delays at higher β. Hence, the trends seen from Figures 1(a) and 1(b) will only be enhanced if g_{slope} were to increase with an increase in β. The results of our study for on-off modulation remain valid if the modal gain depends on spontaneous emission coupling into that mode. However, for on-on modulation an enhancement in g_{slope} with an increase in β improves the high-speed response and reduces the turn-on delay. To study this dependence a self-consistent dynamic model which describes the interplay of β, R_{sp}, and G in a microcavity is required.

5. Conclusion

In conclusion, σ for an on-off modulated laser varies with β in a non-monotonic fashion, while t_d decreases monotonically. Microlasers with $10^{-2} < \beta < 10^{-1}$ give optimum performance for modest bit rate (~ 1 Gb/s), $\sigma < 20$ ps, C > 20 dB on-off modulation and comparatively low values of t_d (~ 40 ps) for on-on modulation.

Acknowledgment:

This work is supported in part by the Joint Services Electronics Program under contract #F49620-94-0022, and DARPA Ultra-II / Air Force Office of Scientific Research under contract #F49620-97-1-0438.

References:

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Figure Captions.

Figure 1: (a) Calculated effect of β on t_d and σ for 1010 .... NRZ 1 Gb/s on-off modulation with I_{high} = 138 μA and I_{low} = 8 μA. Cavity length is 1 μm and volume of the microlaser active region is $2X10^{-13}$ cm^3. The mirror reflectivity is 99% leading to a threshold current of I_{th} = 46 μA. Error bars are due to finite number (~ 800) of samples and the pseudo-random number generator used to calculate jitter. Inset is illustration of electrical signal applied to laser diode versus time and the number of cavity photons, indicating t_d and σ. (b) Calculated log - log plot of $C = S_{high}/S_{low}$ versus β for the device simulated in Figure 1(a). A continuous degradation in contrast ratio with an increase in β is seen. The circles represent the data obtained using our simulations. The line is to guide the eye.

Figure 2: Calculated effect of β on t_d and σ for 1010 .... NRZ 1 Gb/s on-on modulation with I_{high} = 400 μA and I_{low} = 100 μA for the microlaser corresponding to Figure 1.

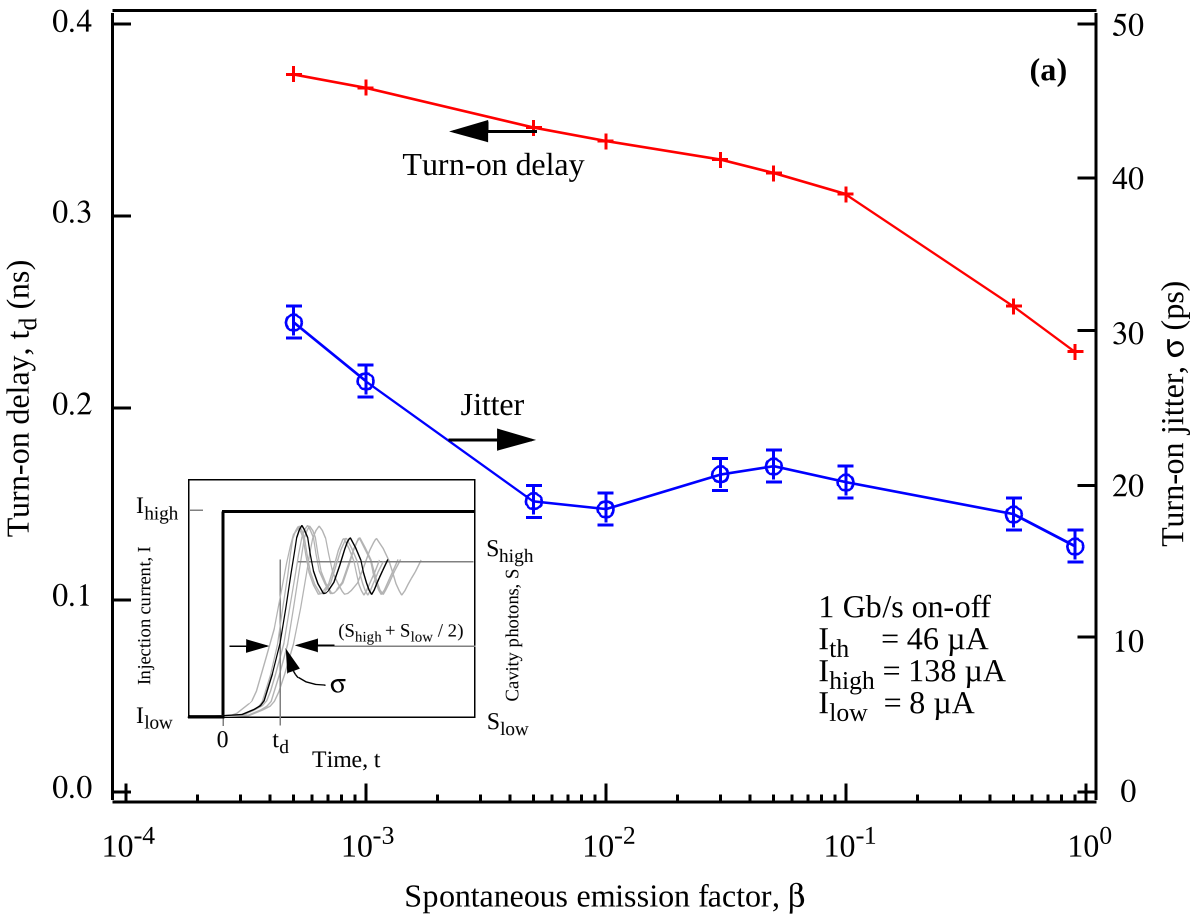
(a)
Turn-on delay
Jitter
1 Gb/s on-off
I_{th} = 46 μA
I_{high} = 138 μA
I_{low} = 8 μA
Turn-on delay, t_d (ns)
Turn-on jitter, σ (ps)
Spontaneous emission factor, β
0.0
0.1
0.2
0.3
0.4
0
10
20
30
40
50
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
I_{high}
I_{low}
Injection current, I
S_{high}
S_{low}
Cavity photons, S
$(S_{high} + S_{low} / 2)$
σ
0
t_d
Time, t

Figure 1(a)

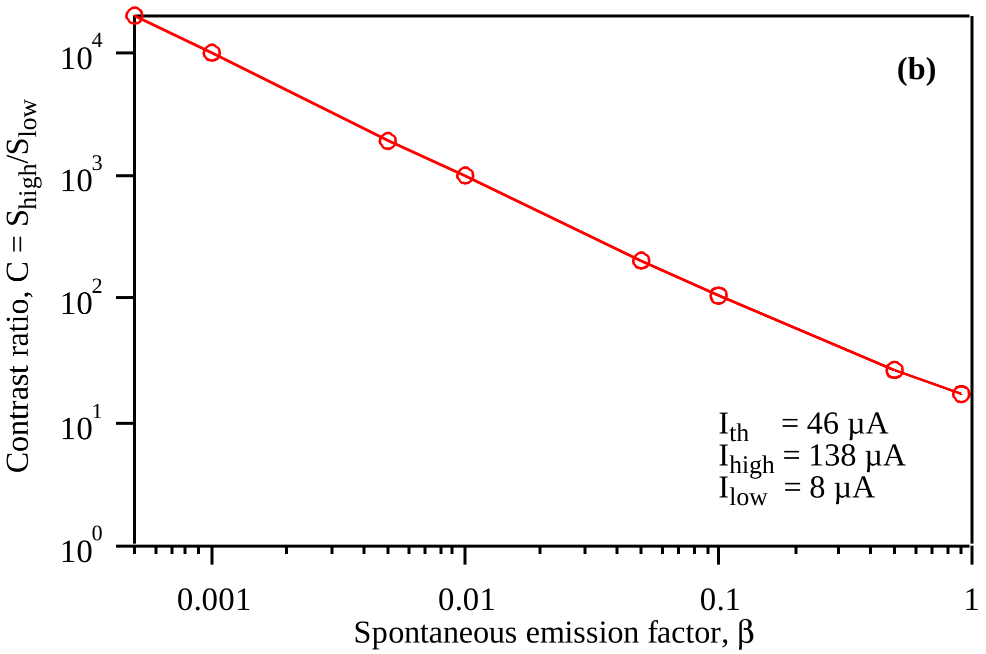
(b)
Contrast ratio, $C = S_{high}/S_{low}$
10^0
10^1
10^2
10^3
10^4
0.001
0.01
0.1
1
Spontaneous emission factor, β
I_{th} = 46 µA
I_{high} = 138 µA
I_{low} = 8 µA

Figure 1(b)

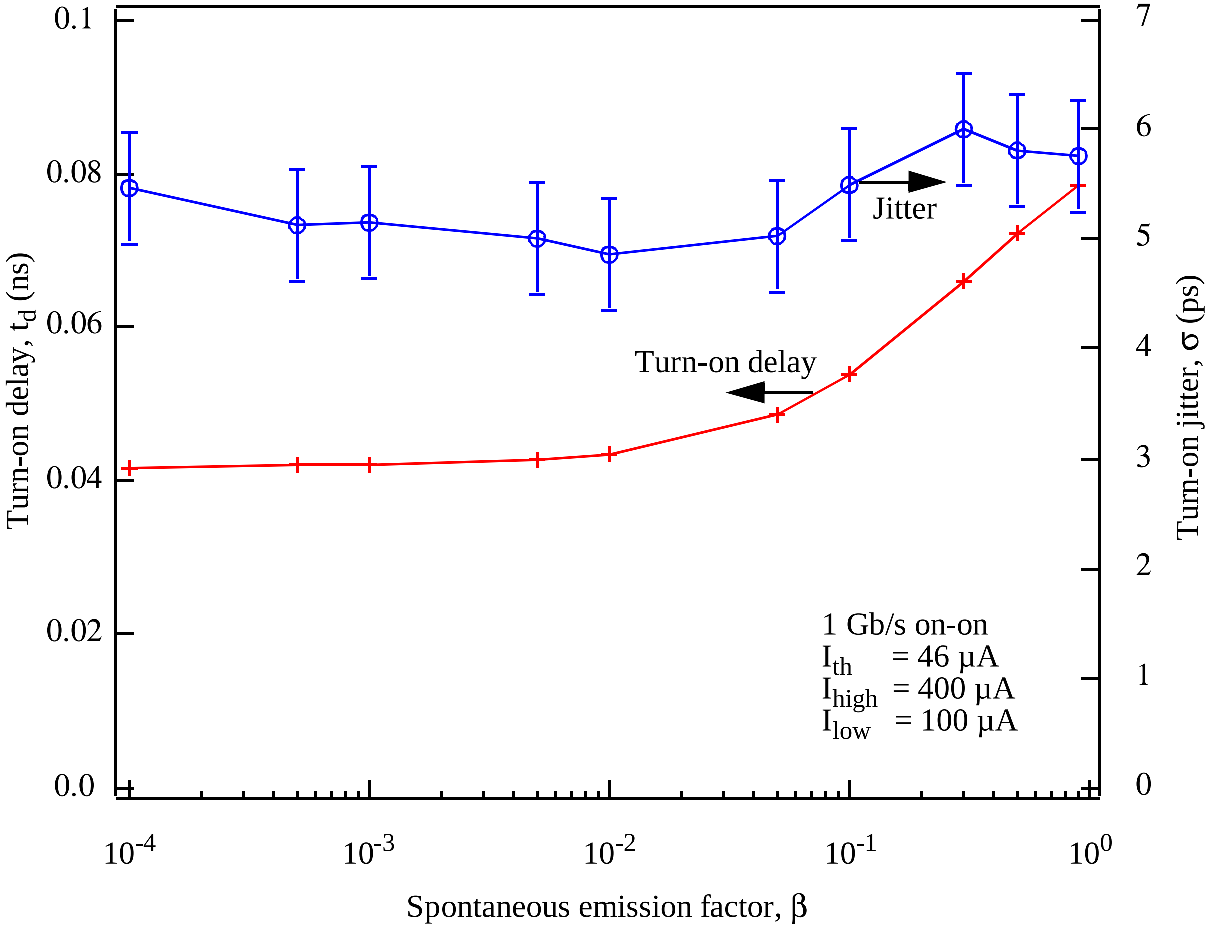
Turn-on delay, t_d (ns)
0.1
0.08
0.06
0.04
0.02
0.0
Turn-on jitter, σ (ps)
7
6
5
4
3
2
1
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Spontaneous emission factor, β
Jitter
Turn-on delay
1 Gb/s on-on
I_{th} = 46 μA
I_{high} = 400 μA
I_{low} = 100 μA

Figure 2