The effect of scaling microlasers on modal noise

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Modal noise and speckle visibility in Gb/s multimode fiber interconnect systems depends on a complex interplay of carrier dynamics, spontaneous emission factor, gain compression, and device dimensions. These competing factors allow scaled low-power microlasers with optimized design and operating conditions to exhibit modal noise comparable to large incoherent multimode devices.
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Future optoelectronic interconnects will use laser diodes with very small dimensions. Such scaled microlasers are attractive because their low threshold currents and high quantum efficiency ensure low total power dissipation. Microlasers will be used with multimode fiber for interconnect lengths varying from 1 m to several 100 m. An important issue is to establish the role of modal noise in future systems utilizing such scaled microlasers.

Modal noise is unwanted random variation in received light intensity stemming from interference effects in multimode fiber.[1] Kanada,[2] Dandliker *et al.*,[3] and Bates *et al.*[4] have studied modal noise due to conventional laser diodes. Hahn *et al.*[5] recognized modal noise from coherent microlaser emission could be reduced using large area multitransverse mode vertical cavity surface-emitting lasers (VCSELs). While various properties of microlasers have been studied,[6–9] the behavior of modal noise in scaled lasers has not been systematically evaluated. In this letter, we describe the impact of reducing laser diode dimensions on modal noise in Gb/s optoelectronic interconnections.

We begin by numerically solving the multimode laser diode rate equations.[10] We use visibility γ_L at the end of a length L of fiber as our measure of modal noise. Visibility is defined by

$$\gamma_L^2 = \int_{-\infty}^{\infty} C_p(\nu) C_h(\nu) d\nu,$$

where $C_p(\nu)$ is the normalized autocorrelation function of the time-averaged laser output power spectrum and $C_h(\nu)$ is the Fourier transform of the autocorrelation of the fiber's impulse response.[3] We assume a fiber modal bandwidth of 1 GHz km. To simulate performance of Gb/s optoelectronic interconnects, we model a detector with 1 GHz, -3 dB high-frequency rolloff as a weighted time average of the received light.

Figure 1(a) shows steady-state light-current ($L_{\mathrm{out}}-I$) and n-I curves for a multimode Fabry–Perot laser diode of cavity length $L_C=500$ μm, spontaneous emission factor $\beta=10^{-4}$, mirror reflectivity $R=0.30$, and lasing emission wavelength near $\lambda=1300$ nm. Figure 1(b) shows relaxation oscillations in the transient carrier density and light output when on-on (above I_{th}) current modulated with a non-return-to-zero (NRZ) signal at the rate of 1 Gb/s between $I_{\mathrm{low}}=20$ mA and $I_{\mathrm{high}}=30$ mA. Figure 1(c) shows time averaged laser spectra for different L_C and constant β. Threshold carrier densities are approximately maintained by adjusting reflectivity R. As may be seen, with decreasing L_C the spectrum becomes increasingly single mode in nature leading to increased coherence and hence high visibility. Figure 1(d) shows γ_L for different L_C, modulation conditions, and ϵ. The $L_C=5$ μm device is essentially single mode and its visibility curve exhibits a smooth decrease with increasing fiber length, L. Larger devices with $L_C=50$ μm and $L_C=500$ μm are multimode in nature with multiple peaks in their autocorrelation spectra and a characteristic plateau in the corresponding visibility curve. This is due to the fact that there is a range of fiber lengths over which fiber bandwidth encompasses the central autocorrelation peak but does not see higher-order peaks. The plateau value of γ_L is dependent upon the relative strength of the central mode of the autocorrelation to the other peaks, which is related to the mode suppression ratio (MSR). Further, a larger envelope width of the autocorrelation function, which in turn depends inversely on MSR and directly on the mode spacing, causes γ_L to decrease at shorter fiber lengths but at a slower rate. Hence, when L_C is increased from 50 to 500 μm, the mode spacing and the MSR decrease but the net effect is to decrease the envelope width, thereby causing an increase in the value of L at which γ_L decreases.

Figure 1(d) shows significant reduction in visibility for on-off (above to below I_{th}) modulation for a $L_C=500$ μm laser. The accompanying large carrier density fluctuations broaden the optical emission spectrum, reducing coherence, and diminishing the plateau in the visibility curve. The presence of gain compression leads to a lack of carrier pinning under current modulation causing wavelength variation (chirp), thereby enhancing the linewidth. However, gain compression also suppresses relaxation oscillations which can reduce the linewidth. For the $L_C=500$ μm device with gain compression shown in Fig. 1(d), the former dominates and the multimode laser behaves effectively as a single-mode laser with a very broad linewidth and the visibility curve does not exhibit a plateau.

Figure 2(a) shows L_{out}-I and n-I for microlasers with the indicated spontaneous emission factors. The $\beta=0.95$ device is almost thresholdless and shows lack of carrier pinning. However, the $\beta=10^{-4}$ device has $I_{\mathrm{th}}=8$ mA and shows carrier pinning. Figure 2(b) shows time-averaged spectra for these two microlasers under modulation. Chirp in the $\beta=0.95$ microlaser results in a two-peaked time-averaged spectra and the corresponding visibility curve exhibits a plateau. This is confirmed by the fact that the $\beta=10^{-4}$ micro-

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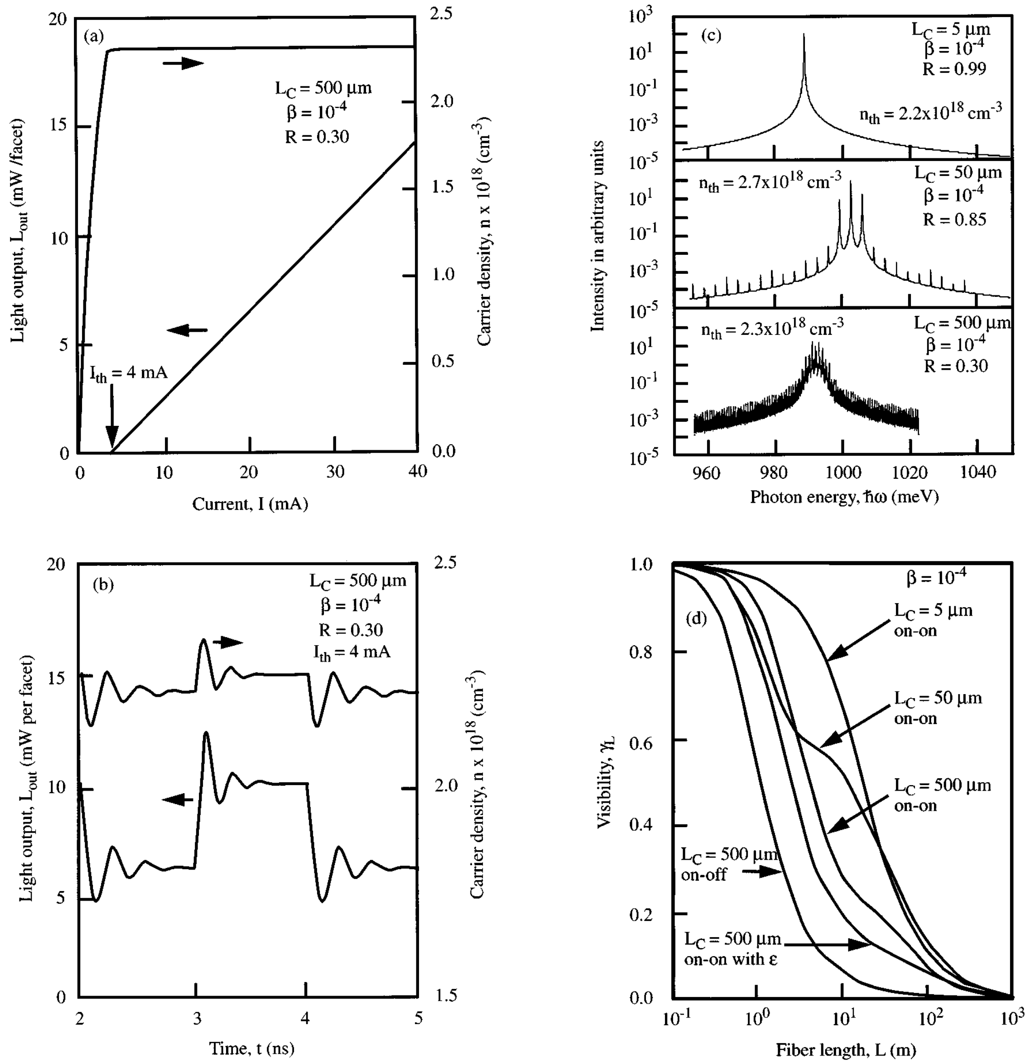

FIG. 1. (a) Steady-state room-temperature L_{out}-I and n-I for a multimode Fabry–Perot laser diode with L_C=500 μm, β=10^{-4}, R=0.30, and lasing emission wavelength near λ=1300 nm. (b) L and n vs time t for the laser of (a) with gain compression factor ϵ=2.5×10^{-18} cm^3. The laser is NRZ on-on modulated at 1 Gb/s. The low (high) current level is 20 mA (30 mA). (c) Time-averaged laser spectra for different L_C, constant β, and on-on NRZ modulation at 1 Gb/s. The low (high) current level is 20 mA (30 mA). Spectral resolution is 10 GHz= 4.14×10^{-2} meV. (d) Visibility, γ_L, as a function of fiber length L for different L_C, under different 1 Gb/s NRZ modulation conditions. The low (high) current level is 20 mA (30 mA) for on-on modulation and 2 mA (12 mA) for on-off modulation. The curve denoting on-on with ϵ represents a laser with gain saturation ϵ=2.5×10^{-18} cm^3. Threshold carrier density for all the curves are in the range $2-3\times10^{18}$ cm^{-3}.

laser, whose n is pinned above threshold, essentially has only a single mode in its time-averaged spectra. Hence, as seen in Fig. 2(c), the visibility curve for this laser does not exhibit a plateau. The presence of chirp may introduce significant speckle noise at the relaxation oscillation frequency[3] which is averaged out by our bandwidth-limited detector. Figure 2(c) shows the effect on γ_L of altering bias conditions for a given current modulation depth. For the microlaser with $\beta=10^{-4}$, the γ_L for given L is lower for on-off modulation due to occurrence of large relaxation oscillations that broaden the lasing spectral line, causing γ_L to decrease at shorter fiber lengths. For the β=0.95 microlaser and a given current modulation depth (I_{mod}=I_{high}-I_{low}), increasing I_{low} decreases the carrier density fluctuation due to the decreasing slope of the steady-state n-I seen in Fig. 2(a). The visibility curve γ_L for a single-mode microlaser under digital modulation conditions depends on separation in energy of the two dominating spectral peaks and the ratio of their intensities in the time-averaged spectra. The separation in photon energy is proportional to variation in carrier density under modulation. When I_{low} is increased, the variation in carrier density decreases and hence the separation in energy decreases tending to cause an increase in γ_L. However, the ratio of intensities of the two time-averaged spectral peaks decreases with increasing I_{low} so that γ_L tends to decrease. This latter effect dominates and hence the visibility at a given fiber length, γ_L, decreases with an increase in I_{low}. This is in direct contrast to the increase in γ_L with an increase in I_{low} seen in conventional lasers for which n is pinned above threshold current, I_{th}. As indicated in Fig. 2(d), the value of L (for a L_C=1 μm microlaser for which γ_L=0.8) varies significantly with I_{low}. In addition, the value of L for which γ_L=0.8 is, under favorable operating conditions, comparable to that of large L_C multimode lasers. These trends also apply to microlasers for which I_{low}<100 μA and I_{mod}~500 μA.

In conclusion, visibility and modal noise depends on

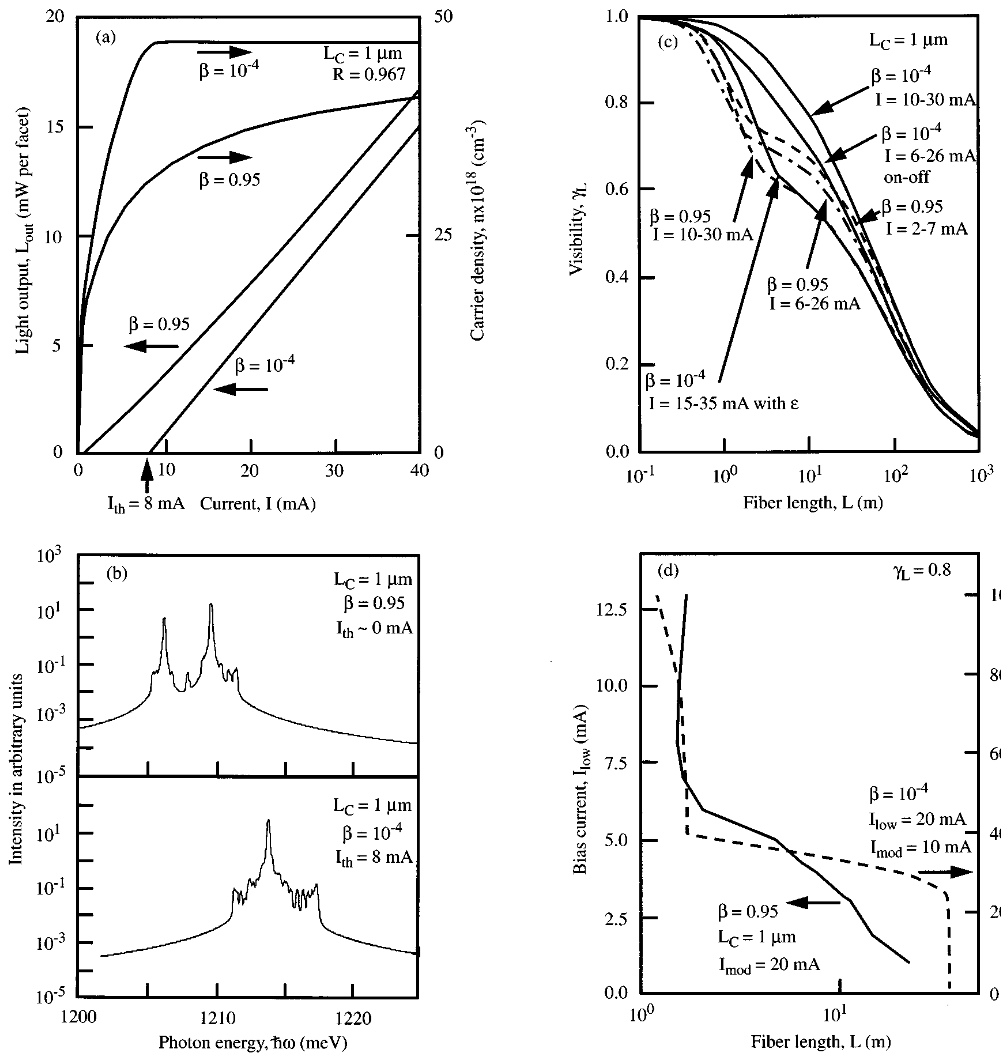

FIG. 2. (a) Steady-state L_{out}-I and n-I for a microlaser with $L_C=1$ μm, $R=0.967$ and the indicated β. (b) The time-averaged spectra for the microlaser when on-on NRZ current modulated at 1 Gb/s. The low (high) current level is 10 mA (30 mA). Spectral resolution is 1.24×10^{-1} meV=30 GHz. (c) Visibility, γ_L, as a function of fiber length L for microlasers with the indicated NRZ 1 Gb/s modulation conditions, spontaneous emission factor β, and gain compression factor $\epsilon=2.5\times10^{-20}$ cm^3 when present. The microlaser with $\beta=0.95$ is essentially thresholdless and the microlaser with $\beta=10^{-4}$ has a threshold current, $I_{\text{th}}=8$ mA. (d) Dependence of the fiber length L, where $\gamma_L=0.8$, on the modulation current, I_{low}, of the microlaser with $\beta=0.95$ (solid line), and cavity length L_C for a laser with $\beta=10^{-4}$ (dashed line).

cavity length, spontaneous emission factor, modulation and gain compression for both conventional and microlaser diode structures. By optimizing the design and operating conditions of low-power microlasers we have shown that they perform as well as the higher-power large incoherent multimode devices. In stark contrast to conventional lasers, microlasers with large β show a lack of carrier pinning and have lower visibility values at higher I_{low}. Microlasers such as VCSELs with their inherently low-power dissipation and low modal noise could be used in system applications involving short lengths of multimode fiber and Gb/s data rates.

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