Direct amplitude modulation of short-cavity GaAs lasers up to *X*-band frequencies

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Experimental and theoretical studies indicate that a high-frequency laser with bandwidths up to X-band frequencies ($\gtrsim 10$ GHz) should be one having a short cavity with a window structure, and preferably operating at low temperatures. These designs would accomplish the task of shortening the photon lifetime, increasing the intrinsic optical gain, and increasing the internal photon density without inflicting mirror damage. A modulation bandwidth of > 8 GHz has been achieved using a 120-μm laser without any special window structure at room temperature.

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The practical direct modulation bandwidth of semiconductor lasers is commonly accepted to be in the lower GHz range ($\lesssim 2$ GHz). Recent experimental work[1] has shown that a modulation bandwidth of 4–5 GHz is possible in a number of common laser structures. However, achieving that kind of modulation bandwidth requires that the lasers be biased at a level well above their nominal ratings, dangerously close to the point of castatrophic damage. Previous work emphasized more on investigating modulation characteristics of existing lasers than on developing lasers with parameters optimized for high-speed modulation. This letter will place its emphasis on the latter. Experimental and theoretical results presented below show that modulation bandwidths in the X band ($\gtrsim 10$ GHz) can be achieved with lasers operating reliably within the limits of their ratings, provided that a number of features are incorporated in the lasers. Among those features was the use of a short laser cavity, which was explicitly investigated in our experiments. The reason underlying the use of these features in high-frequency lasers will be discussed.

The modulation bandwidth of semiconductor lasers is widely accepted to be equal to $v_{\rm rel}$, the relaxation oscillation frequency, although it is well recognized that the relaxation resonance, whose magnitude varies considerably among lasers,[1,2] can limit the useful bandwidth to somewhat below $v_{\rm rel}$. Nevertheless, as a standard for comparison, the modulation bandwidth is simply taken as $v_{\rm rel}$. A small-signal analysis of the common rate equations gives

$$2\pi v_{\rm rel} = \left[\frac{\Gamma n_{\rm tr} A \tau_p + 1}{\tau_s \tau_p}\left(\frac{i_0}{i_{\rm th}} - 1\right)\right]^{1/2}, \tag{1}$$

where i_0 and $i_{\rm th}$ are the pump current and the threshold current, τ_s and τ_p are the spontaneous carrier and photon lifetime, respectively, Γ is the optical confinement factor, A is the optical gain coefficient, and $n_{\rm tr}$ is the carrier density at which the material becomes transparent. Earlier work has often assumed that $\Gamma n_{\rm tr} A \tau_p \ll 1$,[3] which is normally violated since $n_{\rm tr} = 10^{18}$.[4,5] This approximation also leads to numerical differences between measured and calculated values of $v_{\rm th}$.[6,7] Equation (1) is not a very convenient form of expressing how $v_{\rm rel}$ depends on the intrinsic parameters A, τ_s, and τ_p, since the quantity $i_{\rm th}$ in Eq. (1) also depends on these parameters. For instance, the suggestion that the modulation bandwidth can be increased by decreasing τ_s (Ref. 8) is fallacious because this also increases $i_{\rm th}$. A more desirable expression for the laser modulation bandwidth can be obtained by reconsidering the following rate equations:

$$\frac{dn}{dt} = \frac{i}{eV} - Bn^2 - A(n - n_{\rm tr})p, \tag{2}$$

$$\frac{dp}{dt} = A(n - n_{\rm tr})p\Gamma - \frac{p}{\tau_p} + \beta B n^2 \Gamma, \tag{3}$$

where n and p are respectively the electron and photon densities, V is the active volume, B is the radiative recombination coefficient, and a stimulated transition rate linear in the carrier density is assumed[4,5]; β is the fraction of the spontaneous emission entering the lasing model, and

$$\tau_p = \frac{1}{v}\left(\alpha + \frac{1}{L}\ln\frac{1}{R}\right),$$

where v is the group velocity of the light, α is the distributed loss, L is the length of the cavity, and R is the mirror reflectivity. A standard small-signal analysis of Eqs. (2) and (3) (with the only approximation being $\beta \ll 1$) gives

$$v_{\rm rel} = (1/2\pi)(Ap_0/\tau_p)^{1/2}, \tag{4}$$

where p_0 is the steady state photon density in the active region.

Equation (4) suggests three obvious ways to increase the relaxation frequency—by increasing the optical gain coefficient or the photon density, or by decreasing the photon lifetime. The gain coefficient A can be increased roughly by a factor of 5 by cooling the laser from room temperature to 77 K.[5] Biasing the laser at higher currents would increase the photon density in the active region, which simultaneously increases the optical output power density $I_{\rm out}$ according to

$$I_{\rm out} = \tfrac{1}{2} p_0 \hbar\omega v \ln(1/R). \tag{5}$$

Catastropic mirror damage occurs at a power density of $i_{\rm out,cat} \simeq 1$ MW/cm^2 for a laser with a mirror reflectivity of $R = 0.3$.[9] This sets an upper limit on the maximum permissible photon density, and hence the maximum modulation

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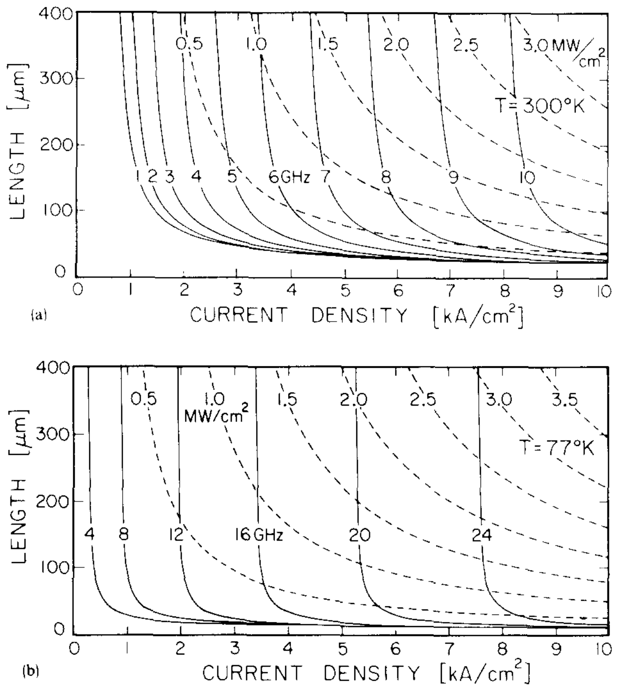

FIG. 1. (a) Relaxation frequency $v_{\rm rel}$ (solid lines) and optical power density outside the mirrors (dashed lines) as a function of the cavity length and pump current density at $T = 300$ K. The following parameters are used: active layer thickness $= 0.15$ μm, $\alpha = 40$ cm^{-1}, $R = 0.34$, $v = 8\times10^{9}$ cm s^{-1}, $A = 2.56\times10^{-6}$ cm^{3} s^{-1}, $\Gamma = 0.5$, $n_{\rm tr} = 1\times10^{18}$ cm^{-3}, $B = 1.5\times10^{-10}$ cm^{3} s^{-1}, $\hbar\omega = 1.5$ eV. (b) Same as (a) but at $T = 77$ K. The same parameters as in (a) are used except $A = 1.45\times10^{-5}$ cm^{3} s^{-1}, $n_{\rm tr} = 0.6\times10^{17}$ cm^{-3}, and $B = 11\times10^{-10}$ cm^{3} s^{-1}.[5]

bandwidth. This limit can be increased very considerably by using a window structure, such as the crank TJS,[10] the window stripe,[11] or the window buried laser.[12]

The third way to increase the modulation bandwidth is to reduce the photon lifetime by decreasing the length of the laser cavity. Such a laser has to be driven at higher current densities and thermal effects due to excessive heating will limit the maximum attainable modulation bandwidth. To illustrate these points the relaxation frequency as a function of the cavity length and the pump current density is plotted in Fig. 1(a) using Eq. (4) and the static solutions of Eqs. (2) and (3). Also plotted in Fig. 1 is the power density at the mirror using Eq. (5). As an example, a common laser with a cavity length of 300 μm operating at an output optical power density of 0.8 MW cm^{-2} possesses a bandwidth of 5.5 GHz, and the corresponding pump current density is 3 kA/cm^2. Operating at an identical power density, the bandwidth is 8 GHz for a shorter laser with a cavity length of 100 μm, but the corresponding current density is 6 kA/cm^2. A higher current density alone may not be a cause for rapid degradation of lasers. For example, lasers with increased optical damage threshold as described above can operate at increased current densities without appreciable degradation of their reliability.[13] Figure 1(b) shows plots of the same functions as in Fig. 1(a) but for a laser operating at liquid nitrogen temperature. The increase in bandwidth is a direct result of the increase in A. It can be seen that a modulation bandwidth beyond 20 GHz can be achieved, however, incorporation of a short optical cavity and/or a window structure is imperative under these operating conditions.

Experiments have been performed to determine the modulation bandwidth achievable in a short-cavity laser. The lasers used were buried heterostructure lasers fabricated on a semi-insulating substrate (BH on SI).[14] In addition to a low lasing threshold (typically $\leqslant 15$ mA) which is necessary to avoid excessive heating when operated at high above threshold, these lasers possess very low parasitic capacitance[15] which otherwise would obscure modulation effects at high frequencies ($\gtrsim 5$ GHz). The lasers were mounted on a 50-Ω stripeline. Microwave s-parameter measurements show that electrical reflection from the laser diode accounts to no more than a few dB (< 5 dB) of variations in the drive current amplitude over a frequency range of 0.1–8.5 GHz. A sweep oscillator (HP8350) was used in conjunction with a network analyser (HP8410 series) and a microwave s-parameter test set (HP8746B) to obtain the modulation data. The photodiode used was a high-speed GaAs *pin* diode fabricated on semi-insulating substrate. Its response was carefully calibrated from 0.1 to 10 GHz using a step-recovery-diode excited GaAs laser which produced optical pulses 25 ps in width full width at half-maximum, as measured by standard nonliner autocorrelation techniques. The response of the diode to the optical pulse, recorded on the microwave spectrum

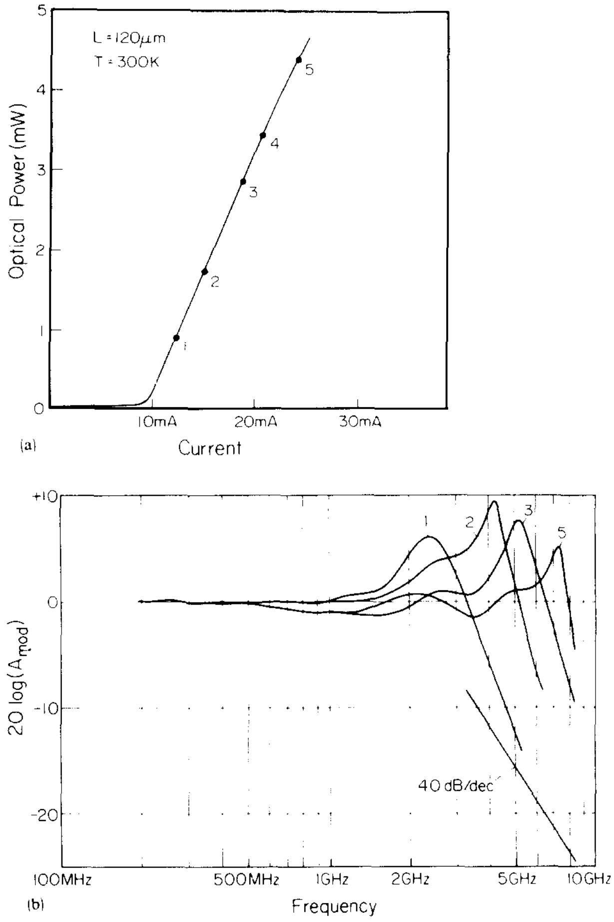

FIG. 2. (a) cw light vs current characteristic of a BH on SI laser. Length of laser $= 120$ μm. Modulation characteristics of this laser at various bias points indicated in the plot are shown in (b).

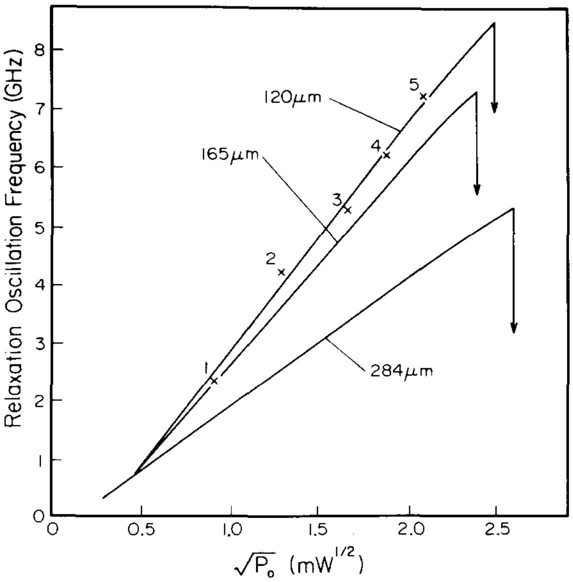

FIG. 3. Measured relaxation oscillation resonance frequency of lasers of various cavity lengths, as a function of $\sqrt{P_0}$ where P_0 is the cw output optical power. The points of catastrophic damage are indicated by downward pointing arrows.

analyser, is then deconvolved by the finite width of the optical pulse. The observed modulation response of the laser is normalized by the photodiode response at each frequency. Figures 2(a) and 2(b) show the cw light versus current characteristic of a short-cavity (120 μm) BH on SI laser, and the modulation responses at various bias points as indicated in Fig. 2(a) are shown in Fig. 2(b). The modulation bandwidth can be pushed to beyond 8 GHz as the catastrophic damage point is approached. Figure 3 shows the relaxation oscillation frequency of this laser as a function of $\sqrt{P_0}$, where P_0 is the output power, together with that of similar lasers with longer cavity lengths. All the lasers tested suffered catastrophic damage between 6–8 mW/facet. The advantage of a short-cavity laser in high-frequency modulation is evident.

It is clear, from the above theoretical and experimental results, that an ideal high-frequency laser should be one having a short cavity with a window structure, and preferably operating at low temperatures. This would shorten the photon lifetime, increase the intrinsic optical gain and the internal photon density without inflicting mirror damage. An absolute modulation bandwidth (at the point of catastrophic failure) of > 8 GHz has already been observed in a 120-μm laser without any special window structure at room temperature. For reliable operation, however, the laser should be operated at only a fraction of its catastrophic failure power. That fraction depends on laser structure and amounts to 1/2 to 1/3 for commercial devices of comparable construction.[16] This would place the useful modulation bandwidth of these short-cavity BH on SI lasers between 4.6 and 5.7 GHz. The same laser at 77 K without a window should have a modulation bandwidth of ≈ 12 GHz.

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