Cavity formation in semiconductor lasers

J. O'Gorman, A. F. J. Levi, D. Coblentz, T. Tanbun-Ek, and R. A. Logan

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

The temporal development of both lasing light intensity and spectral content is influenced by the number of round-trips photons make inside a Fabry–Perot laser. A surprisingly large number of cavity round trips ($n \gtrsim 100$) are required for laser emission intensity and spectral content to approach dc values. With decreasing n the laser increasingly takes on the character of a light emitting diode.

A semiconductor laser is often considered as an optical gain medium inside a Fabry–Perot resonant cavity. Lasing emission into cavity modes requires that photons experience at least one round trip within the resonator. A natural question concerns the effect multiple round trips in the resonator (i.e., cavity formation) has on temporal evolution of lasing light intensity and spectra. Under normal conditions the influence of cavity formation is obscured by (nonlinear) coupling of optical field with gain. In addition, such effects are usually difficult to measure in semiconductor laser diodes due to brevity of cavity round-trip time and charge carrier lifetime. In this letter we describe a fiber external cavity semiconductor laser system which effectively decouples cavity formation from charge carrier dynamics, allowing us to time resolve the intensity and spectral development of lasing light emission.

A schematic diagram of our laser system is shown in Fig. 1(a). An InGaAsP/InP strained layer multiple (10) quantum well laser (Ref. 1) has one antireflection (AR) coated ($R < 0.1\%$) facet which is coupled to a fiber external cavity. The external cavity consists of an approximately 100 m length of single mode fiber, one end of which is lensed and antireflection coated, the other end is cleaved and has a highly reflective gold coating. The cavity round-trip time is accurately determined to be $\tau_{cav} = 0.9951 \pm 0.0001$ μs by measuring the laser mode locking resonance. The as-cleaved solitary laser diode had a threshold current of 10.5 mA prior to AR coating. In Fig. 1(b) we show the static (dc) light-current (L vs j) curve and optical spectra of the device when the diode's AR coated facet is coupled to the external cavity and when the fiber is removed. In the absence of optical feedback the solitary device does not lase as evidenced by the broad emission spectrum and lack of a sharp transition in the light-current characteristic. However, in the presence of the external cavity, the dc emission versus current is characteristic of lasing action. The dc laser threshold current is $j_{th} \simeq 11$ mA indicating that the fiber external cavity is strongly coupled to the diode active region with an effective reflectivity comparable to a cleaved facet. Furthermore, emission above threshold is concentrated in a narrow spectral region around wavelength $\lambda = 1.3$ μm. Introducing large bending losses in the fiber cavity results in the emission level returning to that of the isolated diode while the emission spectrum becomes broad band (similar to the case when the fiber is removed). We note, despite the high quality of

the AR coating on the diode facet, above-threshold spectra are modulated by the residual diode subcavity. It is nevertheless apparent from the light-current curves that, even with a narrow external cavity mode spacing of approximately 1 MHz, the external cavity couples efficiently to the diode gain region and predominantly determines emission.

The large value of τ_{cav} facilitates study of lasing action with increasing number of cavity round trips n. In Fig. 2(a) we show normalized pulsed light-current (L/τ vs j)
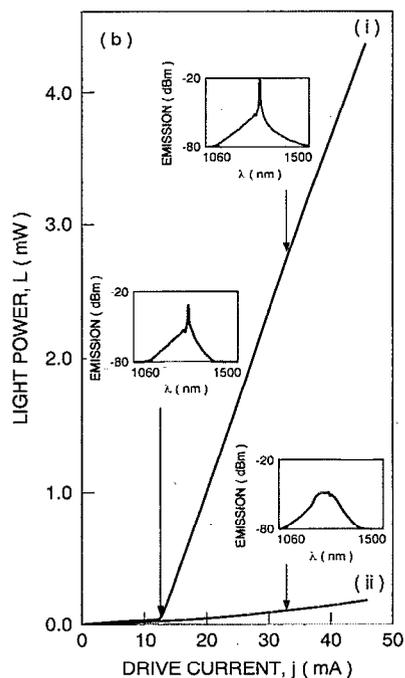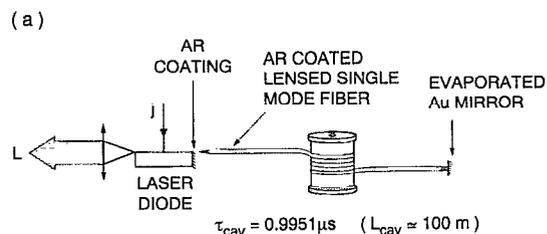

FIG. 1. (a) Schematic diagram of fiber external cavity laser diode. Current j flows through the laser diode. The lensed single mode fiber is of length $L_{cav} \sim 100$ m. (b) Measured room-temperature dc light-current (L vs j) curve and optical spectra of the diode with [curve (i)] and without [curve (ii)] the external cavity. The emission intensity of the optical spectra has not been corrected for collection efficiency.
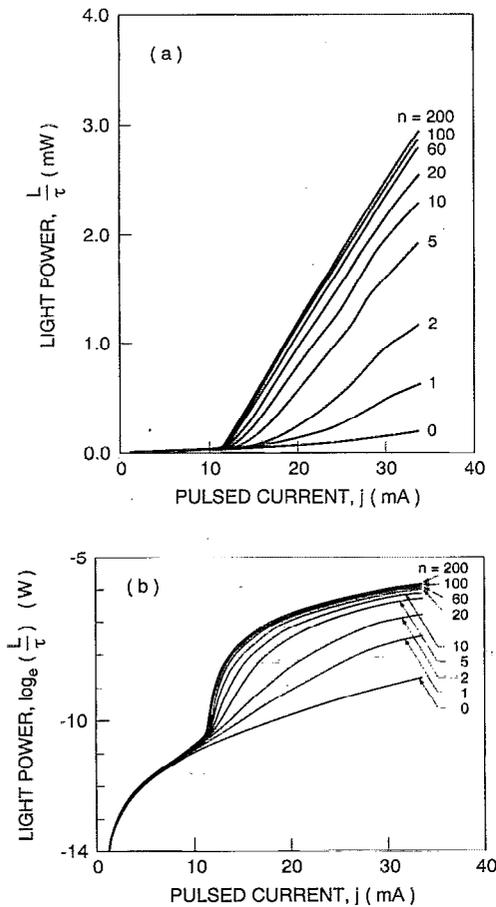
FIG. 2. (a) Measured normalized pulsed light-current (L/τ vs j) characteristics for different values of $\tau = n\tau_{cav} - \delta$ (where $\delta = 0.2$ μs). Pulsing period is 1.3 ms. (b) Natural logarithm of L/τ vs j for data shown in (a).

FIG. 3. (a) Natural logarithm of laser emission intensity as a function of time, t/τ_{cav}. Time is measured in units of the cavity round-trip time $\tau_{cav} = 0.9951$ μs. Light level is normalized to the emission intensity when $0 < n < 1$ and the detection system rise time was measured to be 400 ps. (b) Measured natural logarithm of laser emission intensity as a function of number of round trips. Light level is normalized to emission intensity at long times, i.e., $n \to \infty$.

characteristics for various current pulse durations $\tau = n\tau_{cav} - \delta$ (where $\delta \simeq 0.2$ μs). The quantum efficiency increases rapidly with increase in n and saturates for $n \gtrsim 100$. The same data are shown in Fig. 2(b) as a semilogarithmic plot. From Fig. 2(b) we see that below $j \simeq 5$ mA normalized emission intensity is clearly independent of pulse duration. It is also apparent that for all drive currents, emission intensity does not show a clear lasing transition when $n \lesssim 60$. These results indicate that a large number of cavity round trips ($n \gtrsim 100$) are required to approach the dc light level. In addition, this large number of round trips is not strongly dependent on drive level since, for $n \lesssim 100$ and large j, the laser intensity does not become independent of n (i.e., the L/τ vs j curves do not approach each other at high injection levels). We note that the coincidence of curves for $j \lesssim 0.5 j_{th}$ and the increase in output power with increasing n (for $j \gtrsim 0.5 j_{th}$) show that heating effects are not significant in our experiments.

To further investigate the effect of drive level on temporal evolution of lasing light intensity we measure the laser's time resolved step response. In Fig. 3(a) we show a semilogarithmic plot of laser emission intensity (normalized to the emission level when $0 < n < 1$) for a number of step currents j. It is clear from the data that emission intensity increases in a stepwise fashion with increasing time,
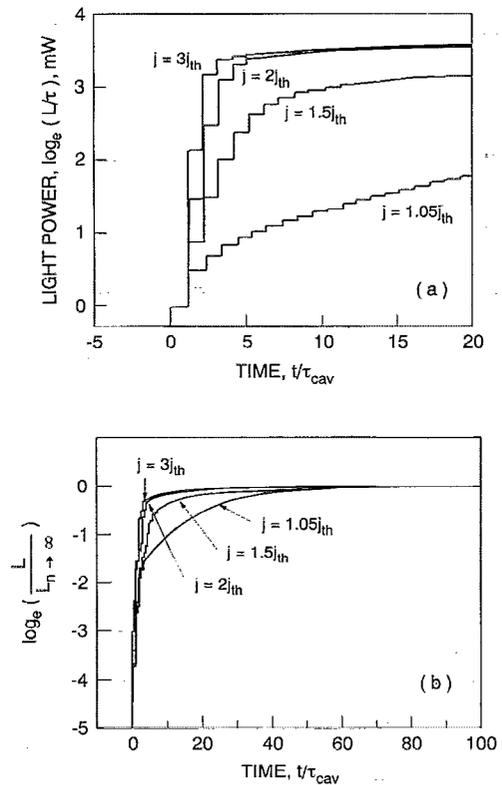
the step duration being τ_{cav}. The effect of increasing j on the emission rise time is illustrated most clearly in Fig. 3(b) where we show a semilogarithmic plot of laser step response, now normalized to the emission intensity at long times ($L_{n \to \infty}$). For pulse currents close to threshold ($j \simeq 1.05 j_{th}$), light intensity increases slowly, approaching the dc level for $n \gtrsim 100$. Increase of drive current steepens the initial intensity rise, however, this tends to saturate for $j \gtrsim 1.5 j_{th}$. We note that these step responses do not exhibit any simple exponential behavior, i.e., there is no single characteristic time constant. It is also clear from Fig. 3(a) that saturation in emission intensity rise time does not simply arise from strong gain clamping in the diode active region when $n < 1$. Close scrutiny of Fig. 3 reveals that the major effect of increase in j is to increase incremental growth in light level at short times. For example, when $j \simeq 3 j_{th}$ the emission intensity reaches 90% of its dc value in about 10 cavity round trips. However, even for these high drive levels, emission intensity subsequently takes considerable time to evolve to the steady state level.

In Figs. 4(a) and 4(b) we show the measured spectral evolution for $j = 3.0 j_{th}$ and $j = 1.05 j_{th}$, respectively, resolved by cavity round trip. In both cases we see that, prior to the first round trip, the emission is just the broad spontaneous emission spectrum of the diode. For large j, we see that after just one round trip, the emission spectral distribution
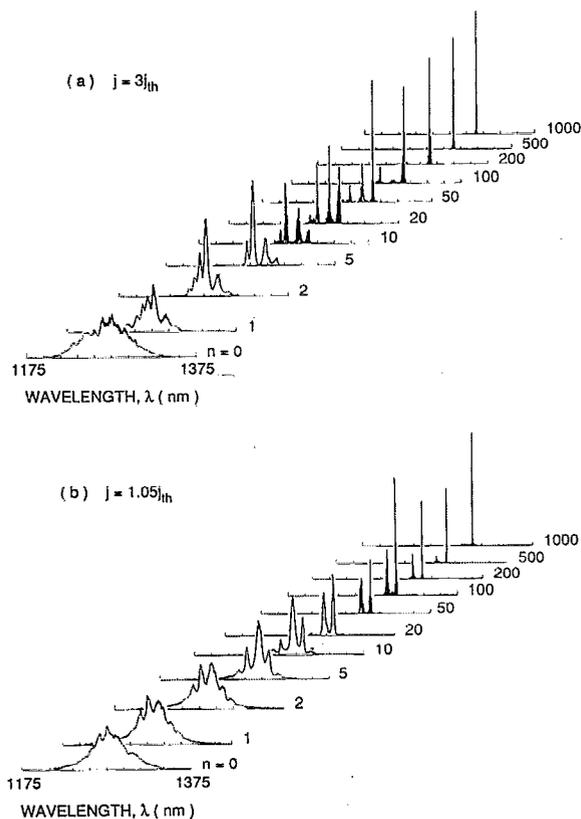
FIG. 4. (a) Measured spectral evolution for $j=3.0j_{th}$ resolved by cavity round trip. The spectra for the nth round trip is obtained by subtracting the spectrum obtained over time $\tau=(n-1)\tau_{cav}$ from that obtained over time $\tau=n\tau_{cav}$. (b) Measured spectral evolution for $j=1.05j_{th}$ resolved by cavity round trip.

changes significantly. These dramatic changes continue on subsequent round trips as the gain spectrum during interval n interacts with the retarded emission, i.e., emission from interval $n-1$. For $j=3.0j_{th}$ and $n \lesssim 10$ the carrier density approaches its dc value and subsequent spectral development is more gradual. (We note that major changes in carrier density only occur when there are major changes in emission intensity, i.e., during brief intervals between successive round trips. Hence, in our experiment, the carrier density and consequently the emission spectrum may be considered as evolving quasistatically.) Semiconductor lasers, especially those with quantum well active regions, exhibit extremely broad gain spectra. As the carrier density slowly approaches its dc value (which is approximately pinned at dc threshold), the optical gain spectrum slowly shifts towards longer wavelengths and the peak optical gain slowly decreases in value approaching that required to just overcome losses. The retarded peak emission now gradually moves and concentrates on the long wavelength side of the initial emission until at $n=200$ only a vestige of the once dominant shorter wavelength emission remains. At $n=500$ the emission still contains many resolved spectral components but by $n=1000$ emission is concentrated in a narrow, instrument limited wavelength interval. In contrast to the high current injection case, for small j a more gradual spectral development is observed [see Fig. 4(b)]. The spectra in Fig. 4 explain the

observed saturation in rise times shown in Fig. 3(b). As j is increased, emission intensity increases more rapidly for small n due to increased carrier density and unsaturated gain. While the emission rise time decreases, the degree of spectral shaping occurring at small n through (initial) gross changes in the carrier density and hence in optical gain spectrum increases. As the carrier density and optical gain approaches the threshold value, spectral development occurs more gradually. Consequently the development of both the emission level and spectrum is relatively independent of j for large values of n and j ($j \gtrsim 2j_{th}$, $n \gtrsim 20$).

Many previous investigations of semiconductor laser transient behavior have focused on modulation induced spectral broadening with the measured spectra time averaged over many cavity round trips. Some reports have concerned themselves with statistics of semiconductor laser gain switching (Ref. 2) or transient behavior (Refs. 3 and 4) but have either not explicitly addressed cavity formation or not resolved laser dynamics on a scale of the cavity round-trip time (Ref. 5). Furthermore, the experiments concerned are obscured by (nonlinear) coupling of the optical field and gain. In addition, such measurements are difficult due to the brevity of both cavity round-trip time (~ 10 ps) and unstimulated charge carrier lifetime (~ 300 ps). Clearly experiments which involve rapid injection of charge carriers (either optically or electrically) into laser diodes cannot be assumed to decouple carrier dynamics and cavity formation. Our results show that a large number of cavity round trips must elapse before either the intensity or spectral characteristics of the device approach those of a laser.

The experimental arrangement we have described is unique in that the optical gain medium is localized in a cavity whose extent is such that charge carrier dynamics are properly, i.e., adiabatically, decoupled from cavity formation. Consequently we have been able to place limits on the number of cavity round trips required to establish the characteristics of lasing action. Furthermore, we see that these limits depend upon injection current and upon which characteristic we are concerned; e.g., linearity of laser light current curve ($n \gtrsim 10$), saturation of emission quantum efficiency ($n \gtrsim 60$), and cavity formation ($n \gtrsim 100$). With decreasing n the laser increasingly takes on the character of a light emitting diode. This is a direct consequence of incomplete cavity formation.

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[5] We note that Arrechi et al. [F. T. Arrechi and V. T. Degiorgio, Laser Handbook, edited by F. T. Arrechi and E. O. Schultz-Dubois (North-Holland, Amsterdam, 1972), Vol. 1.] and Meltzer et al. [D. Meltzer and L. Mandel, Phys. Rev. A **3**, 1763 (1971)] provide detailed experimental investigations into the temporal evolution of statistical properties of optical fields using single-mode gas lasers.