On the temperature sensitivity of semiconductor lasers

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

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

The temperature dependence of below-threshold emission from multiple quantum well semiconductor lasers is well characterized by a power law, in excellent agreement with Landau–Ginzburg theory of second-order phase transitions. We thereby show that it is the temperature dependence of net gain and not that of nonradiative recombination which primarily determines temperature sensitivity of threshold in long-wavelength injection lasers.

Considerable efforts have been made to understand the origin of high-temperature sensitivity of threshold current in long-wavelength semiconductor lasers.[1] In general, the approach taken has been to investigate nonradiative recombination channels in semiconductors which may be highly temperature sensitive. In these investigations long-known analogies between statistical properties of laser light and thermodynamic phase transitions[2-7] have been ignored. In this letter we investigate the temperature dependence of optical output of InGaAs/InP multiple (8) quantum well (MQW) semiconductor lasers. We show that laser output consists of lasing and nonlasing components which may be distinguished by their very different temperature and spectral dependencies. The nonlasing component is a broadband background emission, similar to that of a light emitting diode (LED), whose integrated intensity fits approximately to an exponential temperature dependence in the range investigated.[1] The lasing component is a narrow-band emission whose temperature dependence below threshold is well characterized by a power law, in direct analogy with Landau–Ginzburg theory of second-order phase transitions. These experiments allow us to show that it is the temperature dependence of net gain and not that of nonradiative recombination which primarily determines the temperature sensitivity of long-wavelength injection lasers.

For the experiments reported here, as-cleaved buried heterostructure InGaAs/InP MQW Fabry–Pérot lasers and LEDs, emitting at $\lambda = 1.3 \ \mu m$,[8] were mounted on a copper heat-sink whose temperature could be varied. The devices were grown by low-pressure metalorganic vapor phase epitaxy on an n-type InP substrate with quantum well and barrier thicknesses of 20 and 60 Å, respectively. The devices were driven with a constant current to give a fixed carrier injection rate. The laser threshold current, I_{th}, was 8.5 mA at 20 °C. Measurements of variation of I_{th} with temperature, T, between 10 and 70 °C, when fitted to the function $I_{th} = I_0 \exp(T/T_0^{LD})$, had a characteristic temperature, $T_0^{LD} = 42$ K. In Fig. 1 we show a semilogarithmic plot of laser output versus substrate temperature for a constant laser bias current, $I = 10.5$ mA. It is immediately apparent that the optical output is not exponentially dependent on temperature, except possibly at high temperatures far above the lasing transition at temperature $T \approx 302$ K.

Figure 2(a) shows relative intensity emission spectra for a laser at a number of temperatures while Fig. 2(b) similarly shows the emission spectra of an LED at the same temperatures. It is important to note that the LED used in these experiments is actually the same laser device with antireflection coated ($R < 0.1\%$) facets. This ensures validity of our comparison of laser and LED. Figure 2 shows that at high temperatures the gross spectral features of the laser and the LED are the same. As expected, when the substrate temperature is decreased, broadband emission for both devices shifts to higher energies. As the laser approaches threshold with decreasing temperature, optical power increases rapidly at the lasing wavelength and the spectral distribution of the broadband emission component is unchanged. A major difference in this comparison is a saturation of the broadband component in the laser spectrum. This arises since onset of lasing leads to a substantial pinning of carrier density at a threshold value for a particular temperature. Naturally, with further decrease in temperature this pinned threshold carrier density (and hence integrated spontaneous emission component) can be expected to decrease. These experiments show that, at least within the range of these (DC) experiments, laser output
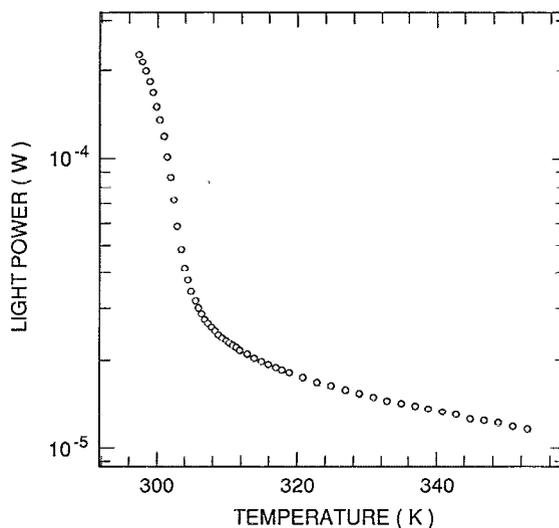

FIG. 1. Optical output of a $\lambda = 1.3 \ \mu m$ MQW laser vs substrate temperature for a constant bias current, $I = 10.5$ mA.
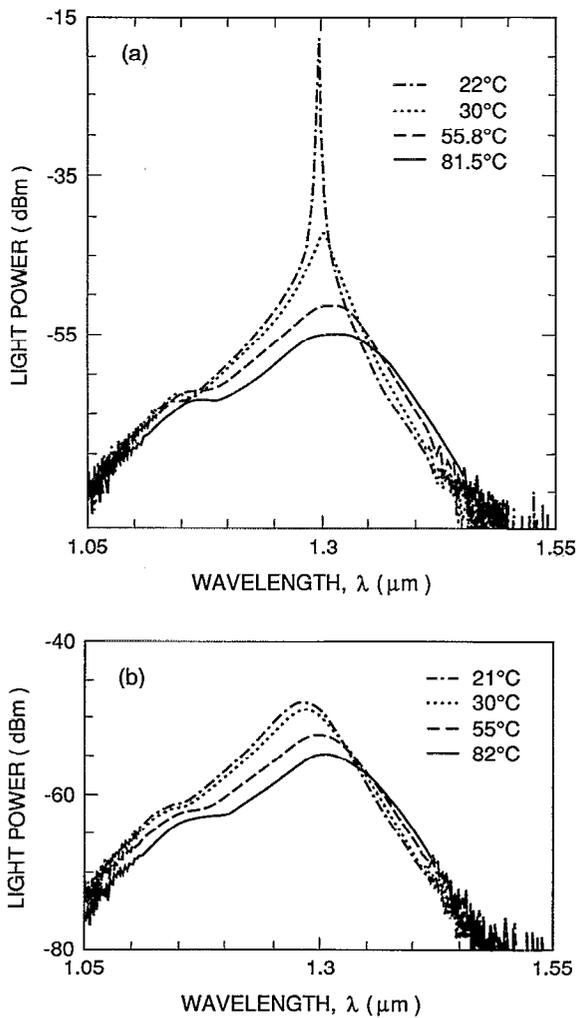
FIG. 2. (a) Emission spectra of a $\lambda = 1.3$ μm MQW laser for various substrate temperatures. (b) Emission spectra of a $\lambda = 1.3$ μm MQW LED, for the same substrate temperatures as in (a). The LED was obtained by AR coating both laser facets of the laser used in (a). The bias current for both figures is $I = 10.5$ mA.

FIG. 3. Lasing light output, S, vs reduced temperature, $(T/T_C - 1)^{-1}$, for a $\lambda = 1.3$ μm MQW laser. $I = 10.5$ mA, $T_C = 301.4$ K. A least squares fit gives the slope $\gamma = 1.02$.

can be viewed as having two additive components, one associated with electroluminescence from the active region, the other associated with lasing action.

Following the first demonstrations of laser action, it was rapidly realized that a (mathematically) formal analogy existed between the statistics of laser emission around threshold and the Landau–Ginzburg theory of second-order phase transitions.[2-7] In these analogies the modulus of laser electric field corresponds to the order parameter. Below threshold, the average photon number of the lasing output, S, is the mean square fluctuation of the field amplitude, and should scale with temperature as a power law, $S \sim | T/T_C - 1 |^{-\gamma}$, where T_C is some critical temperature and $\gamma = 1$. To our knowledge, in all previous experimental investigations of these phase transition analogies, the temperature of the Landau–Ginzburg theory has either been identified with cavity detuning from the gain peak[6] or (nonsaturable) loss in the laser.[7] Furthermore, all previous investigations of these phenomena dealt with single-mode systems using radiative transitions occurring between dis-
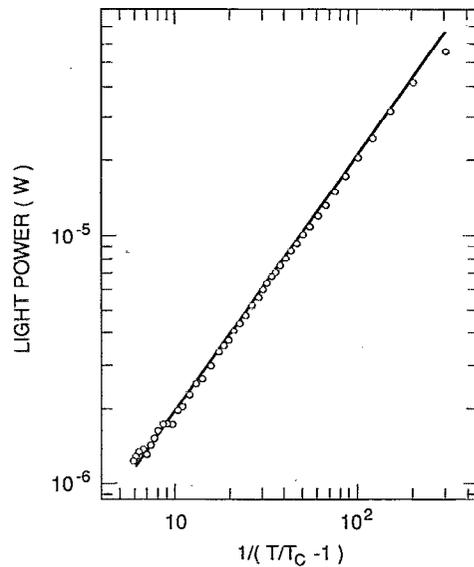
crete atomic states, whereas in semiconductor lasers the transitions occur between continua which have short thermalization times. Figure 3 shows a logarithmic plot of the lasing light component of a $\lambda = 1.3$ μm MQW laser diode versus reduced temperature, $(T/T_C - 1)^{-1}$. The lasing light component is obtained by subtraction of the measured temperature-dependent integrated LED output $[P_{\mathrm{LED}}(T)]$ from the total measured light output of the laser. (We note that $P_{\mathrm{LED}}(T)$, when fitted to an exponential dependence, gives $T_0^{\mathrm{LED}} = 115$ K.) The good fit in Fig. 3 over nearly two orders of magnitude, together with a least squares determination of $\gamma = 1.02$, amply demonstrates the analogy with a second-order phase transition. The deviation from simple power-law behavior as $T \to T_C$ can be explained[4] by the increasing importance of nonlinear fluctuations which remove the singularity at $T = T_C$.

These results have significant implications for the temperature sensitivity of long-wavelength semiconductor lasers. The temperature-sensitive parameters of semiconductor lasers may be identified via the single-mode laser rate equations[9]

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau} - GS, \tag{1}$$

and

$$\frac{dS}{dt} = [G - \kappa]S + R_{\mathrm{sp}}, \tag{2}$$

where n, I, V, e are the carrier density, pumping current, active region volume, and electronic charge, respectively. G is the gain function, S the photon density, and κ the general loss of the laser. τ is the (unstimulated) carrier lifetime, given explicitly in terms of n by

$$\tau^{-1} = (A_{\mathrm{nr}} + Bn + Cn^2), \tag{3}$$

where A_{nr} and C describe nonradiative recombination due to traps or surfaces and Auger processes, respectively, while B is the radiative recombination coefficient. $R_{sp} \propto B\, n^2$, is the spontaneous emission coupled into the lasing mode. Conventionally, temperature-dependent nonradiative recombination rates are concluded to be the primary cause of low T_0 in lasers by inappropriate use of Eq. (1) to define laser threshold. This entails using a steady-state approximation in Eq. (1) *and* (incorrectly) assuming $S = 0$ at threshold, to get $I_{th} = eVn_{th}/\tau$.[10] Our data show that, over the temperature range investigated, the integrated LED emission may be fitted to an exponential temperature dependence while variation of lasing output with temperature is characteristic of a second-order phase transition. Figure 3 shows that lasing output is not zero at or below threshold. Consequently, in a rate equation formalism, laser threshold and its dependence on temperature is only unambiguously defined via Eq. (2) where, in steady state, $S(T) = R_{sp}(T)/[\kappa(T) - G(T)]$. Temperature-dependent nonradiative recombination contributes to determining T_0^{LED} which, from our experiments, is 115 K implying that the low T_0^{LD} ($= 42$ K) is predominantly determined by the temperature dependence of net gain, $[\kappa(T) - G(T)]$. We note that this conclusion is in agreement with Jung *et al.*[11] whose data suggests a correlation between gain mechanisms and temperature sensitivity of quaternary lasers. We also note, that variation in gain (ΔG) due to change in nonradiative recombination with temperature (ΔT) may be written as $\Delta G(n,T) = (\delta G/\delta n)/(\delta n/\delta T)\delta T$. Here $\delta n/\delta T$ is typically due to temperature dependent nonradiative recombination and influences gain through $\delta G/\delta n$. The extent to which $\delta G/\delta n$ influences $\Delta G(n,T)$ is, however, not sufficient to explain the observed temperature dependence of laser threshold.[12]

In conclusion, we investigated temperature dependence of optical emission from $\lambda = 1.3$ μm MQW semiconductor lasers. We have shown that laser output consists of two components which, for these experiments, may be treated independently. A nonlasing broadband background emission, treated as an LED component, exhibits a moderate (possibly exponential) temperature dependence in the temperature range investigated. The lasing component is a narrow-band emission whose temperature dependence is well characterized by a power law, analogous to Landau–Ginzburg theory of second-order phase transitions. These results allow us to show that the extreme temperature sensitivity of laser threshold in long-wavelength semiconductor lasers is primarily determined by the temperature dependence of optical gain in these materials.

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