Wavelength dependence of T_0 in InGaAsP semiconductor laser diodes

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The temperature sensitivity of laser threshold current in single mode, wavelength tunable, InGaAsP bulk active region semiconductor lasers diodes is measured in the temperature range, $293 \text{ K} \lesssim T \lesssim 355 \text{ K}$ and wavelength range $1.23 \ \mu\text{m} \lesssim \lambda \lesssim 1.35 \ \mu\text{m}$. When proper account is taken of peak gain variation with temperature, the temperature dependence of laser threshold current (parameterized by T_0) is insensitive to lasing wavelength over a wide tuning range.

It is well known that the radiative recombination coefficient in InGaAs and InGaAsP materials decreases with increasing carrier density.[1] Consequently, due to the relationship between radiative recombination and gain, these materials might also be expected to exhibit a sublinear dependence of gain at high carrier densities. Hence, it is reasonable to consider the influence of cavity loss level (and hence carrier density at threshold) and lasing wavelength (via detuning from the material gain peak) on laser threshold current. Such issues are of technological interest since both modulation performance[2] and high-temperature performance[3] of distributed feedback (DFB) lasers may be separately enhanced by appropriate detuning from the gain peak.

In this letter we report results of experiments using an external cavity laser to investigate the temperature sensitivity of threshold current of a single mode laser diode as emission wavelength is detuned from peak gain. We find that, in the temperature range $293 \text{ K} (20 \,^\circ\text{C}) \lesssim T \lesssim 355 \text{ K}$ ($82 \,^\circ\text{C}$) and the wavelength range $1.23 \ \mu\text{m} \lesssim \lambda \lesssim 1.35 \ \mu\text{m}$, when account is taken of gain peak wavelength variation with temperature, the laser threshold current dependence on temperature (parameterized by T_0) is insensitive to the imposed emission wavelength.

The devices used in our experiments are a standard bulk active region InGaAsP buried heterostructure design (however similar results were obtained with multiple quantum well lasers). The active region is a $0.14 \ \mu\text{m}$ thick InGaAsP layer with band gap $\lambda_g = 1.28 \ \mu\text{m}$, lattice matched to an n-type InP substrate and capped by a p-type InP layer. After a two step regrowth process, the active region has width $w = 1 \ \mu\text{m}$ and is surrounded by index guiding InP. As-cleaved devices, of length $\ell = 260 \ \mu\text{m}$, lase with wavelength $\lambda \simeq 1.31 \ \mu\text{m}$ and have threshold current $I_{\text{th}} = 8.5 \text{ mA}$ at $T = 298 \text{ K}$. The variation of lasing threshold with temperature when fitted to the phenomenological expression

$$I_{\text{th}} = I_0 \exp(T/T_0), \tag{1}$$

yields $T_0 = 39 \text{ K}$ when averaged over the temperature range $293 \text{ K} \lesssim T \lesssim 333 \text{ K}$ (when averaged over the temperature range $293 \text{ K} \lesssim T \lesssim 318 \text{ K}$, T_0 improves to 42 K).

The experimental arrangement for our external cavity experiments is shown in Fig. 1. Light output from a high quality antireflection coated facet is efficiently coupled to the external cavity by a low loss lens. The external cavity, of length $L_C \simeq 20 \text{ cm}$, is closed by a 600 groove/mm dif-

fraction grating allowing laser emission to be tuned in a single instrument limited line ($< 0.15 \text{ nm}$) across the semiconductor gain spectrum. Initially, however, the diffraction grating was replaced by a band high reflectivity mirror to form an external cavity laser with broadband feedback (ECL).

In Fig. 2 we show cw light-current characteristics of the ECL for two substrate temperatures, $T = 293 \text{ K}$ ($I_{\text{th}} = 7.7 \text{ mA}$) and $T = 318 \text{ K}$ ($I_{\text{th}} = 14 \text{ mA}$) together with above-threshold spectra. We note that the ECL threshold current and that of the uncoated device are the same at $T = 298 \text{ K}$, indicating that the effective reflectivity of the external cavity is similar to a cleaved facet. ECL emission is modulated by multiple diode subcavity modes which are not resolved in the inset spectra. We examined the variation of ECL threshold current with temperature, the results of which are presented in Fig. 3. In order to prevent an increase in device temperature due to ohmic heating at high drive currents, the laser was driven with 1 μs pulses at a 1 kHz repetition rate. Figure 3 shows the temperature variation of ECL threshold current. Also shown in T_0 which is identical to the uncoated device (indeed use of a single T_0 averaged in the temperature range $293 \text{ K} \lesssim T \lesssim 318 \text{ K}$ yields $T_0 = 41 \text{ K}$). ECL peak emission, λ_p, was measured to shift to longer wavelengths with increasing temperature in a linear fashion according to the relation

$$\lambda_p(T) = \lambda_0 + \zeta T', \tag{2}$$

where $\lambda_0 = 1.3078 \ \mu\text{m}$, $\zeta = 3.8 \times 10^{-4} \ \mu\text{m K}^{-1}$, and $T' = (T - 293.6 \text{ K})$.

The broadband mirror was now replaced by the diffraction grating as shown in Fig. 1. In Figs. 4(a) and 4(b) we show (cw) light-current characteristics for the resultant tunable external cavity laser (TECL), at two temperatures and for two tuning conditions; (a) $T = 45 \,^\circ\text{C}$, (b) $T = 21 \,^\circ\text{C}$, (i) lasing emission close to peak gain, and
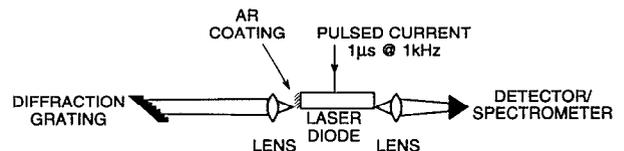

FIG. 1. Schematic diagram of external cavity laser diode. The grating feeds light back into the AR coated facet of the laser diode which is electrically pumped with current, I.
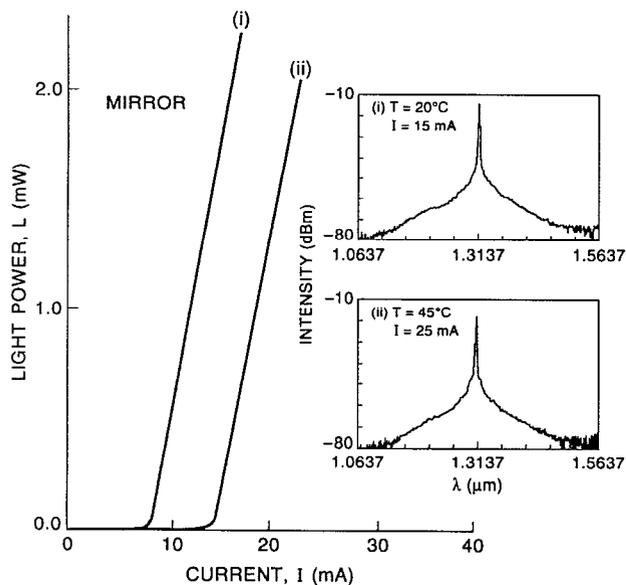
FIG. 2. Measured light-current characteristics for broadband mirror feedback for (i) $T = 20$ °C, (ii) $T = 45$ °C. Inset shows spectra measured at the indicated currents.

(ii) lasing emission detuned to the short wavelength side of the gain spectrum. For both temperatures, TECL threshold current near the gain peak ($I_{th} = 8.5$ mA when $T = 298$ K and $I_{th} = 16$ mA when $T = 318$ K) is similar to that achieved with broadband external feedback. The insets show above-threshold spectra. It is to be noted that, for both temperatures, when the laser is widely detuned from the gain peak, background emission exhibits pronounced asymmetry resulting from large amplification of spontaneous emission (ASE) occurring at wavelengths around the gain peak. For modest bias currents around room temperature ($I \lesssim 30$ mA) a large tuning range of approximately 100 nm is exhibited while a single instrument limited line is preserved.

Encouraged by the consistency between the dependence of ECL threshold current on temperature and that of the as-cleaved device, the temperature dependence of the TECL threshold current, parameterized by temperature and emission detuning from the gain peak, was investigated. In Fig. 5(a) we show laser threshold current vari-
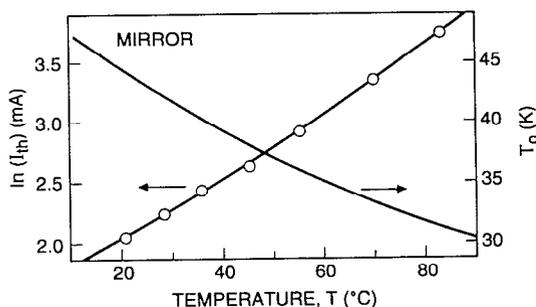

FIG. 3. Natural logarithm of measured ECL threshold current (broadband mirror feedback) as a function of temperature. The corresponding T_0 is also indicated.
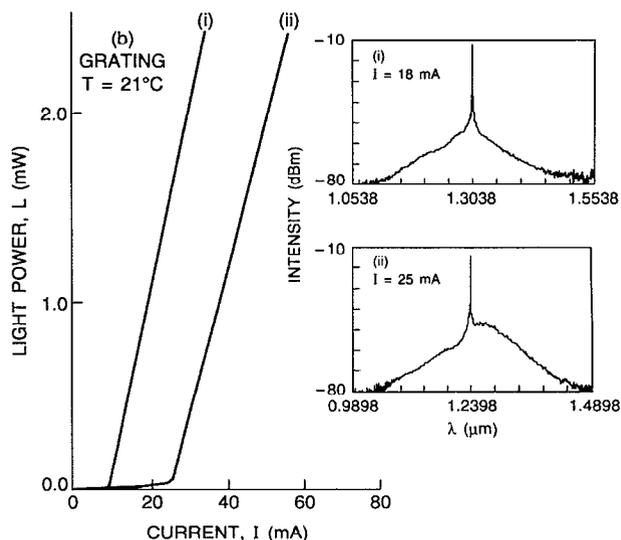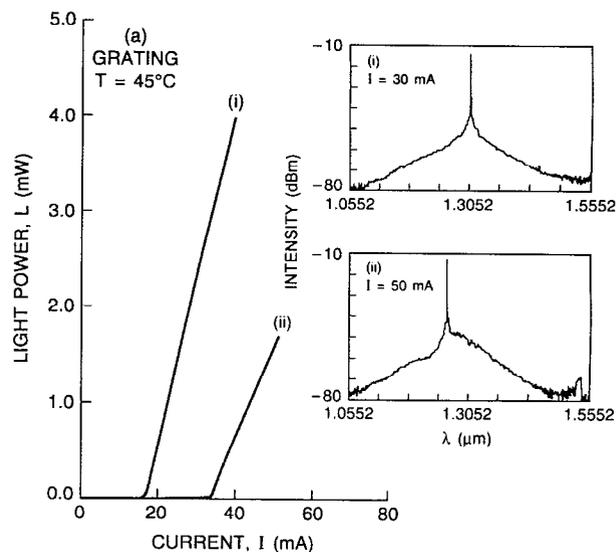

FIG. 4. Measured light-current characteristics for TECL single mode emission. (a) Measurements performed at temperature $T = 45$ °C. (i) $\lambda = 1.3052$ μm and (ii) $\lambda = 1.2602$ μm. Inset shows spectra measured at the indicated currents. (b) Measurements performed at temperature $T = 21$ °C. (i) $\lambda = 1.3038$ μm and (ii) $\lambda = 1.2398$ μm. Again, inset shows spectra measured at the indicated currents.

ation with wavelength for seven temperatures lying in the range 293 K $\leqslant T \leqslant$ 360 K. At each temperature, threshold current increases rapidly with increased detuning from the gain peak. This occurs since the separation in conduction band and valence band chemical potentials $\Delta\mu$ must be increased to bring net gain at the detuned wavelength above the total cavity loss level. However, due to asymmetry of laser gain spectrum[4] together with shift in gain peak to shorter wavelengths with increasing $\Delta\mu$, the lasing threshold increases more rapidly with detuning to short wavelengths. A remarkable feature of Fig. 5(a) is that, despite the large range of injection currents, the general shape of the detuning curve is the same for all temperatures while the wavelength of minimum threshold current shifts to longer wavelengths with increasing temperature at
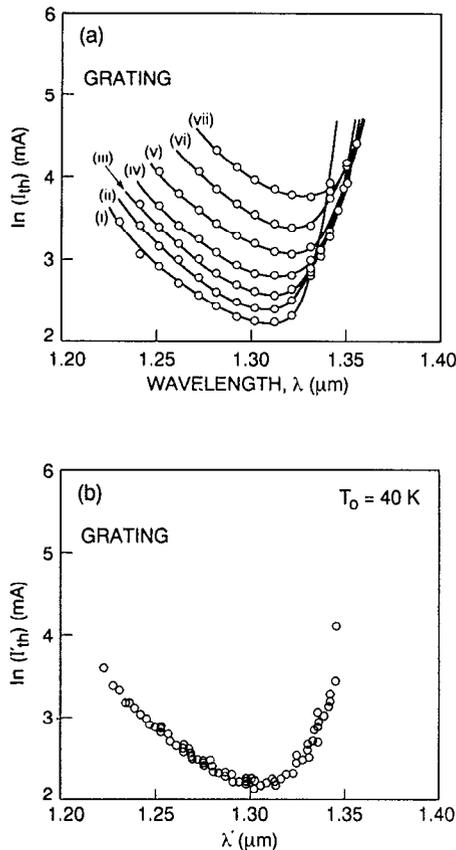
FIG. 5. (a) Natural logarithm of measured laser threshold I_{th} as a function of wavelength λ for temperatures (i) $T=20.6\,°C$, (ii) $T=28.1\,°C$, (iii) $T=35.6\,°C$, (iv) $T=43.3\,°C$, (v) $T=54.0\,°C$, (vi) $T=69.0\,°C$, (vii) $T=81.8\,°C$, for the device in Fig. 1. (b) Natural logarithm of normalized measured laser threshold I'_{th} as a function of λ' for the data presented in (a).

the same rate observed with the broadband feedback ECL. Taking the wavelength of the minimum threshold current as the location of peak gain at a particular temperature, we now consider how temperature sensitivity of laser threshold current varies with detuning from peak gain.

In Fig. 5(b) we show the result of rescaling, via Eq. (2), lasing wavelength to wavelength detuning from the gain peak (thereby accounting for the wavelength shift in peak gain with temperature), and subsequently rescaling all threshold currents to the threshold current at 293 K via Eq. (1). Using a single (average) $T_0=40$ K all rescaled threshold currents, I'_{th}, collapse upon each other

This result shows that over a large temperature range (293 K $< T <$ 355 K) and wide tuning range 1.23 μm $\lesssim \lambda \lesssim$ 1.35 μm (corresponding to an energy range of ~ 90 meV) laser threshold current is well characterized by a simple expression:

$$I_{th}(\lambda,T) = I'_0(\lambda')\exp(T'/T_0), \qquad (3)$$

where $\lambda' = (\lambda - \zeta T')$. Equation (3) is a remarkable result. Since the diffraction grating is blazed at $\lambda = 1.25$ μm and the optics coupling to the cavity have broadband antireflection coatings, the magnitude of cavity coupling efficiency does not vary substantially over the range of detunings investigated. Consequently, the increased threshold current required with detuning from the gain peak is not a consequence of changing loss level, but of changing energy distribution of charge carriers (and hence gain) in a forward biased laser diode. These results suggest that, above room temperature, semiconductor laser gain is relatively insensitive to band structure effects on a 50–100 meV scale for the carrier densities required to overcome the cavity loss levels of these experiments. Futhermore, the increased carrier density required for lasing threshold at detuned wavelengths, together with this relative constancy in T_0 confirms the assertion[5,6] that, at the carrier densities required for lasing threshold at and above room temperature, highly temperature sensitive nonradiative recombination does not normally play a major role in determining the temperature sensitivity of laser threshold.

It is worth remarking that these results are obtained even in the presence of considerable ASE at detuned wavelengths [e.g., inset (ii) of Figs. 4(a) and 4(b)] suggesting this process may have a hitherto unconsidered role in the observed increase of T_0 with decreasing mirror loss. We note that a recently reported (absorptive) loss coupled DFB laser diode[7], emitting at $\lambda = 1.55$ μm displayed a remarkable high T_0 of 80 K. Assuming that the grating is not detuned to the red side of the gain spectrum[8] one might be tempted to speculate that this impressive high-temperature performance may in part be due to suppression of ASE by the periodic absorption grating distributed along the active region.

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[1] R. Olshansky, C. B. Su, J. Manning, and W. Powazinik, IEEE J. Quantum Electron. QE-20, 838 (1984).
[2] S. Ogita, N. Yano, H. Ishikawa, and H. Imai, Electron. Lett. 23, 393 (1987).
[3] W. T. Tsang, F. S. Choa, R. A. Logan, T. Tanbun-Ek, A. M. Sergent, and K. W. Wecht, Appl. Phys. Lett. 60, 18 (1992).
[4] For example, see, E. O. Göbel, in GaInAsP Alloy Semiconductors, edited by T. P. Pearsall (Wiley, New York, 1982), Chap. 13, and J. O'Gorman, S. L. Chuang, and A. F. J. Levi (unpublished).
[5] J. O'Gorman, A. F. J. Levi, T. Tanbun-Ek, D. L. Coblentz, and R. A. Logan, Appl. Phys. Lett. 60, 1058 (1992).
[6] Y. Zou, J. S. Osinski, P. Grodzinski, P. D. Dapkus, W. Rideout, W. F. Sharfin, and F. D. Crawford, Appl. Phys. Lett. 62, 175 (1993).
[7] W. T. Tsang, F. S. Choa, M. C. Wu, Y. K. Chen, R. A. Logan, A. M. Sergent, and C. A. Burrus, IEEE Photon. Technol. Lett. 4, 212 (1992).
[8] J. O'Gorman and A. F. J. Levi, Electron. Lett. 28, 2091 (1992).