Broadband tunability of gain-flattened quantum well semiconductor lasers with an external grating

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Quantum well lasers are shown to exhibit flattened broadband gain spectra at a particular pumping condition. The gain requirement for a grating-tuned external cavity configuration is examined and applied to a semiconductor quantum well laser with an optimized length of gain region. The predicted very broadband tunability of quantum well lasers is confirmed experimentally by grating-tuning of uncoated lasers over 85 nm, with single longitudinal mode output power exceeding 200 mW.

In this letter, a theoretical investigation and an experimental verification of the gain characteristics of quantum well semiconductor lasers are presented which demonstrate that nearly constant gain can be achieved over an extended spectral range. Such a wide, flat gain spectrum is a prerequisite for practical broadband tunability, whose utility has been proved by the popularity of dye lasers. Experimentally, the flattened gain spectrum is demonstrated by broadband tuning of quantum well lasers in a grating-tuned external cavity.

Tuning of semiconductor lasers with an external grating has been demonstrated previously, and refined versions have produced a tuning range in excess of 3.5% at 1.5 μm (a spectral width of 30 meV).[1] Subsequently, a tuning range of 9% was published.[2] In the GaAs/GaAlAs system, superluminescent light-emitting diodes (SLEDs) fabricated from multiple quantum well material have been tuned in an external cavity over a range of 6.0% (cw) and 8.0% (pulsed) in the vicinity of 780 nm.[3] In this work, we demonstrate the existence, under the proper pumping, of a flattened gain spectrum in quantum well media. By taking advantage of the flat gain spectra, we demonstrate tuning of an uncoated single quantum well, broad area semiconductor laser over a range exceeding 10% near 800 nm.

For this work, a new model for the gain of quantum well semiconductor lasers has been developed which results in more accurate calculation of gain spectra at high pumping strengths. The details of the model will be published elsewhere[4]; the gain calculated as a function of photon energy E is given by

$$\mathrm{Gain}(E) = \frac{E}{W(E)}\,\frac{1}{n(E)c\epsilon_0\hbar^3} \times \sum_i\sum_j O_{ij}I_{ij}|\mu_i(E)|^2\rho^t_{ij}(E)\,, \qquad (1)$$

where O_{ij} is the overlap of electron and hole eigenfunctions, I_{ij} is the population inversion factor, $\mu_i(E)$ is the dipole matrix element, ρ^t_{ij} is the joint density of transitions in two dimensions assuming rigorous k selection, $n(E)$ is the index of refraction, and ϵ_0 and c are the permittivity and velocity of light in free space, respectively. Note that this model shows explicitly the dependence of the gain on the effective width $W(E)$ of the transverse optical mode. Furthermore, the step-like onset of each subband in ρ^t_{ij} is smeared in a non-Lorentzian fashion[4,5] to account for fast ($\simeq$0.1 ps) intraband transitions. In quantum well structures, the discrete onset of subbands in ρ^t_{ij} allows for more than one local maximum in the gain spectrum. Specifically, in a single quantum well structure, the pumping strength can be adjusted so that equally high-gain peaks arise from the first and second quantized state transitions, resulting in a wide spectral region of near equal gain. Figure 1 shows the theoretical gain spectra of Eq. (1) at various pumping strengths for the single quantum well structure defined in the inset. Curve (b) in Fig. 1 shows the gain-flattened spectrum, with a resulting spectral width considerably exceeding that of the simple bell-shaped spectrum of conventional double heterostructure lasers.

To experimentally examine these gain spectra, a grating-tuned external resonator is used, as shown schematically in Fig. 2. The effect of the external resonator can be modeled simply as a change in the effective complex reflection at the rear crystal facet from the value without external feedback r, to a value r':

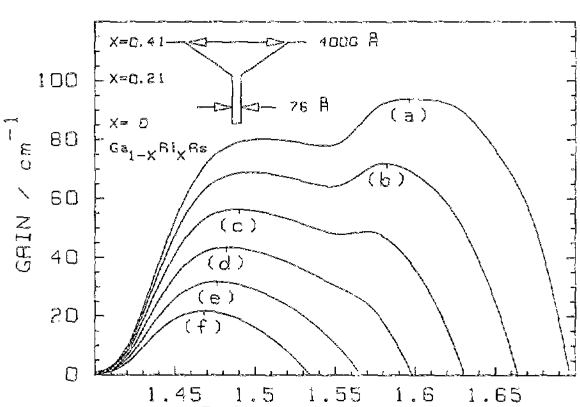

FIG. 1. Computed gain spectra of a single quantum well laser under various pumping strengths. The pump current density is (a) 1830, (b) 1350, (c) 950, (d) 630, (e) 405, and (f) 255 A cm^{-2} respectively. The particular linear GRINSCH-SQW structure considered is indicated in the inset.

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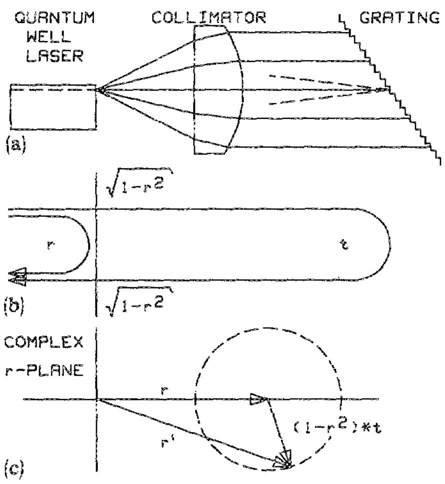

FIG. 2. Schematic of (a) the external resonator configuration and (b) the two main contributing beams for the rear side reflectivity. (c) Scheme of the coherent addition of the amplitudes of the two main contributing beams to form the complex reflectance r'.

$$r'(\omega) = r + (1 - r^2)t(\omega)e^{2i\omega L_{ex}/c}, \tag{2}$$

where ω is the radian frequency $\omega = E/\hbar$, L_{ex} is the length of the external resonator, and $t(\omega)$ is the round trip amplitude transmission of the single-sided external cavity into the lasing mode just outside the crystal. t therefore includes mode mismatch losses in the coupling arrangement. Equation (2) neglects multiple reflections in the external resonator which is permissable as long as $|rt| \ll 1$. For grating-tuned feedback, the transmission amplitude of the external cavity $t(\omega)$ peaks at the Littrow frequency ω_0, i.e., the frequency which is retroreflected by the grating. As ω departs from ω_0, the coupling back from the grating into the laser mode just outside the facet becomes progressively smaller. Consequently, the spectral reflectivity $r'(\omega)$ is changed from the value r of the crystal facet alone only near the Littrow frequency. The requirement that the electric field reproduces itself after one round trip in the crystal resonator is expressed as

$$\exp[(g(\omega) - \alpha_i)L - 2in(\omega)\omega L/c]rr'(\omega) = 1, \tag{3}$$

where $g(\omega)$ is the modal gain of the semiconductor medium, α_i are its distributed modal losses, and L is its length. Considering separately the amplitude and phase of (3) gives the following requirements for the modal gain at threshold and the composite cavity oscillation frequencies:

$$g(\omega) = \alpha_i + \frac{1}{L}\ln\left(\frac{1}{|rr'(\omega)|}\right), \tag{4}$$

$$2\pi m = 2n(\omega)\frac{\omega L}{c} + \tan^{-1}\left(\frac{(1-r^2)t(\omega)\sin(2\omega L_{ex}/c)}{r + (1-r^2)t(\omega)\cos(2\omega L_{ex}/c)}\right), \tag{5}$$

where m is an integer. The phase condition, (5), is satisfied for a group of frequencies[6] clustered near the grating-selected longitudinal mode of the crystal resonator; the spacing within the group is approximately $\pi c/L_{ex}$. The corresponding threshold gains of these modes vary, however, due to the fast "oscillation" of $|r'|$ with ω [see Eq. (2)]. In general, there will be one mode which corresponds closely to constructive interference from the external cavity if the number of solutions of (5) in the vicinity of each mode of the crystal cavity is sufficiently large. In the case of constructive interference at $\omega = \omega_0$, the gain requirement is minimized, and Eq. (2) with $\omega L_{ex}/c = m\pi$ and Eq. (4) give

$$g(\omega_0) = \alpha_i + \frac{1}{L}\ln\left(\frac{1}{r(r + (1-r^2)|t(\omega_0)|)}\right). \tag{6}$$

If the round trip gain first reaches unity at the tuned frequency ω_0, the composite resonator will lase at the corresponding photon energy. The tuning range is then determined by the flatness of the gain spectrum relative to the amount of grating feedback. If the variation in gain is small over a wide spectral range, then broadband tuning is possible even with only a small amount of external feedback: $(1 - r^2)t \ll 1$.

In Fig. 3 the gain and photon energy for free-running (A) and grating-tuned operation (B) are illustrated. The dashed line shows the gain requirement of the laser with no grating feedback. In this case the laser oscillates at a frequency corresponding to point A at a pumping level corresponding to curve (a). The addition of the external cavity tuned to ω_0 reduces the gain requirement in cases of constructive interference according to Eq. (6). Oscillation occurs at point B at a reduced pumping strength corresponding to curve (b). The narrow spike represents the reduction in theshold near ω_0 due to the (constructive) grating feedback. Consequently, as long as point B lies on a gain spectrum (b) corresponding to a reduced pumping requirement, lasing will occur at the grating selected wavelength.

For the experiment a Hänash type tunable laser oscillator is used: the waveguide/air interface at the rear facet of the laser and a $f/1.8$ 14.5 mm lens system for a telescope to illuminate a blazed diffraction grating in Littrow orientation. The orientation of the grating is such that the small transverse width of the waveguide forms the selective element for the dispersed light. The spectral resolution is estimated to be a quarter of a nm, and is sufficient to discrimi-

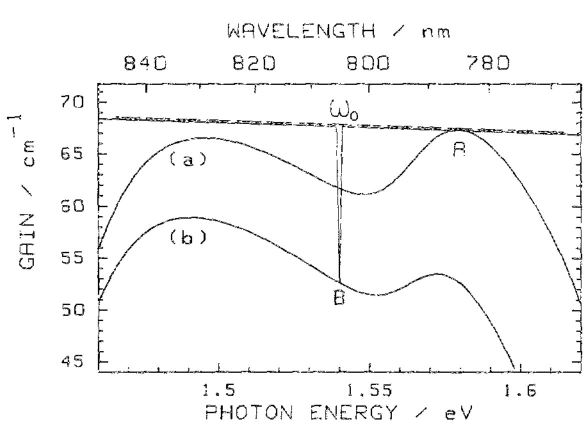

FIG. 3. Computed minimum gain requirement for the crystal cavity laser along (dashed line) and the composite cavity of a grating-tuned external cavity laser (solid line). The gain spectrum (a) corresponding to free-running operation at A and the gain spectrum (b) corresponding to grating-tuned operation at B are shown. The length of the gain region is 190 μm and the structure considered is as indicated in Fig. 1. The round trip transmission used is $t(\omega_0) = 0.26$ and $\alpha_i = 4$ cm^{-1}.

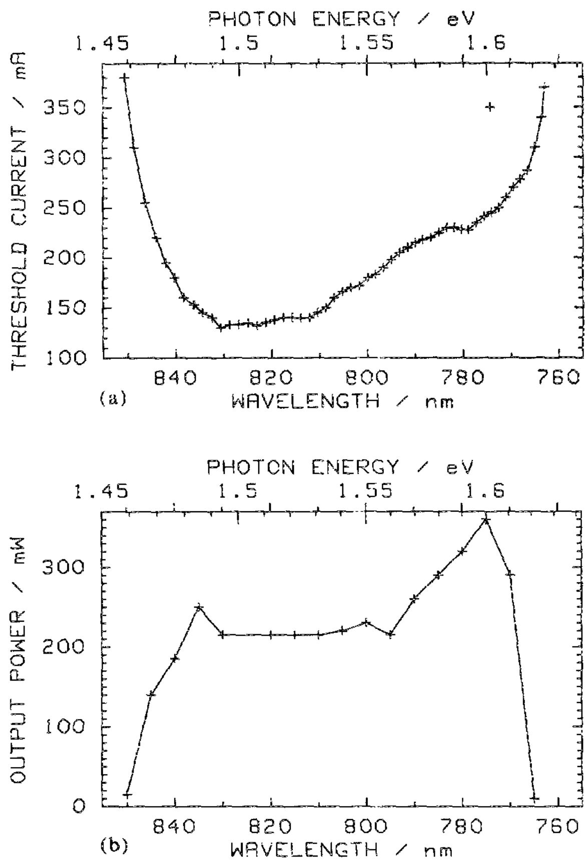

FIG. 4. (a) Experimental spectral pump current required for threshold, and (b) resulting single mode output power of an external cavity grating-tuned single quantum well laser.

nate between adjacent longitudinal modes of the short semiconductor lasers used. Power output from the laser is taken at the front facet.

The lasers used in the experiments are uncoated, 60 μm wide, oxide-isolated broad-area devices. They were fabricated from a linear graded-index separate confinement heterostructure single quantum well (GRINSCH-SQW) wafer grown by metalorganic chemical vapor deposition (MOCVD) at Ortel Corporation. For the tuning experiment, devices were cleaved just short enough so that, free-running, they lased from the second quantized state at a wavelength near 770 nm. The total gain requirement for lasing from such 190-μm-long devices is close to 65 cm^{-1}.

Figure 4(a) shows the threshold current measured as a function of wavelength for over 200 longitudinal laser modes spanning some 85 nm. The lasers were operated pulsed (200 ns, 1 kHz) to alleviate heating. The free-running operation is indicated near 770 nm, at 330 mA. The threshold was determined as described elsewhere.[5] Figure 4(b) indicates the maximum power output as measured at the front facet for grating-tuned modes up to which single longitudinal mode operation was maintained. Beyond that current, additional lasing was generally observed in a group of longitudinal modes near the free-running wavelength of 770 nm. Approximately 200 mW was measured over most of the width of the tuning range. Transverse electric polarization was maintained throughout.

In conclusion, a theoretical model for the gain spectrum of quantum well semiconductor lasers was applied to conditions of relatively high pumping levels. The gain flattened condition was described. The gain requirements for broadband tunability of such devices in a grating-coupled external cavity were detailed. The feature of gain flattening in quantum well structures is general and independent of the material in which the quantum well is constructed. Experimental evidence for the predicted broadband tunability was given: an uncoated single quantum well broad area laser, which emitted free-running from the second quantized state, was tuned in an external cavity over a range of 85 nm about 800 nm.

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[1]R. Wyatt and W. J. Devlin, Electron. Lett. **19**, 110 (1983).
[2]R. Wyatt, K. H. Cameron, and M. R. Matthews, Br. Telecom. Technol. J 3, 5 (1985).
[3]J. E. Epler, G. S. Jackson, N. Holonyak, Jr., R. L. Thornton, R. D. Burnham, and T. L. Paoli, Appl. Phys. Lett. **47**, 779 (1985).
[4]M. Mittelstein and A. Yariv (unpublished).
[5]M. Mittelstein, Y. Arakawa, A. Larsson, and A. Yariv, Appl. Phys. Lett. **49**, 1689 (1986).
[6]The number of requencies fulfilling the phase condition near each mode of the crystal cavity is $2(1 - r^2)t(\omega_0)L_{ex}/nL \pm 1$. In our experiment, the number is estimated to be 40.