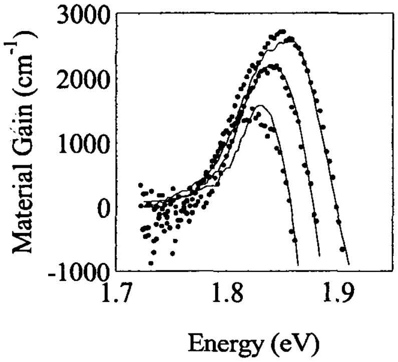
quences of the existence of such distributions is that there is a *known* detailed balance relation between the spontaneous emission and gain spectra of excited semiconductor systems. This relation is used explicitly in some theories to derive the spontaneous emission spectrum (R_{spon}) from the material gain/absorption spectrum (g) to calculate the intrinsic radiative current. This relation was first derived by Henry et al[1] by a thermodynamic argument and can be written

$$g(h\nu, \Delta E_f) \propto -\frac{R_{spon}(h\nu, \Delta E_f)}{(h\nu)^2}\left[1 - \exp\left(\frac{\Delta E_f - h\nu}{kT}\right)\right] \quad (1)$$

where ΔE_f is the quasi-Fermi level separation. This equation breaks down in situations where carrier scattering is not sufficiently fast to maintain internal equilibrium in the presence of the stimulated recombination process, or where there are significant spatial variations in the structure of the gain medium, such as dimensional or composition fluctuations. In the latter case we may expect the energy spread of the thermal carrier distribution to be important in determining the effect of the inhomogeneity.

The recent development of a segmented-contact, single-pass method for measuring optical gain[2] has enabled us to measure the optical modal gain spectrum, the spontaneous emission spectrum, and the quasi-Fermi level separation simultaneously under the same pumping conditions, and thereby to explore the validity of equation (1). The spontaneous emission was measured through a narrow window in the top contact of the device[3] and an imaging spectrograph in conjunction with an intensified two dimensional CCD array allowed us to select the required optical mode and to reject any unguided light in the measurement of modal gain. The measured modal gain was transformed to material gain using a calculated wavelength-dependent optical confinement factor.

We have measured modal gain and spontaneous emission spectra for segmented-contact GaInP/AlGaInP quantum well structures. Fig. 1 shows material gain spectra obtained by transforming the spontaneous emission spectra using equation (1) (lines) and obtained directly from modal gain spectra (dots) at room temperature. The temperature used in equation (1) was taken to be that of the lattice. There is reasonable agreement between the two methods, though there are some differences at photon energies below the gain peak. Further measurements as a function of drive current and temperature enable us to explore this comparison in detail. At low photon energies and at low temperature the comparison is particularly sensitive to inhomogeneities and in these samples the dominant influence is In composition fluctuations in the well. We will discuss the implications of these results for gain calculations in this material system and in other systems, such as wide-gap nitride structures, where the compositional fluctuations may introduce inhomogeneous broadening comparable with kT at room temperature. In this latter case the breakdown of equation (1) has serious implications for the modelling of blue-emitting devices.



CMB3 Fig. 1. Measured gain spectra (dots) and transformed spontaneous emission spectra (lines) at 300K for differing current injection.

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CMB4 **8:45 am**

Internal thermoelectric heating and cooling in heterostructure diode lasers

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Pulsed electrical injection of a semiconductor laser typically results in better performance versus continuous wave operation. Pulsed lasers tend to have lower threshold current,[1,2] higher quantum efficiency,[2] more stable performance over varying ambient temperature,[3] and the ability to operate at longer wavelengths.[3] This dramatic difference in performance underscores the importance of heat generation and transport in semiconductor lasers.[4–6] We develop here a new heat model for a semiconductor device that takes into account more rigorously the thermoelectric properties of the constituent layers.

Previous thermal models of semiconductor lasers have self-consistently incorporated the effects of Joule heating and non-radiative recombination on the characteristic temperature T_0 and on the laser threshold.[7] These models have neglected the effect of Peltier heat exchange at semiconductor heterointerfaces. Shakouri et al. have shown that significant thermoelectric cooling can be realized in an InP/InGaAsP structure at room temperature.[8] Here we apply the concept of heterostructure integrated cooling to a SCH quantum well laser.

The Peltier coefficient is a thermoelectric quantity which describes the average energy of those charge carriers within an equilibrium distribution that participate in conduction.[9] It is an increasing function of the depth of the Fermi level within the band gap, due to the increasing asymmetry of the carrier density of states with respect to the Fermi level.

When carriers move from one material to another in which their average transport energy is different, they can exchange thermal energy with the lattice and thus heat or cool the junction between the two materials. In a conventional SCH structure under applied bias (Fig. 1a), Peltier heating occurs as carriers are injected into the active region, while Peltier cooling occurs as leakage current flows out of the active region, while Peltier cooling occurs as leakage current flows of the active region.

Self-consistent drift-diffusion/Poisson equations were used to calculate carrier flow. The average transport energy of carriers in each layer was then calculated in order to estimate the Peltier heat exchange at each interface. The power dissipated in the device is given by taking into account the I*V product across the device, the contact resistance, the radiative recombination, and the Peltier heat exchange. This dissipation term can be related to surface temperature through the thermal impedance model for a linear stripe heat source on a thick substrate.[7]

This model was tested with experimental surface temperature data obtained through the use of a microthermocouple probe on a conventional InGaP/GaAs/InGaAs device.[10] The probe used was approximately 25 µm in diameter, and gave a reading that was precise to 10 mK and accurate to 0.2 K (calibrated against a NIST-traceable thermocouple calibrator). The results are shown in Fig. 2.

Peltier cooling can be optimized in a device by engineering the band offsets in such a way that current both into and out of the active region removes heat from the lattice. We call this device an ICICLE (Injection Current Internally Cooled Light Emitter) and show a typical band structure in Fig. 1b. The type-II band alignment can be achieved in a material system such as InGaAsSb; the surface temperature predicted by this model is shown in Fig. 2. Note that Peltier heat exchange produces a heating of 5 mK/mA in the conventional structure and a cooling of 14 mK/mA in the sample ICICLE structure.

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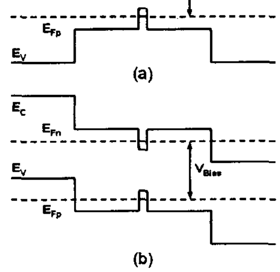
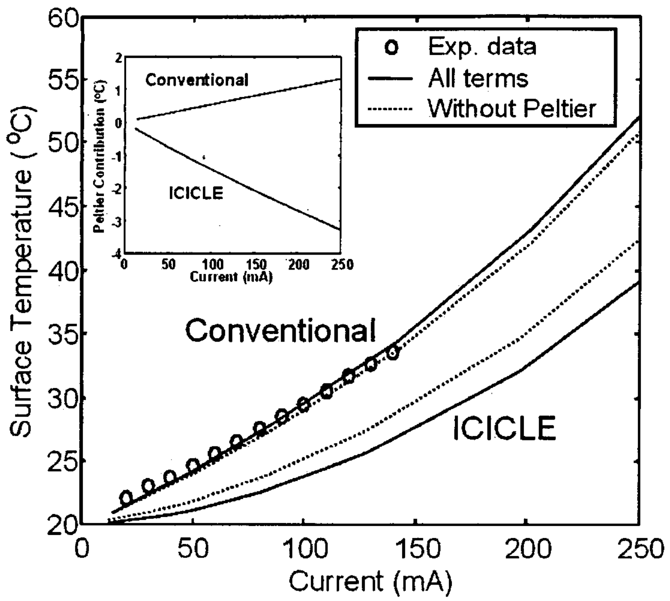


CMB4 Fig. 1. Band structures for (a) conventional SCH and (b) ICICLE designs



CMB4 Fig. 2. Model of surface temperature vs. current for conventional SCH and ICICLE designs. Experimental data for the SCH device is also shown for comparison. Inset: The contribution of Peltier heat exchange in each design.

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CMB5 **9:00 am**

Hot Phonons and Auger Heating in Semiconductor Optical Amplifiers

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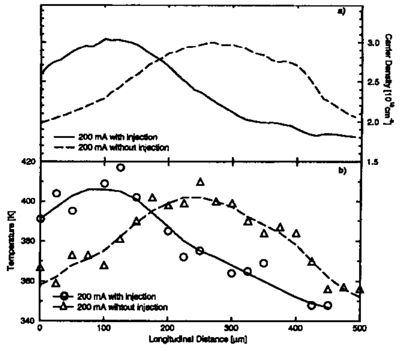
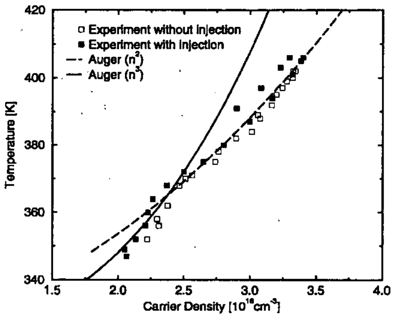
We have designed a setup to observe the spatially resolved spontaneous emission of semiconductor optical amplifiers, with or without light injection. Clear longitudinal hole burning due to ASE has been reported last year at this conference, which depends on the power of the injected optical signal.[1] The same experiment directly shows that the carrier temperature may be higher than 400K. We have studied the carrier temperature as a function of the current density flowing in the device, as well as depending on the light beam injected and amplified. It follows from our experimental observations (see Fig. 1 a and b) that the main heating mechanism is Auger in the valence band (CHHH or CHHS), which brings large excess temperature for densities above 2.10^{18} cm^{-2}.

A rate equation model for the energy density of electrons, holes and phonons is then developed, assuming that each distribution follows the appropriate equilibrium distribution with its own temperature. Auger is indeed found to be the main heating mechanism, but the very fast interaction with LO phonons prevents the carriers from reaching a temperature appreciably larger than that of the lattice. Injection heating as well as recombination heating, which appear to have a strong influence on the short time dynamics of the gain compression in SOAs, as well as on the dynamics of lasers, do not change appreciably the cw temperature of the electron-hole plasma in a SOA.



CMB5 Fig. 1. a) Measured carrier density along the active layer of a SOA. Clear LSHB is evidenced due to carrier removal by ASE. b) Corresponding carrier temperature. The highest temperature is obtained in the region of higher concentration and weaker ASE, suggesting an Auger related mechanism.

The introduction of hot phonon effects is then mandatory since Auger recombination alone is not strong enough to heat the plasma. Hot phonon effects are introduced separately for electrons and holes due to the differences in the Fermi filling as well as in the effective masses. Care is indeed taken for the relevant portion of the Brillouin zone involved in the emission-absorption of phonons. The volume of the reciprocal space available for interaction with phonons is much larger for holes, which will contribute most efficiently to the cooling process. With these ingredients, and with standard values for the Auger coefficient, our model has no adjustable



CMB5 Fig. 2. Measured temperature as a function of the estimated carrier density. Dots correspond to measurements without injection, and triangles with injection. The full line correspond to the result of a fit with a cubic dependence of the auger rate, and the dashed line, to a quadratic dependence.