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Detuning of the gain and reflectivity spectra and its effect on the output characteristics of vertical cavity surface emitting lasers

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We have investigated the effect of mismatch between the reflectivity resonance and the gain spectra of vertical cavity surface emitting lasers. Detuning was caused by hydrostatic pressure and self-heating. Hydrostatic pressure shifts the gain peak towards shorter wavelengths with respect to the Fabry-Pérot (FP) resonance without modifying the gain spectrum. The threshold current remained unchanged for a positive mismatch of up to 18 nm. It increased four-fold for a negative mismatch of −13 nm at 0.5 GPa, where lasing disappeared. Increased threshold current and quenching of the emission are a consequence of the decrease of the gain at the FP resonance. A similar effect was observed when the gain peak was red-shifted with respect to the FP resonance by increasing the injected power. Increased mismatch is accompanied by a decrease of the gain at the emission wavelength which is responsible for the laser output quenching at high injected powers.

Vertical cavity surface emitting lasers (VCSELs) are becoming mature optical sources for applications such as optical interconnects and optical logic devices. Detailed understanding of their design and operating characteristics is therefore of considerable interest. It is known that the output characteristics of a VCSEL are determined by the gain medium and the optical design of the resonant cavity. A close match between the gain peak and the Fabry-Pérot (FP) resonance in the reflectivity spectrum is needed to obtain the desired combination of low threshold current and high power output.[1,2] However, during operation this condition can not be maintained exactly since the power dissipated in the VCSEL results in self-heating which in turn shifts the gain peak with respect to the FP resonance. To examine the effect of the resulting mismatch on the laser threshold current and power output of InGaAs/GaAs VCSELs, we shifted the gain peak across the high reflectivity region of the distributed Bragg reflector (DBR) by self-heating and hydrostatic pressure. The gain peak shifts toward the long wavelength region of the reflectivity spectrum when the temperature of the active region increases with injected power. Hydrostatic pressure shifts the gain peak towards shorter wavelengths, without increasing the gain, as is unavoidable in low temperature measurements.

The InGaAs/GaAs VCSELs used in our experiments were designed to emit at 960–970 nm. A detailed description of these structures is given in Ref. 3. Threshold currents of these devices varied from 4 to 7 mA and threshold voltages were in the 4–6 V range for device diameters of 6–15 μm. This results in a threshold power dissipation of 16–40 mW, depending on the VCSEL diameter. In order to allow comparison between lasers of different threshold currents and voltages we express our results in terms of the dissipated power.

To quantify the mismatch in the self-heating experiments the stimulated and spontaneous emission spectra were measured at different injected powers. The mismatch between the gain peak and the FP resonance was then calculated as the wavelength difference of the spontaneous emission peak and the stimulated emission peak. From the wavelength shift of the stimulated emission with injected power, and using the previously measured temperature rate of change of the laser emission[3] we determined the thermal resistance of the lasers to be 1 °C/mW.

In the pressure experiments the mismatch change was evaluated from the measured shift of the laser emission and that of the gain peak which was assumed to be equal to the pressure rate of the bandgap. The effect of the mismatch change was determined from the light output versus current curves. Details of these measurements have been described previously.[4] The 15 μm diameter lasers were driven at a low (~1%) duty cycle to minimize self-heating which is estimated to be ~4 °C.[2] Measurements were taken with increasing and decreasing pressure, up to 0.5 GPa where lasing disappeared. When the pressure was reduced lasing was recovered, an indication that the laser was not damaged during the cycle.

The pressure dependence of the laser threshold current normalized to its atmospheric pressure value is shown in Fig. 1(a). The threshold current remained constant up to about 0.25 GPa and then increased rapidly by about a factor of 4 at 0.5 GPa. The origin of these large changes in the VCSEL threshold current can be accounted for by the changes in the mismatch between the FP resonance and gain peak which

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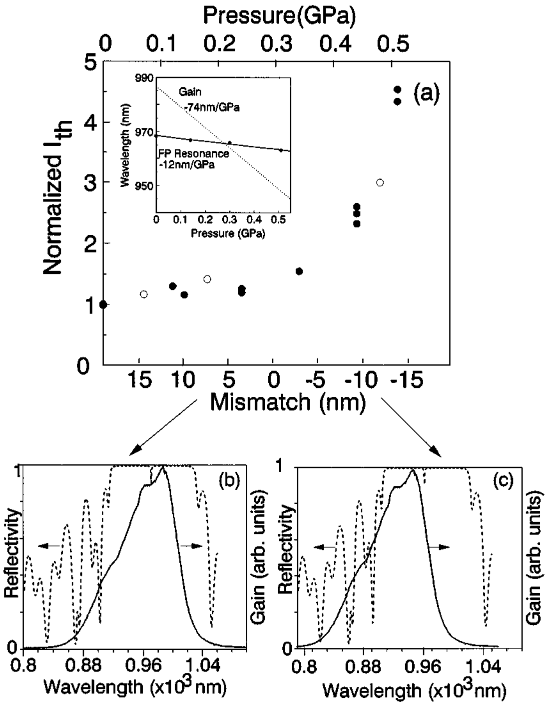

FIG. 1. (a) Variation of the threshold current as a function of pressure and mismatch. The inset shows the pressure variation of the FP resonance (solid line) and that of the gain peak (dotted line), from which the mismatch is calculated at different pressures. (b) and (c) show the variations in the gain at the Fabry-Perot notch for a mismatch of 18 nm (0 GPa) and of -13 nm (0.5 GPa).

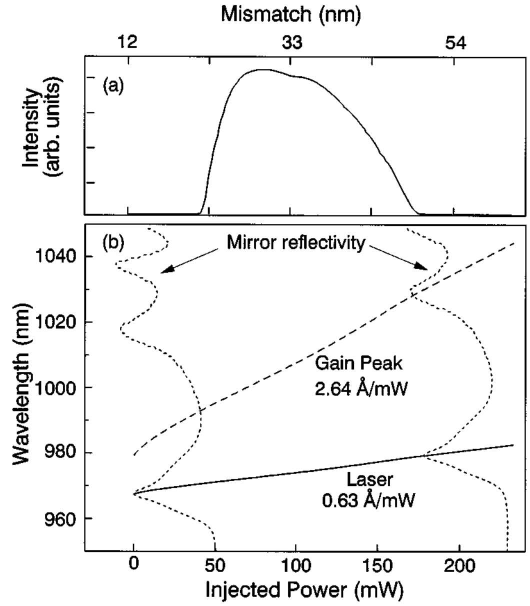

FIG. 2. (a) Light output vs injected power. Its relationship with the temperature induced mismatch can be obtained from the shift of the gain peak and FP resonance wavelength with injected power, shown in (b).

occur under pressure. Under pressure the bandgap of the active region blue shifts at a rate of -74 nm/GPa[5] causing the gain peak to shift at the same rate. The FP resonance also blue shifts but at a lower rate of -13 nm/GPa, determined by the pressure dependence of the index of refraction of the materials composing the cavity and the geometrical changes of the cavity.

In Fig. 1(a) we also plot the laser threshold current as a function of the mismatch. When the mismatch is decreased from 18 nm to 0 the threshold current remains unchanged. It then increases quadratically for negative mismatch. Varying the mismatch changes the gain at the FP resonance. This is shown in Figs. 1(b) and 1(c) where we plot the calculated mirror reflectivity and the experimental gain curve for a positive and negative mismatch condition. The gain curve in these figures corresponds to that measured under cw excitation for a current of 7 mA, comparable to the threshold current of the pulsed driven devices. Figure 1(b) shows that in the region of positive mismatch, as the FP resonance and gain peak are being aligned, the gain at the FP resonance does not change significantly, thus resulting in constant threshold current. On the contrary, for negative mismatch [Fig. 1(c)] the gain at the FP resonance sharply decreases, giving rise to the quadratic increase in the threshold current.

Comparing our results with low temperature measurements in VCSELs with a similar initial mismatch,[1] we find that there is no minimum in the laser threshold current when the mismatch is zero and that a faster increase is obtained for a similar negative mismatch. These differences can be accounted for by the variations in the magnitude of the gain. Increased pressure results only in a blue shift of the gain while lowering the temperature also increases the gain. For a positive mismatch the gain increase with decreasing temperature is responsible for the reduction in the threshold current. For a negative mismatch, the abrupt decrease in the long wavelength side of the gain overcomes the temperature induced changes and the threshold current increases. Thus, it is not the zero mismatch condition that produces a minimum in the threshold current but rather the competition between the temperature and wavelength variations in the gain at the FP resonance.

The changes in the gain with temperature influence the VCSEL output characteristics during cw operation. With increased injected power the temperature in the laser active area increases considerably resulting in a reduction of the gain and a shift toward longer wavelengths with respect to the FP resonance. To quantify the effect of the temperature induced mismatch on the laser output we plot the variations of the light output and that of the gain peak and FP resonance as a function of the injected power for an 8 μm VCSEL (Fig. 2). The gain peak shifts at a rate of 2.64 Å/mW and the FP resonance shifts at a much slower rate of 0.63 Å/mW. For the laser structures used in these experiments, the gain peak and the FP resonance are separated by $+12$ nm under no injection conditions.[3] The mismatch increases to 23 nm at threshold, reaches 30 nm at the peak light output and at 50 nm the lasing disappears. At this point the gain peak tunes out of the high reflectivity region of the DBR. Increased mismatch in this case results in decrease of the gain at the FP resonance, as shown in Fig. 3, where we plot the calculated mirror reflectivity and the gain measured at threshold for a mismatch of (a) 23 nm and (b) 50 nm. The gain decreases with temperature, but only a temperature induced shift was considered here. Figure 3 shows that for large mismatch the gain at

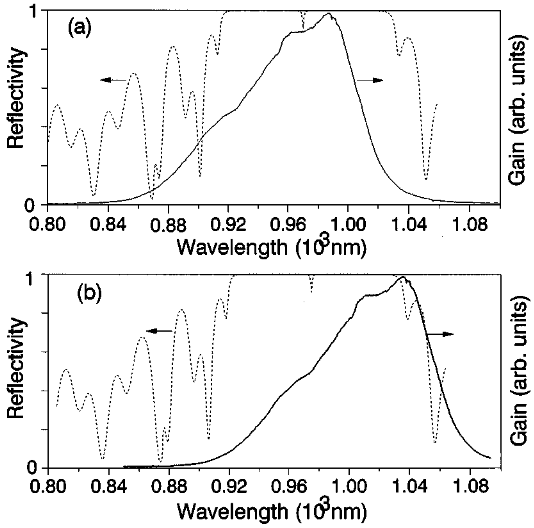

FIG. 3. Gain and reflectivity spectra for mismatch changes of (a) +23 nm, measured at threshold and (b) +50 nm when lasing disappears.

the FP resonance decreases considerably, reaching a value about half its threshold value when lasing disappears. This reduction in the gain at the FP resonance is responsible for the decrease and quenching of the laser emission at high injected powers.

Both self-heating and pressure experiments show the role played by the changes in the gain and its mismatch with the FP resonance on the output characteristics of VCSELs. Our results also provide a quantitative measure of the mismatch required for optimum operation which is useful in the design of VCSELs. For cw operation of VCSELs with a threshold power dissipation of ~40 mW and a thermal resistance of 1 °C/mW it is advantageous to design a structure with an initial negative mismatch of about −12 nm such that at threshold the FP resonance would almost align with the gain peak. Moreover, since the gain spectrum is not symmetric and its decay is less abrupt at shorter wavelengths, devices with an initial negative mismatch are expected to have reduced temperature sensitivity. VCSEL structures which incorporate these design characteristics have been reported to have threshold currents which are basically temperature independent in the 25–90 °C range.[6]

In summary, we have quantified the effect of the mismatch between the FP resonance and the gain peak in the output characteristics of 960 nm VCSELs. The mismatch was varied from positive to negative by more than 60 nm by self-heating and hydrostatic pressure. Increased mismatch due to self-heating results in a reduction of the gain at the lasing wavelength which is responsible for the decrease and quenching of the laser emission. Decreasing the mismatch by using high pressure showed that when the FP resonance is at shorter wavelengths than the gain peak, the threshold current remains unchanged. Large increases in the threshold current occur when the FP resonance falls on the long wavelength region of the gain spectra.

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