Mode splitting in side emission from vertical-cavity surface-emitting lasers

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We present side-emission (luminescence) data from vertical-cavity surface-emitting lasers which show cavity-induced effects on the emission spectrum. In particular, the heavy-hole luminescence spectrum contains two peaks when pumped in such a way as to excite electron-hole pairs well inside the cavity region, where coupling to free-space modes is minimized, and only one peak when pumped near the edge of the cavity (near a cleaved facet), where coupling to free-space modes is maximized. This splitting can be distinguished as a cavity-induced effect with little ambiguity from other factors present in semiconductor quantum-well radiation, such as the light- and heavy-hole splitting. A fit to the data using Lorentzian line shapes gives a vacuum-field Rabi splitting of roughly 34 meV, which is consistent with theoretical calculations and with other reports on this phenomenon. We therefore conclude that the two peaks in the spectrum are due to Rabi oscillation in the cavity, and that they represent an actual change in the energy configuration of the quantum well.
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INTRODUCTION

Cavity-induced effects, both interference and feedback driven, can play a large role in the overall performance of vertical-cavity surface-emitting laser (VCSEL) devices. The match between cavity resonance and quantum-well (QW) emission, as well as the position of the QW within the mode field of the cavity, are crucial to laser performance. Atom-cavity (or exciton-cavity, in this case) coupling, the feedback of its own radiation to the emitter, can induce phenomena such as thresholdless and squeezed-state lasing.[1,2] The high fields in the cavity can cause a mode splitting[3] that can be observed in the surface-normal absorption and emission spectra. Yet few VCSEL probes exist that can distinguish feedback effects from dispersive or interference-driven ones.

In this report, we show that cross-sectional photoluminescence (XPL), which measures the side emission from VCSEL's,[4] is a good probe for observing coupling phenomena in the cavity. The experimental arrangement reported here allows the degree of spontaneous emission coupling to free-space modes to be varied. This side-emission probe has been applied successfully to cavity-modification studies in gas-plasma systems,[5] but no one to our knowledge has reported such observations in semiconductor microcavities. Here we report a correlation of cross-sectional emission data from regions where the influence of the cavity is vastly different, showing that mode splitting occurs only in the regions where cavity influences are strong. These results are well modeled using the quantum-mechanical, strong-coupling formulation of Agarwal,[6] Sanchez-Mondragon, Narozhny, and Eberly,[7] and others,[8] and can therefore be viewed as a *real* change in the energy configuration of the quantum well, rather than a filtering effect caused by changing the resonance conditions in the cavity.

The utility of this technique of measuring side emission becomes particularly apparent in this case, where a mode splitting must be distinguished from a number of other possibilities. By measuring the side emission when the QW in the cavity is pumped from the side and comparing this with data taken with surface-normal pumping, we observe changes in the spectra that material defects and impurities do not adequately explain. By measuring polarized emission, we show that the mode splitting can be differentiated from light- and heavy-hole recombination. We also present simulated data, based on reflectance measurements on the actual VCSEL structure, which indicate that the splitting we observe is not due to a spatial and spectral redistribution of the energy radiated by the quantum well. Finally, we show that a fit to the side-emission measurement of the mode-split spectrum yields a vacuum-field Rabi frequency which is consistent with theoretical calculations and other reports on mode splitting.[8]

RABI SPLITTING IN VCSEL'S

The theory of a two-state system oscillating between states in a strong field, originally due to Rabi, has well-known quantum-mechanical or semiclassical[9] solutions. Both Sanchez-Mondragon, Narozhny, and Eberly[7] and Agarwal[10] showed that this type of oscillation between absorption and emission can also lead to mode splitting in the emission spectrum of a dipole in a laser cavity. More recently, Zhu *et al.*[11] fit the splitting of peaks in surface-normal spectra using classical Lorentz oscillators with linear dispersion.

The quantum-mechanical solution arises from including a photon-atom interaction term in the Hamiltonian and then simply rediagonalizing the system. The result of this procedure is that a single excited state is replaced by two (symmetric and antisymmetric) states, with different eigenenergies. The difference between the two levels is[6]

$$\hbar\omega_{N,\delta}=\hbar\sqrt{4g^2(N+1)+(\omega_c-\omega_e)^2}=\hbar\sqrt{\Omega_R^2-\delta^2}, \quad (1)$$

where N is the number of photons in the mode, $\omega_{c(e)}$ is the cavity (emitter) resonant frequency, and g is the coupling constant, equal to the dipole interaction $e\mathbf{r}\cdot\mathbf{E}$.

The general idea behind the derivation of Zhu *et al.*[11] is that the absorption of the oscillators themselves changes the round-trip phase condition necessary for resonance. When the single-pass absorption (or the density of emitters) is very high, the requirement that the round trip phase be equal to an even integer times π can be satisfied at three different wavelengths (since the refractive index changes with the absorption). This then leads to two peaks (i.e., two modes) in the transmission spectrum of the cavity/oscillator system, the central peak (mode) being squelched by the absorption of the emitters.

This model does not explicitly specify the energy configuration of the oscillators, as the standard Rabi-splitting model (as described above) does. In the picture which uses only refractive index changes to explain the splitting, one might easily assume that only the round-trip phase conditions had changed, and that the oscillators themselves continued to emit their free-space spectrum. If it were true that only the round-trip condition had changed, one could obtain different spectra in different directions, very much like the differing angular spectra obtained from a broadband source inside a Fabry-Perot etalon. Looking at the emission out the side of the etalon, it would be reasonable to expect to see something like the free-space spectrum.

If, however, the energy spectrum of the oscillators themselves had changed, then the spectrum in all directions would change (as demonstrated in gas-plasma systems by Heinzen and Feld[5]). The center wavelength of the spectrum emitted out the side of the etalon would be closer to the modified peak than the free-space peak. We note here that either of these results can be obtained either quantum mechanically or classically; the differences in the results are not attributable to the quantum or classical nature of light, but rather to a difference in the physical process which changes the measured spectrum. This is the strength of the XPL probe: surface-normal emission data, distorted in many cases by the etalon response, can be compared with side-emission data to resolve unambiguously what part of the spectrum is due to changes in the emitter itself.

OTHER "SPLITTING" MECHANISMS

In the case of the mode splitting, several other possibilities must be ruled out before a bimodal spectrum can be attributed to Rabi oscillations. Most importantly, the valence band in a quantum well is no longer degenerate: conduction electrons recombine with light and heavy holes to emit radiation of different energies. These transitions have different selection rules, and produce radiation that is orthogonally polarized[12] when viewed in the plane of the quantum well. Simple polarization selection can thus identify this phenomenon easily. Figure 1 shows the side emission for a simple quantum-well structure, with both emission polarizations resolved. The unpolarized emission (solid line) clearly segregates into two distinct peaks (dashed and dotted lines), corresponding to the light- and heavy-hole recombination.

Another important consideration is the "subtractive filtering" of the etalon. A simple analysis[13] shows that the intensity transmitted by an unspecified point source inside a Fabry-Perot cavity is

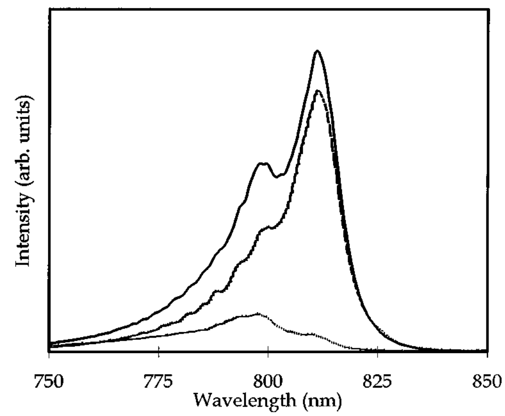

FIG. 1. Polarization-resolved side emission from a simple, single-quantum-well structure. The solid line is the unpolarized data; the dashed and dotted lines are orthogonal linear polarizations of the emitted light.

$$I(\omega)=I_0|t_1|^2\left(\frac{1+|r_1|^2-2|r_2|^2\cos(2\delta_a)}{1+|r_1|^2|r_2|^2-2|r_1r_2|\cos(2n\delta_c)}\right),\quad (2)$$

where t_1, r_1, and r_2 are the Fresnel coefficients of the mirrors, $\delta_a=n\omega a\cos\theta/c$, $\delta_c=n\omega l_c\cos\theta/c$, a is the distance from the point source to the back mirror (farthest from the observation point), n is the index of refraction of the material, and l_c is the length of the cavity. A short computation will show that $I(\omega)$ can greatly exceed I_0, the free-space value of the radiant intensity at ω at any angle. Yet a numerical integration of Eq. (2) over a sphere produces the free-space value $4\pi I_0$. The intensity change is thus due to a spectral and spatial redistribution of energy; in keeping with the principle of conservation of energy, those frequencies favored in surface emission [up to the total internal reflection (TIR) point] must be absented from the side emission. If Eq. (2) is applied to a VCSEL and then integrated, the result is a "window" that describes the subtractive filter for the XPL spectrum caused by the conservation of energy constraint.

The filter window, for a single-quantum-well VCSEL—one which exhibits a mode splitting—is shown in Fig. 2, which also plots the impact of this filtering on the XPL spectrum of the emitter. Though one might expect a sort of step-function response, owing to the continuous blueshift of the cavity resonance, this is not the case in Fig. 2. The reason for this is that as the cavity resonance blueshifts with increasing angle, so does the dip at the long-wavelength end of the high-reflectance band. The combination of the two serves to flatten the overall response. As is apparent from Fig. 2, the actual spectrum is not greatly altered by this effect, in this particular device.

SIDE-EMISSION MEASUREMENTS

In order to ascertain the penetration of the side-emission probe, we used two different pump orientations. For what we refer to as "standard" XPL measurements, the pump and collection paths were collinear, both normal to a cleaved facet of the wafer. For what we call surface-pumped XPL, the pump beam was normal to the surface of the wafer and orthogonal to the collection path.

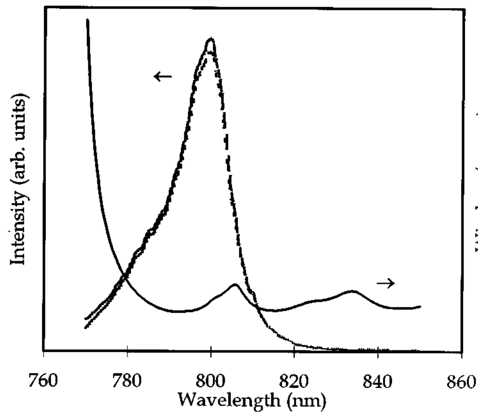

FIG. 2. Subtractive filter window for a single-quantum-well VCSEL. The basis spectrum (dashed line) does not change much when the subtractive filter effects are accounted for (solid line).

The reason for performing both types of measurements is that the emitters will begin to couple more light into the free-space modes as the excitation spot approaches the facet. More transverse modes of the cavity will give way to internally reflected guided modes or free-space modes as the point at which the light originates moves closer to the facet. As the quantum well has a relatively high absorption coefficient, most of the recombination will occur a very short distance from the cleaved edge. An order-of-magnitude calculation follows.

Viewing the multilayer mirrors in a VCSEL as an aggregate cladding with an index of approximately 3.2, TIR occurs at approximately 18°. A 20-pair mirror of roughly 2.5-μm total thickness thus describes a depth of about 0.8 μm where the totally internally reflected ray will hit the edge of the cleaved facet. The situation is depicted in Fig. 3: the angle β represents all the rays that escape the structure without coupling to a cavity mode. For emission at A, $\beta = \pi - 2\theta_{\mathrm{TIR}}$, its minimum value. The last point at which β is a minimum is B, where the TIR ray hits the edge of the structure. At point C, β is larger purely due to geometry, and continues to grow (to a value of π) as the point of emission gets closer to the facet; note that the maximum full angle, however, is $2\pi - 2\theta_{\mathrm{TIR}}$. The excitation point should thus lie at least 1 μm from the cleaved edge in order to probe more

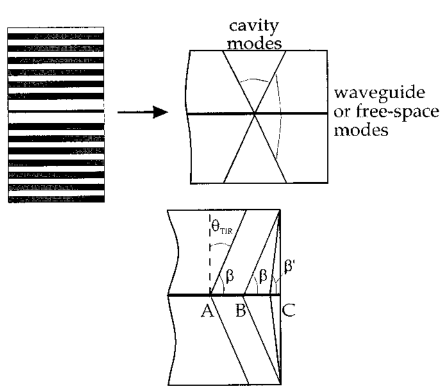

FIG. 3. Diagram of internal reflection, and coupling to cavity modes for emission from different points inside a VCSEL.

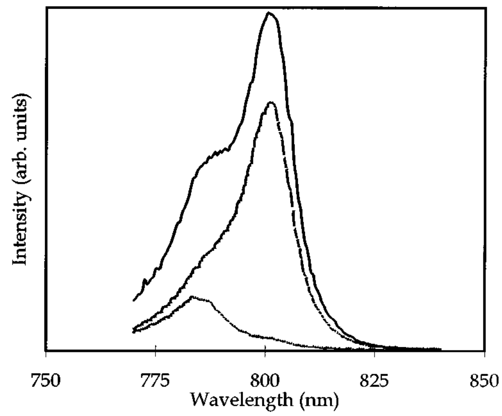

FIG. 4. Side emission from the detuned VCSEL structure when pumped from the side, perpendicular to the cavity axis. The solid line is the unpolarized data, the dashed line is polarized in the plane of the QW, the dotted line perpendicular to it.

of the cavity modes and cavity effects.

For a typical quantum-well absorption coefficient of 4 $\mu\mathrm{m}^{-1}$, 99% of the pump power (incident on the cross section of the well) will be absorbed in a region roughly 1 μm from surface of the facet, and $1/e^2$ of it in 0.5 μm. As this last figure is well within the ''window'' of uncoupled regions (described by point B), we conclude that the side-pumped XPL measurement is thus a very shallow surface probe, which yields the energy configuration of the quantum well with much less influence from the cavity than that experienced by an emitter at a point farther from the facet.

Pumping from the top of the structure and measuring the emission from the cleaved facet, on the other hand, allows regions beyond the 1-μm limit to be probed, and collecting the emission from the side allows acquisition of spectra that are free from the etalon-filtering effects of surface-normal emission. Comparison of these two techniques, for points not greatly disparate on the wafer, should reveal cavity-induced effects, such as level shifts and mode splitting, in the energy configuration of the quantum wells.

RESULTS AND ANALYSIS

Two structures were used for this study. The first was a single quantum well, sandwiched by $Al_{0.3}Ga_{0.7}As$ barriers only, used as a control. The second was a single quantum-well VCSEL with mistuned cavity resonance and quantum-well emission peaks. As the Rabi splitting should vary with the amount of detuning, we expected this specimen to be a good candidate for such behavior.

The side-emission spectrum for the simple quantum-well structure is shown in Fig. 1. The side-pumped side emission of the VCSEL structure is shown in Fig. 4. The cavity mode of the VCSEL is at 811 nm and the quantum-well peak at approximately 800 nm. The measured Q factor was approximately 2500; since the QW is detuned to shorter wavelength than the cavity resonance, the absorption at 811 nm is quite low, and this Q is probably very close to the cold-cavity value.

Figure 5 is the top-pumped side-emission spectrum of the quantum-well structure, which is identical to the side-

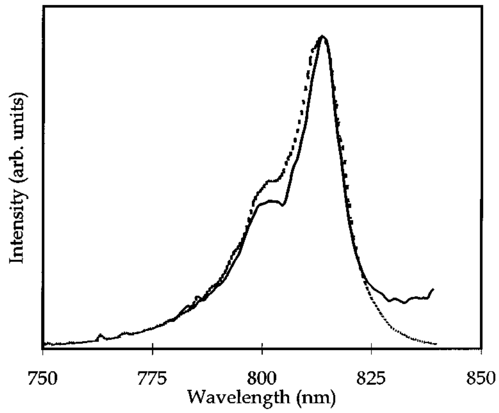

FIG. 5. Unpolarized side emission from the quantum-well control structure when pumped from the top (surface normal). The dashed line is the unpolarized data from the side-pumped spectrum.

pumped spectrum of Fig. 1 (dotted line). The spectrum of Fig. 5, which was not analyzed for polarization, resolves into two polarizations which segregate the two peaks, much the same as in Fig. 1. This demonstrates that there is no inherent difference in pumping the quantum well from the side or from the top.

Figure 6 shows the side emission obtained from the VCSEL when pumped from the top, along with the two orthogonal polarizations. Due to the resonant distribution of the pump field in the VCSEL structure, the power density was reduced significantly when pumping from the top, from approximately 2.5 mW/μm^2 (250 kW/cm^2) to 0.1 mW/μm^2. However, in both cases, side and top pumped, no evidence of thermal effects was observed. The three spectra in Fig. 6 have been normalized to a common value for comparison; when analyzed by its polarization state, the emission changes only in absolute intensity, not in the character of the spectrum. The obvious distinction between orthogonal polarizations due to the light- and heavy-hole recombination peaks, as seen in Fig. 4, is absent from Fig. 6, showing that the two peaks are not due to the nondegenerate valence states of the quantum well.

As indicated in the theoretical analysis above, the subtractive filtering for this structure is not likely to have a significant impact on the side emission. The absence of polarization differences strongly indicates that light- and heavy-hole emission is not responsible for the two peaks in Fig. 6. A great number of other factors such as impurities and structural defects can be dismissed as causing the differences between the top-pumped (Fig. 6) and side-pumped (Fig. 4) spectra, simply because dramatic changes like this, occurring within a few micrometers of each other, are not consistent with the measured uniformity of the wafer, and because this difference reproduces at varying locations on the wafer. That the dips in the spectra of Fig. 6 are not a manifestation of an absorption phenomenon different from the resonant absorption of Rabi oscillations was determined by moving the excitation spot further from the facet, whereupon the character of the spectrum remained constant (though its overall intensity decreased). Neither did the spectrum change character when the pump wavelength was changed, indicating that pump-coupling effects are not significant here.

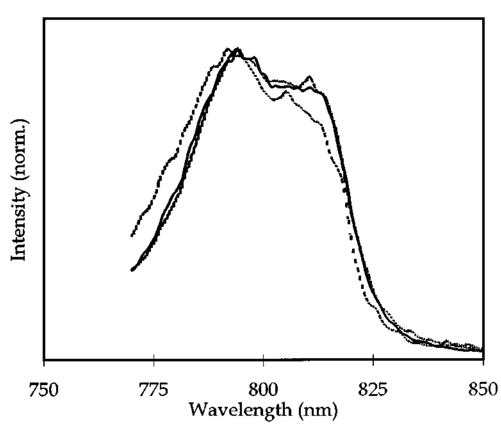

FIG. 6. Side emission from the detuned VCSEL structure when pumped from the top. The solid line is the unpolarized data, the dashed is polarized in the plane of the QW, and the dotted perpendicular to it.

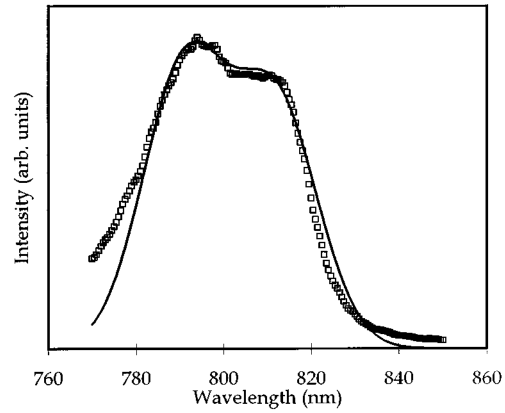

FIG. 7. Fit of model (solid line) to data (open squares) for the side emission of the VCSEL structure. The model uses two Lorentzian curves, roughly 11 nm apart and adjusted for slight increases in absorption with longer wavelengths.

By fitting the data with a pair of Lorentzian lines, as shown in Fig. 7, the magnitude of the splitting can be gauged. The fit we arrive at from the data in Fig. 7 works out to a splitting of roughly 40 meV. Using Eq. (1), then, we can estimate the so-called vacuum-field Rabi splitting,

$$\hbar\Omega_R = 2\hbar g\sqrt{n+1} = e\mathbf{r}\cdot\mathbf{E}_{\mathrm{cav}}, \tag{3}$$

or, of greater utility to this case,

$$\hbar\Omega_R = \sqrt{(\hbar\omega_{n,\delta})^2 - (\hbar\delta)^2}. \tag{4}$$

By measuring δ (the detuning of QW and cavity) and $\omega_{n,\delta}$ (the splitting of the mode we observe in the side emission), we can determine the Rabi frequency. In this case, the detuning works out to an energy difference of about 21 meV, so $\hbar\Omega_R$ is about 34 meV, or a little less than twice that reported for a VCSEL structure by Weisbuch, Houdré, and Stanley.[8]

This is not a surprising difference for several reasons. First, the Rabi frequency depends on the magnitude of the cavity (mode) field at the position of the dipole, which can vary dramatically even for similar VCSEL structures. Second, the coupling also depends on the effective mode volume, estimates of which can vary significantly in semiconductor microcavities. Third, the dipole moment estimate used in Ref. 8 was based on an oscillator strength appropriate to a 10-nm GaAs quantum well in 40% $Al_xGa_{1-x}As$, as opposed to 5 nm and an alloy content of 30% in this case. These differences can easily account for a factor of 2.

CONCLUSIONS

We have shown that the two different pumping configurations (side and top) yield different results in VCSEL (cavity) and simple quantum-well (noncavity) structures. The explanation that best fits the data is that of mode splitting due to Rabi oscillation; the differences cannot be adequately explained by any of the other explanations discussed herein. The correlation of side emission (unperturbed by etalon filtering) from two regions in the same structure, differing primarily in their levels of free-space coupling, shows this effect to be of true cavity-induced origin, making this the first report of such an observation in semiconductor microcavities. In addition, the fact that the mode splitting is observable in the side-emission spectrum strongly suggests that it represents an actual change in the energy configuration of the quantum well itself.

This is an important distinction: the linear dispersion model predicts a splitting which should change with emission angle and should disappear in the side emission, whereas the excitonic quantum model predicts a change in (scalar) energy levels, or an isotropic splitting. What we have observed is thus more consistent with the latter interpretation, while there have been other reports (as cited earlier) which have observed effects consistent with linear dispersion. It thus appears that there are two distinct phenomena at work in these microcavities.

We have also demonstrated the utility of measuring side emission from VCSEL structures, especially when probing for cavity-induced effects. Due to the scalar nature of the atom-cavity interaction, measurements of side emission should be highly sensitive to phenomena such as mode splitting, energy-level shifts, and decay rate alteration. Using alternate pumping schemes to excite different regions in the VCSEL can also aid in identifying the differences between the unperturbed spectrum and that which has been influenced by the presence of the cavity.

ACKNOWLEDGMENTS

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