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Mode Coupling and Intersubband Transition Rabi Splitting in Microcavities

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Abstract. — We theoretically study the absorption in grating coupled quantum wells in a cavity. We describe the coupling between the three oscillators present in the structure: the intersubband transition, the grating and cavity modes. We show that optical mode anticrossings should be observed. The splitting between the cavity mode and the intersubband transition is calculated but its experimental observation would require electronic coherence times longer than what was measured.

During the last ten years, two important fields in the physics of semiconductor heterostructures have experienced spectacular developments in large part owing to the improvement of crystalline growth methods such as molecular beam epitaxy.

The first field deals with intersubband transitions (ISBT) in quantum wells [1, 2]. Many infrared devices have been proposed and fabricated for modulation [3, 4] detection [5] and emission [6]. In n-doped structures and in large bandgap materials, the polarization selection rule prevents any coupling between the light and the wells at normal incidence (only the electric field $E_z$ perpendicular to the well is coupled with it, $z$ being the growth axis). The coupling can be obtained by increasing the incidence angle thereby creating a $z$ electric field component. However, due to the refraction, the coupling remains weak. A grating can also be used which diffracts photons along directions where the $E_z$ may be important. The grating coupling has been introduced first for detectors [5, 7] and then extended to the case of modulators [8].

The second rapidly growing field is related to microcavity effects [9]. The recent developments of deposition techniques have allowed the fabrication and the accurate control of microcavities, and many resonant cavity enhanced devices have been realized. A good review of these devices was published recently [10]. As far as light emission is concerned, microcavities in VCSEL’s have allowed to drastically reduce semiconductor laser thresholds and the spectral width of LED’s [9]. Cavity finesse as high as 5000 have been obtained thanks to the high quality of the MBE growth [11]. These microcavities are planar and use materials which are optically active at normal incidence. They will be called regular microcavities hereafter.

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At the merging of these two fields, the possibility of obtaining microcavity effects with intersubband transitions was remained unexploited up to now because of the polarization selection rule. Recently [12], it has been proposed to introduce a grating inside the cavity in order to get both the cavity field enhancement and the grating coupling (Fig. 1). From the point of view of the photons oscillating in the cavity, the grating and well regions may thus be simply considered as a lossy region and are equivalent to the active region in a regular microcavity device. The electromagnetic field in a cavity and the electronic transition (band-to-band in general, intersubband transition here) can be viewed as two oscillators that are broadened by the finite photon lifetime in the cavity and the coherence time $T_2$ respectively. In a regular cavity, the coupling between these oscillators has led to the observation of the absorption enhancement [10], modifications of the spontaneous emission [9] or even Rabi splittings [13].

We discuss here more specific features that may arise from the coupling between oscillators: anticrossings and intersubband Rabi oscillations. In this regards, we recall here that the analysis of the coupling from the transmission or the reflection may be ambiguous [9] so that we study the coupling from the absorption. All calculations are performed at normal incidence. Details of the calculation can be found elsewhere [12]. For completeness, we briefly recall the principle of the calculation that is used here. We calculate the modes in the dielectric grating with an optical index modulation in the $x$ direction. Below and above the grating, the field is developed in propagating and evanescent orders that verify the periodicity of the system in the $x$ direction. In the $z$ direction, transfer matrices are used in order to account for the multilayer structure. The field continuity right above and below the grating leads to relations between modes and orders. By keeping a limited number of modes and orders, we end up with a system of coupled linear equations that is solved by a matrix inversion. As the grating is working in the $+1$ and $-1$ orders, a good accuracy is obtained with a small number of orders.

**Weak Coupling Regime**

In the calculations presented in this paper, the active region is made of 40 GaAs/AlGaAs quantum wells. The 4 nm GaAs well is doped to $10^{10}$ cm$^{-2}$. The 40% Al rich barrier is 35 nm thick. The transition wavelength is 5.5 µm and the Full Width at Half Maximum is 10 meV unless otherwise stated. This active region is in between two doped (10$^{17}$ cm$^{-3}$) GaAs regions.
as in a regular detector based on ISBT. A transparent phase grating is defined in the top GaAs layer. The high and low optical indices in the grating are 3.27 and 1.4 respectively and the grating period, profile ratio and height are 1.8 $\mu$m, 0.5, and 0.45 $\mu$m respectively. These layers define a $3\lambda/2$ active region and are placed in between two Bragg mirrors. The optical indices for top mirror are $n_1 = 1.4$ and $n_2 = 2.43$ (as for CaF$_2$ and ZnSe respectively). In this part, the top mirror is CaF$_2$/ZnSe/CaF$_2$ while the bottom one is made of 5 GaAs/AlAs periods. These parameters were chosen as they describe a cavity that can realistically be fabricated. The number of periods is small and the overall layer thickness remains compatible with growth techniques. The reflection coefficient of both mirrors is 0.5. We calculated the field in this planar cavity and found an enhancement of the electromagnetic energy density ($Q$ factor) close to 22, in agreement with the width of the transmission spectrum. As the mirrors are distributed Bragg mirrors, we define here the finesse using the local free spectral range that takes into account the light penetration in the mirrors [11]. The finesse in this cavity is thus equal to 4.45. We first calculated the absorption $\alpha$ in the active region with the grating but without the cavity and found 1%. Then we calculated the absorption in the complete structure. Figure 2 shows that the absorption increases with the bottom mirror reflectivity and exceeds 45% for $R = 0.5$ (5 AlAs/GaAs periods). At this point, it is important to clarify the double role played by the low index layers of the mirror. They first constitute the mirror that partially reflects the non diffracted order and gives the cavity mode. Second, because of their low optical index, they totally reflect the diffracted orders propagating in the active layer. The modes propagating in the latter non planar optical guide defined on one side by the bottom mirror and on the other side by the grating will be called grating modes. In Figure 2, part of the absorption enhancement is due to the guiding effect that increases with the low index layer total thickness. We calculated that this guiding effect can lead to an absorption as large as 20%. We observe that the absorption is peaked at the electronic transition wavelength independent of the mirror reflectivity. We recall here that three oscillators are present in this structure: the cavity field, the grating resonance and the electronic transition. The grating parameters and the cavity length were chosen in order to give resonances at the same wavelength as the ISBT. However, we do not observe any special feature due to the coupling between oscillators: We are thus in a weak coupling regime. This means that the coupling energy $h\Omega$ is small compared with the width of individual transitions $h/T_2$ or $h\nu/Q$ for the ISBT and the cavity respectively. This can be translated in terms of mirror reflectivity $R$ and total absorption in the structure $\alpha$ [14]: $\alpha < \pi/\text{finesse} = (1 - R)/\sqrt{R}$. The latter relation is verified with an absorption with guiding effects of 20% and $R = 0.5$. 

![Fig. 2. Calculated absorption in a 40 quantum well structure in a grated cavity at normal incidence. The top mirror indices are $n_3/n_2/n_1$ with $n_1 = 1.4$ and $n_2 = 2.43$. The bottom mirror indices are $n_3 = 2.75$ and $n_4 = 3.27$. The number of pairs in the bottom mirror varies from 1 to 5. The grating parameters are $(d, c/d, h) = (1.8 \mu$m, 0.5, 0.45 $\mu$m). The FWHM of the intersubband transition is 10 meV. The doping density is equal to $10^{10}$ cm$^{-2}$.](image_url)
Fig. 3. — Calculated absorption spectrum in a grated cavity as a function of cavity length. Top and bottom mirrors are made of 3 $n_1/n_2$ periods with $n_1 = 1.4$ and $n_2 = 2.43$. The grating parameters are $(d, c/d, h) = (1.865 \mu m, \ 0.5, 0.1 \mu m)$. Other parameters are as in Figure 2.

Strong Coupling Regime

We now use a symmetric cavity with both top and bottom mirrors made of 3 CaF$_2$/ZnSe periods. The reflectivity is close to 90%. The finesse is now close to 30. The cavity length $L$ is around $m\lambda/2$ with $m = 3$. The $Q$ factor reaches 130 indicating a penetration of the light in the mirrors equal to $m_0\lambda/2$ with $m_0 = 1.3$ ($Q = (m + m_0) \times$ finesse). We first calculated the absorption without any cavity. We took the guiding effect into account by placing the active region in between two CaF$_2$ thick layers. For the following grating parameters: $(d = 1.865 \mu m, \ c/d = 0.5, \ h = 0.1 \mu m)$, the absorption without cavity was found to be around 35%, weakly dependent on the cavity length. We also noted that the peak wavelength of the grating mode increases from 5.46 $\mu m$ for $L = 2.57 \mu m$ to 5.49 $\mu m$ for $L = 2.75 \mu m$. Then, we calculated the transmission spectrum of the cavity without any grating, replacing it by a layer of the same thickness and with an optical index equal to an average of the grating optical indices. As expected, we found that the transmission peak was increasing from 5.35 $\mu m$ for $L = 2.57 \mu m$ up to 5.64 $\mu m$ for $L = 2.75 \mu m$, in agreement with the cavity order (4.3) and the cavity average optical indices. Finally, we calculated the absorption spectrum in the whole structure as a function of the cavity length. The result is presented in Figure 3. We observe the grating and cavity modes as they were described above. The interesting phenomenon occurs when these two modes are resonant for the same wavelength: We observe a clear anticrossing, with a splitting between modes. We now have $(1 - R)/\sqrt{R} = 0.1 < \alpha = 0.35$ which states that we are in the strong coupling regime. It is important to note that the electronic transition remains spectrally broad and we do not observe here the splitting between the ISBT and an optical mode but the splitting between two optical modes (mode coupling). This splitting can also be observed in reflection and transmission spectra in the non diffracted mode, even in the absence of intersubband transition. Intersubband transitions allow here to measure the energy lost along one round trip of photons in the cavity due to the diffraction by the grating. It can be shown that in this case almost all the energy diffracted out of the normal mode is absorbed by the quantum wells (Equivalently, we could replace $\alpha$ in the Zhu criterion by $1 - r - t$ where $r$ and $t$ are the non diffracted reflection and transmission coefficients of the grating region). In fact, the absorption represents the strength of the coupling in the same way as does the absorption in the conventional system of Zhu. Furthermore, this coupling strength is found little dependent on the electron density in the range of $10^{10}$ cm$^{-2}$, showing the secondary role of intersubband transitions in the splitting.
Intermediate Coupling Regime

The coupling between the cavity and the active region can be tuned in different ways. The relation describing the strong coupling regime ($\alpha > \pi$/finesse) can be obtained by increasing either the absorption or the cavity finesse.

Increase of the Absorption with the Grating Diffraction Efficiency. — We calculated the absorption in the active region (grating and quantum wells) placed between two CaF$_2$ layers. Hence, there is no cavity but guiding effects are taken into account. We performed this calculation for the same grating period and profile as above but the height is varied from 0 to 0.4 \( \mu \)m. We found that the absorption increases roughly linearly from 0 for \( h = 0 \) to 50\% for \( h = 0.15 \) \( \mu \)m. It equals 35\% for \( h = 0.1 \) \( \mu \)m as already mentioned, and 13\% for \( h = 0.05 \) \( \mu \)m. For \( h > 0.15 \) \( \mu \)m it saturates and finally decreases for \( h > 0.3 \) \( \mu \)m. Then, we calculated the absorption in the whole structure, with the same mirror as above (\( R = 0.90 \)) with a grating height that varies from zero to 0.2 \( \mu \)m. The result is presented in Figure 4. For a weak diffraction efficiency, we observe a single peak. As the coupling increases, this peak is split in two peaks and the splitting varies almost linearly with the grating height and thus with the coupling. The splitting becomes visible for \( h \) around 0.05 \( \mu \)m. We thus verify that we go from the weak coupling to the strong coupling regime for \( (1 - R)/\sqrt{R} = 0.1 \approx \alpha = 0.13 \).

Increase of the Finesse with the Mirror Reflection Coefficient [15]. — This can be done continuously by varying the optical indices of the quarter wave layers. We kept the low index constant (\( n_1 = 1.4 \)) and varied the high index \( n_2 \) from 1.5 up to 4. We kept 3 periods. The reflection coefficient increases almost linearly from 0.1 (\( n = 1.5 \)) to 0.8 (\( n = 2.2 \)). Thereafter, the increase is sublinear and the reflection coefficient tends asymptotically towards unity for \( n = 4 \). We note that \( R = 0.68 \) for \( n = 2.2 \). We calculated the absorption in the active region placed in the cavity with a grating height equal to 0.1 \( \mu \)m. The result is shown in Figure 5. For a low mirror reflectivity, a single peak is observed. As the optical index \( n_2 \) and thus the reflectivity increases, the peak is split in two peaks. The splitting occurs for \( n = 2.2 \) where we verify again the relation \( (1 - R)/\sqrt{R} = 0.38 \approx \alpha = 0.35 \).

Let us recall here that the ISBT remains broad compared to the optical resonances studied here and the observed splittings are between optical modes. Experimentally, it should be...
possible to observe these features as the structures and the parameters used for the simulation are very realistic.

**Rabi Splitting**

Let us now push the parameters to make splittings between optical modes and the ISBT observable. It is necessary that the FWHM of the electronic transition be equal to or smaller than that of optical modes and smaller than the coupling energy. Choosing a geometry where we observe a splitting between optical modes, the latter condition will be satisfied if the former one is. We thus have to satisfy the condition that the electronic FWHM is smaller than the cavity mode width. A mirror reflectivity of 0.9 gives a finesse of 30 and a $Q$ factor of 130. The cavity mode width thus equals $\lambda/130 = 0.042 \, \mu m$ or $1.7 \, meV$. As a result, a Rabi splitting involving the ISBT and the cavity mode should be observed if one could reduce the FWHM of the ISBT to $1.7 \, meV$. This implies a long coherence time, longer than what has ever been observed for ISBT in quantum wells. At present, it seems unrealistic that an ISBT Rabi splitting could be observed in the grated microcavity. For the simulation, let us suppose that a FWHM as small as $1 \, meV$ can be reached. We calculated the absorption in the cavity described above. We increased the doping to $2 \times 10^{10} \, cm^{-2}$ The grating parameters are $d = 1.865 \, \mu m$, $c/d = 0.5$ and $h = 0.1 \, \mu m$. Three CaF$_2$/ZnSe periods are used. The cavity length varies from 2.61 to 2.70 $\mu m$. We present the result in Figure 6. As the cavity length increases, the cavity mode resonance wavelength increases from 5.4 to 5.55 $\mu m$. The grating mode is around $\lambda = 5.45 \, \mu m$, almost independent of the cavity length, while the ISBT peaks at $\lambda = 5.50 \, \mu m$. When $L$ increases, we first observe an anticrossing of the grating and cavity modes that occurs for $L \approx 2.65 \, \mu m$. Then, we observe the splitting between the cavity mode and the ISBT for $L \approx 2.68 \, \mu m$. This one is a Rabi splitting. In other words, for these cavity parameters, one would observe an oscillatory energy transfer from the quantum wells to the cavity mode. This transfer is not direct as it implies the transfer *via* the grating mode. In order to confirm the nature of the splitting observed for $L$ around 2.68 $\mu m$, we studied its dependence on the well doping. We observed that the splitting increases as the square root of the doping, as expected for a Rabi splitting.
Conclusion

The use of grated microcavities for ISBT had been proposed previously [12]. In this paper, we have discussed specific features associated with the coupling between cavity, grating and electronic modes. We have calculated splittings between optical modes that should be observable experimentally. We have verified the criteria for the strong coupling regime where the mode anticrossing appears. In this anticrossing region, quantum wells will absorb or emit photons that are bouncing back and forth from the cavity to the grating mode. In the case of emission for instance, the spontaneous emission lifetime can be reduced. However, it still remains in the regime of a damped oscillator. On the other hand, for ideal unrealistic ISBT parameters, we also calculated a splitting between the ISBT and the cavity modes. In this case, the ISBT considered as an oscillator is not in a damped regime anymore but energy should be transferred between the wells and the cavity at the Rabi frequency. With the present day values of ISBT coherence time, this cannot be experimentally observed.

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References


[15] The field intensity or the electric field per photon in the cavity, described by the *Q* factor, increases with the index contrast in two ways. First, the mirror reflection coefficient increases. Second, the photon penetration length in the mirrors decreases. As the finesse is defined by the local free spectral range, it increases due to the first factor only, so that we can keep using the Zhu criterion.