Bragg suppression for optical absorption in multi-quantum well structures

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Direct calculations of absorption spectra for multi-quantum well structures by extracting field distributions at well positions are performed. Results demonstrate the previously reported Bragg suppression, and agree exactly with the indirect calculation by linear dispersion theory. This reveals that Bragg suppression effect in fact originates from the remarkably decreased intensities at well positions by Bragg interference condition, rather than from the formation of supperradiant modes.

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The collective effects on dispersive properties of periodic multiple quantum well (MQW) structures are widely investigated[1−11]. In the linear regime, it brings two results significantly different from a single quantum well, remarkable radiant broadening and dramatic absorptive suppression for exact Bragg arrangements[4,5]. The broadened exciton linewidth used to be thought as proportional to the well number. And the dramatic Bragg suppression for absorption was thought to be resulted from the remarkably shortened radiant decay by the Bragg-induced superradiant modes[5]. Thus, just as the authors themselves mentioned in Ref. [5], such an interpretation based on the superradiance model inevitably reached an important deduction that a QW is nonabsorptive before its dephasing. However, recent work[12] pointed out that the discussion of quantum well structures with a large number of wells is more appropriate in terms of normal modes of infinite periodic structures rather than in terms of super- or sub-radiant modes. In fact, when the layer number N is extremely large, the expression derived from the superradiance model for polariton linewidth, $\gamma + N\Gamma_0$, results in a much broader width than the real one.

In this work, we focus on analyzing the real physical origin of the absorptive Bragg suppression. Surprisingly, exactly based on the being challenged traditional viewpoint of QW's intrinsic excitonic absorption by Ref. [5], our direct calculations of the absorption spectra with the knowledge of stable field distributions at well positions can also result dramatic Bragg suppressions. More importantly, the results agree well with the absorption spectra obtained by the usual indirect calculation $(A = 1 - T - R)$[1,4], which justifies the validity of our processes and reveals the physical origin of the Bragg suppression. Thus, besides its invalidity for the polariton broadening for large number MQW structures, the superradiance model also appears inappropriate for interpreting the Bragg suppression for absorption.

Restricting our discussion to the linear interaction between the resonant normal incident light and a perfect MQW structure with only its theoretical 1s-hh excitonic susceptibility taken into account, one can obtain the stable field distributions inside the structure by the transfer matrix technique[4]. Explicitly, the transfer matrix for a single period, containing a barrier and a QW, can be written as[1]

$$M_{\mathrm{QW}} = \begin{bmatrix} 1+Y & Ye^{-2iqn_b d} \\ -Ye^{2iqn_b d} & 1-Y \end{bmatrix}, \tag{1}$$

with $Y = i(q/2\varepsilon_0 n)\chi(\omega)$, which accounts for a QW's response. And the period width d is the crucial parameter to which the results in the next part are extremely sensitive. The transfer matrix for a system of MQW is directly derived by successively multiplying those of the single QWs', which includes the effect of layer number N on the following numerical results.

According to Ref. [1], the electric field between the n-th and $(n+1)$-th wells can be expressed as

$$E(\omega, z) = L_n^+(\omega)e^{iqn_b z} + L_n^-(\omega)e^{-iqn_b z} \tag{2}$$

$$= [L_n^+(\omega) - L_n^-(\omega)]e^{iqn_b z} + 2L_n^-(\omega)\cos(qn_b z), \tag{3}$$

where L_n^+ and L_n^- are complex amplitudes of the forward- and backward-propagating waves to the left side of the n-th quantum well, respectively. Here a "standing" and a moving wave components are obviously shown by Eq. (3), whose intensities are related to $|2L_n^-|^2$ and $|L_n^+ - L_n^-|^2$, respectively. Whereas all the L_n^+ and L_n^- for different n can be readily obtained once the complex reflective or transmissive coefficient for the total structure is known. Thus, according to the traditional definition for QW's intrinsic absorption

$$\Delta I(\omega) = I_0(\omega)[1 - e^{-\alpha(\omega)l}]. \tag{4}$$

We can directly obtain the absorptive spectra by assuming that the barriers are transparent for any frequency. Here $I_0(\omega) \propto |E_n(\omega)|^2$, and the absorptive coefficient relates to the complex dielectric constant $\varepsilon(\omega)$.

$$\varepsilon(\omega) = \varepsilon_r(\omega) + i\varepsilon_i(\omega), \tag{5}$$

$$n(\omega) = \sqrt{\frac{1}{2}\varepsilon_r(\omega) + \frac{1}{2}\sqrt{\varepsilon_r^2(\omega) + \varepsilon_i^2(\omega)}}, \tag{6}$$

$$\alpha(\omega) = \frac{\omega}{n(\omega)c}\varepsilon_i(\omega). \tag{7}$$

Note that obtaining absorption by this direct method radically differs from the usual used indirect one, where the absorption spectrum is acquired by transfer matrix technique according to $A(\omega) = 1 - |r(\omega)|^2 - |t(\omega)|^2$. The results should agree with each other, if our method is justified. From the following calculations, they are found to really coincide well with each other. Thus, the superradiance model should be carefully checked. In fact, if absorption really occurs only after dephasing, then theoretical zero-absorption will be expected as long as an enough large layer's number is provided so that the exciting pulse leaves the structure much earlier than any dephasing occurs. However, as well known[11], such a case will never occur if only the nonradiative broadening $\gamma \neq 0$. Thus, the authors in Ref. [5] may be based on an unsubstantial point that the absorbed frequencies have the same amplitudes at any position of the structure and under any periodic conditions so that the only left possible account is limited within the temporal domain. Then, to explain the Bragg suppression, quite a few previous opinions have to be violated such as the QW's intrinsic absorption and the disappearing of superradiant modes for high exciting powers or high temperature. On the contrary, the model described in this work is logical and substantial for interpreting the Bragg suppression. Under this model, the stability of the suppression at high excitation powers or at high temperatures in Ref. [5] is readily explained. For higher powers, if only within the linear regime, the ratios of field distributions at Bragg to off-Bragg arrangements keep constant respecting to lower power conditions. Whereas for high temperatures, which increase the inhomogeneous broadening, hence broaden the absorption spectrum of a single quantum well, we can see that the effects of broadening are the same on both conditions of exact- and near-Bragg and do not change the field distributions. So, on both conditions, the relative suppression under Bragg period to near-Bragg certainly still holds.

For all results in this paper, the excitonic radiative and nonradiative homogeneous broadenings are set as $\Gamma_0 = 26$ μeV and $\gamma = 320$ μeV, respectively, for the theoretical linear 1s-hh excitonic susceptibility[1] $\chi_{1s} = -g\frac{|d_{cv}|^2}{\hbar\omega - E_{1s} + i\gamma} = -\frac{2\varepsilon_0 n\Gamma_0/q}{\hbar\omega - E_{1s} + i\gamma}$, which determines the QW's response.

In Fig. 1, we plot the internal field distributions for a 30-layer MQW structure. For Bragg arrangement (dotted line), energy is distributed mostly in the barrier layers and almost vanishes at well positions. While for off-Bragg, the total internal energy of the resonant frequency reduces remarkably, but the energies at wells increase significantly, especially for the first few wells.

Figure 2 shows field intensities of the resonant frequency at well positions. Comparing of 30- with 100-layer structures, we find that for Bragg arrangement, the intensities are smaller for larger well numbers. This is also resulted from the interference effect, i.e., larger well numbers induce more times of reflections so that L_n^- increases closer to L_n^+, hence the moving wave component becomes less important according to Eq. (3). Thus, for perfect MQW's samples, the suppression effect will be more significant for longer structures, which agrees well with the experimental results in Ref. [5]. When periods deviate from Bragg, both structures drastically increase their field intensities at the front wells, but the intensities exponentially decrease along the propagating path. However, the integrated intensities are obviously much larger than those under Bragg conditions.

Figure 3 illustrates the spectra of the sum of fields at all wells for different arrangements. This process is justified because according to Eq. (4), the absorption is proportional to $\sum_n |E_n(\omega)|^2$. Firstly, Fig. 3 indicates that the intensities for those frequencies far away from ω_0 are almost

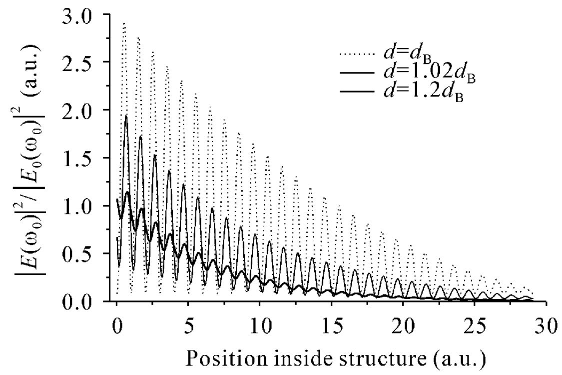

Fig. 1. Stable field distributions of the resonant frequency in a 30-layer structure for different arrangements.

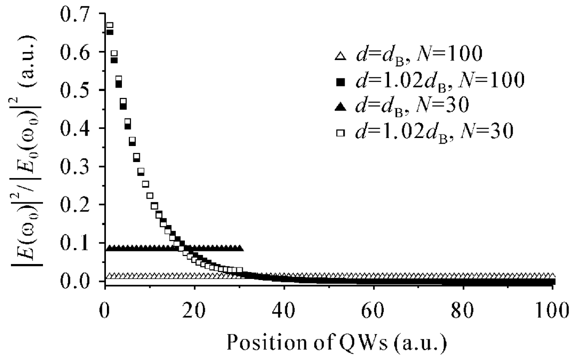

Fig. 2. The resonant frequency's field distributions only at the well positions under different periods for 30- and 100-layer MQW structure, respectively.

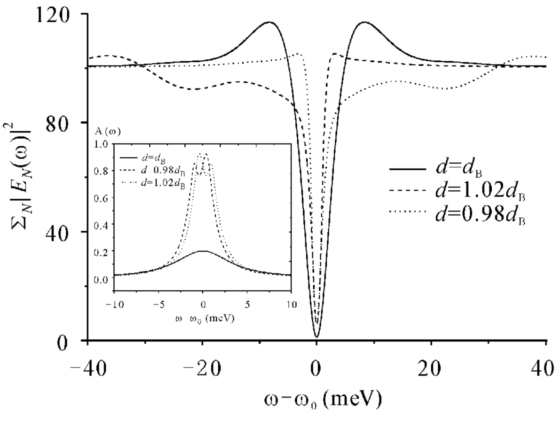

Fig. 3. Sums of intensities at each wells normalized to the incident intensity as a function of frequency under different periods for a 100-layer structure. Insert shows the suppression of absorption for Bragg arrangement compared to periods $d = 0.98$, $1.02d_B$ for a 100-layer MQW structure.

unitary within the structure, whenever the period is at or away from Bragg arrangement. According to Eq. (3), this indicates that $L_n^-(\omega) \approx 0$ and $L_n^+(\omega) \approx 1$ for these frequencies, resulting that light penetrates the structure without any absorption or reflection. The vanished absorption is due to absorption coefficients vanish for these frequencies, whereas the zero reflections are resulted from the fact that the refractive index of the structure become unitary for these frequencies, hence, the structure equals to a bulk semiconductor. Then, we can also see that the sums for the absorbed frequencies are much smaller than those within the transparent region for any periodic condition, which indicates that a MQW structure is in fact such a design that the wells are located close to the nodes of the standing waves of the absorbed frequencies. That is the reason that the resonant excitation can penetrate or be reflected by a MQW structure without significant absorptions, while fails for a same structure but without any barriers. More importantly, Fig. 3 shows another significant result that all the sums of frequencies within the absorption regime (a Lorentz spectral range centered at ω_0 and with a broadening of γ) under Bragg arrangement are much smaller than those under the other two near-Bragg arrangements, which in fact indicates the real physical origin of the Bragg suppression. The inserted plot is obtained from Fig. 3 by directly multiplying the term $[1 - e^{-\alpha(\omega)l}]$ corresponding to Eq. (4). The resulted absorptive spectra exactly agree with those from the indirect calculation, $A(\omega) = 1 - R(\omega) - T(\omega)$. Significant Bragg suppression for absorption compared with periods of $d = 0.98, 1.02d_{\rm B}$ is very obvious. This indicates that the true physical origin of the Bragg suppression is from the significantly changed field distributions by Bragg interference condition. Finally, note that the expression for absorptive coefficient $\alpha(\omega)$ in Eq. (4) is only for a single quantum well in our calculations. However, the calculated spectra are obviously broadened (about 7.22 meV) compared to the single well spectrum (0.32 meV). This means that the only included physical event, interference effect, naturally results in the broadening.

In conclusion, we directly calculate the absorptive spectra of the MQWs structures with the knowledge of field distributions inside the structures and the single QW's intrinsic absorption coefficient. Results demonstrate a dramatic Bragg suppression for absorption and coincide exactly with those by the indirect process in the linear dispersion theory and also agree well with the experimental reports. The corresponding spectral broadening in absorption with respect to the linear dispersion theory is also consistently obtained. This indicates that the Bragg suppression in fact originates from the interplay of the Bragg interference condition with the single QW's intrinsic Lorentz absorption spectrum.

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