One-dimensional photonic crystals based on periodic quantum well structures

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Periodic multiple quantum well (MQW) structures represent an example of resonance one-dimensional photonic crystals. Optical properties of MQW's depend upon interplay between interaction of electromagnetic waves with periodic modulations of the refraction index along the structure and coherent radiative coupling between quantum well excitons. This circumstance distinguishes MQW's from regular photonic crystals, whose properties are determined solely by a modulation of the refraction index as well as from optical lattices, in which radiative coupling is the only mechanism affecting their optical spectra. Optically active photonic crystals attract a great deal of attention because the presence of resonant excitations such as excitons allows for tuning dispersion properties of these structures. The effect of radiative coupling is most prominent in the so-called Bragg structures, when the period of the structure, d, is in resonance with exciton resonant wavelength, λ_{ex}, $d = dB = \lambda_{ex}/2$. The dispersion of electromagnetic waves in this case is characterized by a wide band gap, Δ_Γ in the vicinity of the exciton frequency $\Omega_{ex} : \Delta_\Gamma \propto \sqrt{\Gamma\Omega_{ex}}$, where Γ is the light-exciton coupling constant. The width of this band gap is by a factor of $\sqrt{\Omega_{ex}/\Gamma}$ larger than band gaps for non-Bragg structures. In most of the previous studies of MQW's the effects of the contrast between indexes of refraction of well and barrier layers were neglected and MQW's were treated as pure optical lattices [1-3]. While some aspects of the role of the contrast were discussed in Ref. 4, a complete description of band structure of MQW's with the refraction index contrast has not yet been obtained. To elucidate effects of the interplay between radiative coupling and periodic modulation of the refraction index is one of the objectives of this paper. In particular, we find that under the standard Bragg condition the spectrum of the structure consists of two band gaps separated by a narrow propagating window, which is a structure typical for off-Bragg structures in optical lattices [3]. However, the propagating window closes and two band gaps form a single gap, when a condition $K(\Omega_{ex})d = \pi$ is fulfilled. Here $K(\Omega_{ex})$ is the Bloch wave number of excitations of the photonic structure with modulated indexes of refraction at the frequency of the exciton resonance. Thus, this equation is a natural generalization of the Bragg condition for the structures with the contrast; it coincides with the result obtained earlier in Ref. 4. Under this condition the width of the polariton band gap can be presented in the following form: $\Delta \approx \sqrt{\Delta_\Gamma^2 + \Delta_c^2}$,where Δ_c is the width of the band gap in a standard non-resonant photonic crystal with the same contrast of the refraction index as in our MQW structure. In this work we also consider the properties of the band gaps in the periodic MQW structure with two wells in a unit supercell. We show that the dispersion equation of normal electromagnetic modes in such a structure can be presented in a simple and elegant form

$$\cos^2(Kd/2)=\prod_{i=1}^{2}\left[\cos(kd/2)+\frac{\Gamma_i\sin(kd/2)}{\omega-\Omega_{ex_i}+i\gamma_i}\right]-\sin^2(k\delta/2)\prod_{i=1}^{2}\frac{\Gamma_i}{\omega-\Omega_{ex_i}+i\gamma_i}, \qquad (1)$$

where d is the period of the structure, $\delta=d-2d_1$, d_1 is a distance between wells of different kind within the same supercell, and γ_i takes into account non-radiative decay of excitons of i-th well. Band structure described by equation (1) depends upon the composition of the elementary cell. If, for instance, two wells forming a cell are identical, then for the structure with $d=2d_B$, the spectrum in the vicinity of Ω_{ex} consists of three band gaps, one of which is narrow and proportional to Γ, while two others are bounded by the lines $\omega-\omega_0=\pm\Delta\sin(\pi d_1/d)$ and $\omega-\omega_0=\pm\Delta\cos(\pi d_1/d)$. The results of our work show that MQW based photonic crystals provide great opportunities for devising structures with pre-determined optical properties.

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