Superlattices and Microstructures 120 (2018) 642–649

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Effects of elastic strain and structural defects on slow light modes in a one-dimensional array of microcavities

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ARTICLE INFO

Keywords:
Microcavity
Quantum dot
Polariton
Photonic crystal

ABSTRACT

We calculate the dispersion of exciton-polariton modes in one-dimensional arrays of microcavities. We consider a two-sublattice array and a one-sublattice array of unevenly spaced spherical microcavities some of which contain embedded quantum dots. In both cases the dispersion of polariton eigen modes is shown to be efficiently controlled by a weak applied uniform strain. The structures we consider sustain slow-light modes that are of a specific importance for quantum optics applications. The high sensitivity of the optical response of microcavity arrays to the applied strain may be used in classical and quantum optical switches and the polariton based integrated photonics.

1. Introduction

The design of sources of coherent radiation based on new structures and materials is an extensive interdisciplinary research area that combines the laser physics, condensed matter physics, nanotechnology, chemistry, and information science. One of the important challenges in this field is controlling the propagation of light in resulting composite structures by subjecting them to various kinds of external actions such as e.g. elastic strains [1]. From this point of view, photonic superstructures based on optical microcavities with embedded non-linear elements (e.g. semiconductor quantum dots) represent one of the most promising systems for integration in future optical circuits [2,3]. Arrays of coupled optical cavities as well as periodic arrays of coupled exciton/cavities have been considered in Refs. [4,5].

In this context, a rapidly developing research sub-area is the photonics of imperfect structures. Some of our previous works have been devoted to the design of multi-microcavity structures [6] where the dispersion of photon modes may be altered by introduction of a defect in the photonic supercrystal [7,8]. For applications, the structural defects in supercrystals are less practical than temporary defects introduced by application of external fields or strain.

In the present work we consider the effect of a uniform elastic strain (which is assumed to be much weaker than any breaking deformation) on one-dimensional arrays of microcavities with embedded quantum dots. This system combines advantages of an extreme optical non-linearity provided by the coupling of quantum dots to photonic modes and the high sensitivity of the optical eigen-modes to the applied strain. We focus on two particular realizations of a topologically ordered microcavity system composed by

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https://doi.org/10.1016/j.spmi.2018.06.043
Received 7 May 2018; Received in revised form 21 June 2018; Accepted 21 June 2018
Available online 21 June 2018
0749-6036/

tunnel-coupled optical microcavities: a two-sublattice array and a one-sublattice array of unevenly spaced spherical microcavities. We show that both systems have a high potentiality for applications in optical integrated circuits.

2. Theoretical background

Basing on the approach developed in Refs. [7–10], let us first consider the dispersion of optical eigen modes in the most general case of a microcavity supercrystal composed of s sublattices. Each of the tunnel-coupled microcavities is assumed to confine a single optical mode. In the considered cases of elastic deformations in chains of microcavities with embedded quantum dots and otherwise, Hamiltonian $\hat{H}(\hat{\varepsilon})$ depends on the deformation tensor $\hat{\varepsilon}$, which is a function of the applied strain. Under the assumption that the density of excited states of structural elements in the resonator and atomic subsystems is a small quantity, the quadratic part $\hat{H}^{ex}(\hat{\varepsilon})$ (responsible for the elementary excitations) of Hamiltonian $\hat{H}(\hat{\varepsilon})$ within the Heitler-London approximation and a one-level model can be written as (see e.g. Ref. [11]):

$$\hat{H}^{ex}(\hat{\varepsilon}) = \sum_{\mathbf{n},\mathbf{m},\alpha,\beta,\lambda,\sigma} D^{\lambda\sigma}_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon})\hat{\Phi}^{+}_{\mathbf{n}\alpha\lambda}\hat{\Phi}_{\mathbf{m}\beta\sigma} = \sum_{\alpha,\beta,\lambda,\sigma,\mathbf{k}} D^{\lambda\sigma}_{\alpha\beta}(\mathbf{k},\hat{\varepsilon})\hat{\Phi}^{+}_{\alpha\lambda}(\mathbf{k})\hat{\Phi}_{\beta\sigma}(\mathbf{k}), \tag{1}$$

where

$$D^{11}_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon}) = \hbar\omega^{at}_{\mathbf{n}\alpha}\delta_{\mathbf{n}\alpha,\mathbf{m}\beta} + V_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon}),\quad D^{22}_{\mathbf{n}\alpha,\mathbf{m}\beta} = \hbar\omega^{ph}_{\mathbf{n}\alpha}\delta_{\mathbf{n}\alpha,\mathbf{m}\beta} - A_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon}),\quad D^{12}_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon}) = D^{21}_{\mathbf{n}\alpha,\mathbf{m}\beta}(\hat{\varepsilon}) = g_{\mathbf{n}\alpha}(\hat{\varepsilon})\delta_{\mathbf{n}\alpha,\mathbf{m}\beta},\quad \hat{\Phi}^{\lambda=2}_{\mathbf{n}\alpha} = \hat{\Psi}_{\mathbf{n}\alpha},\quad \hat{\Phi}^{\lambda=1}_{\mathbf{n}\alpha} = \hat{B}_{\mathbf{n}\alpha}. \tag{2}$$

In Eqs. (1) and (2) $\omega^{ph}_{\mathbf{n}\alpha}$ is the frequency of the photonic mode localized in the $\mathbf{n}\alpha$-th lattice site (microcavity), $\hat{\Psi}^{+}_{\mathbf{n}\alpha}$, $\hat{\Psi}_{\mathbf{n}\alpha}$ are bosonic creation and annihilation operators for this mode written in the node representation, $\hbar\omega^{at}_{\mathbf{n}\alpha}$ is excitation energy of the quantum dot in the $\mathbf{n}\alpha$-th lattice site, $\hat{B}_{\mathbf{n}\alpha}$, $\hat{B}^{+}_{\mathbf{n}\alpha}$ are bosonic creation and annihilation operators of quantum dot excitons, $A_{\mathbf{n}\alpha\mathbf{m}\beta}(\hat{\varepsilon})$ is the matrix of resonance interaction, which describes an overlap between optical fields of resonators in the $\mathbf{n}\alpha$-th and $\mathbf{m}\beta$-th lattice sites and hence defines the jump probability of the corresponding electromagnetic excitation, $V_{\mathbf{n}\alpha\mathbf{m}\beta}(\hat{\varepsilon})$ is the matrix of resonance interaction between quantum dots embedded in the $\mathbf{n}\alpha$-th and $\mathbf{m}\beta$-th lattice sites, $g_{\mathbf{n}\alpha}(\hat{\varepsilon})$ is the matrix of resonance interaction between quantum dot in the $\mathbf{n}\alpha$-th lattice site and electromagnetic field localized at the same site. Values 1 and 2 of indices λ, σ indicate, respectively, the presence or absence of quantum dots in corresponding cavities.

In the right-hand side expression of Eq. (1) (summation over $\mathbf{k}$) matrices $D^{\lambda\sigma}_{\alpha\beta}(\mathbf{k},\hat{\varepsilon})$ and $\Phi_{\alpha\lambda}(\mathbf{k})$ have the forms $D^{\lambda\sigma}_{\alpha\beta}(\mathbf{k},\hat{\varepsilon}) = \sum_{\mathbf{m}} D^{\lambda\sigma}_{\mathbf{n}\alpha\mathbf{m}\beta}(\hat{\varepsilon})\exp[i\mathbf{k}\cdot(\mathbf{r}_{\mathbf{n}\alpha} - \mathbf{r}_{\mathbf{m}\beta})]$ and $\hat{\Phi}_{\alpha\lambda}(\mathbf{k}) = \frac{1}{\sqrt{N}}\sum_{\mathbf{n}}\hat{\Phi}_{\mathbf{n}\alpha\lambda}\exp(-i\mathbf{k}\cdot\mathbf{r}_{\mathbf{n}\alpha})$ ($N$is the number of elementary cells in the lattice). Such representation of matrices is possible due to preservation of the translation invariance of the system under the uniform strain. Let us note that the wave vector $\mathbf{k}$, which characterizes eigenstates of electromagnetic excitations, ranges within the first supercrystal Brillouin zone, whose boundaries are in their turn functions of strain through the dielectric tensor $\hat{\varepsilon}$.

Eigenvalues of the Hamiltonian (1) are found by its diagonalization through the Bogolyubov-Tyablikov transformation [11]. This yields the following equation for elementary excitation spectrum $\Omega(\mathbf{k},\hat{\varepsilon})$:

$$\det\|D^{\lambda\sigma}_{\alpha\beta}(\mathbf{k},\hat{\varepsilon}) - \hbar\Omega(\mathbf{k},\hat{\varepsilon})\delta_{\alpha\beta}\delta_{\lambda\sigma}\| = 0 \tag{3}$$

On the basis of this equation below we investigate in detail the spectrum of exciton-polariton modes in a two-sublattice chain of microcavities and in a one-sublattice chain of unevenly spaced cavities with embedded quantum dots.

3. Results and discussion

3.1. Exciton-like excitations in a one-dimensional two-sublattice microcavity array under a uniform elastic strain

Let us consider a one-dimensional microcavity chain subjected to the elastic strain (extension or compression) directed along the chain. Under a uniform strain described by the dielectric tensor $\hat{\varepsilon}$ each cavity changes its position so that the lattice constant $d(\varepsilon)$ varies as:

$$d(\varepsilon) = (1+\varepsilon)d_0, \tag{4}$$

where d_0 is the lattice constant of a strain-free structure, and ε is the corresponding component of tensor $\hat{\varepsilon}$. The reciprocal lattice constant $b(\varepsilon)$ can be obtained from the simple relation:

$$b(\varepsilon)\cdot d(\varepsilon) = 2\pi, \tag{5}$$

In what follows we shall assume that the microcavity array is constituted by two sublattices. Positions of microcavities are defined by the equality $r_{n\alpha}(\varepsilon) = r_n(\varepsilon) + r_\alpha(\varepsilon)$. For example, the positions in the zeroth cell of the first and second sublattices ($r_{n=0} = 0$) are given by: $r_{01} = 0$ and $r_{02}(\varepsilon) = a(\varepsilon)$, respectively. The spectrum of exciton-like excitations $\Omega(k,\varepsilon)$ is found from the relation (3) as:

$$\begin{Vmatrix} \hbar\Omega(k,\varepsilon) - \hbar\omega^{ph}_1(\varepsilon) & A_{12}(k,\varepsilon) \\ A_{21}(k,\varepsilon) & \hbar\Omega(k,\varepsilon) - \hbar\omega^{ph}_2(\varepsilon) \end{Vmatrix} = 0 \tag{6}$$

The quantities $A_{\alpha\beta}(k,\varepsilon)$ in Eq. (6) are the Fourier-transforms of matrix $A_{n\alpha m\beta}(\varepsilon)$ of resonance interaction: