

Optical Modes in Photonic Molecules

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Photonic molecules have been fabricated by coupling pairs of micrometer-sized semiconductor cavities via a narrow channel. The optical modes in these structures have been studied spectroscopically as a function of the coupling and the mode energies are compared to detailed calculations. These results provide a rich picture of photonic modes in these molecules. [S0031-9007(98)07060-4]

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The modification of electromagnetic modes in microcavities and their impact on optical properties have been of considerable interest in recent years both for their basic properties and for their potential in applications [1]. Over the years, extensive studies of these effects at microwave frequencies involving atoms in microcavities have been carried out. Recently, it has become possible to fabricate high quality solid state structures with sizes on the scale of the wavelength of light. These developments make it possible to modify the interaction between light and matter within a single solid state system [2–5], a feature which is of interest for applications such as semiconductor lasers where, e.g., low spontaneous emission is of importance. In addition, these structures make possible the study of confined photon properties such as that of the detailed work done on confined electron states in nanostructures.

Closely related to this work on microcavities is the extensive work on photonic band gap systems [6]. Here the dielectric properties are modulated periodically, and the electromagnetic modes can exhibit gaps such as those of electrons in solid state band structures [7–9]. When defects are introduced into such a system, photonic modes can appear in these gaps which are discrete in frequency and are localized in space [10].

Sharp, fully quantized photonic modes can also be observed in laterally patterned semiconductor microcavities [11,12]. In these cavities light is confined vertically within the cavity layer by highly reflecting mirrors, and it is confined laterally by the differences between the refractive indexes of the cavity and air. The fully confined optical modes in these photonic dots are the photon analogs of the electron states of atoms.

Here we report studies of the optical modes in molecule-like structures made from pairs of interacting photonic dots which are coupled by narrow channels. The con-

finer photon modes have been studied by photoluminescence spectroscopy as functions of the coupling which can be varied through the structure design. The coupling of the photon modes of the individual dots in the molecules results in an interaction dependent splitting of the modes. By using angle-resolved spectroscopy, detailed information about the internal electric field distributions of the photonic molecules is obtained. From these studies we find that the optical modes in photonic molecules exhibit strong similarities to those of electronic states of diatomic molecules.

In the present structures the resonator cavity for the photons has a size of approximately one light wavelength and was formed by a GaAs layer surrounded by highly reflecting GaAs/AlAs Bragg mirrors [13]. A 7 nm wide $\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$ quantum well, which acts as the optically active medium, was placed in the center of the GaAs cavity [14]. Photonic molecules were fabricated by lithographic patterning of this cavity [13]. The structures were etched through the top mirror and through the GaAs layer, and the bottom mirror remained essentially unetched. The molecules were formed by connecting two square photonic dots each with a lateral size of $3\ \mu\text{m}$ by a channel of variable length and width. Figure 1(a) shows a scanning electron micrograph of such a photonic molecule in which the dots are coupled by a channel with a width of $W = 1\ \mu\text{m}$ and a length $L = 1\ \mu\text{m}$. On top of the molecule the upper GaAs/AlAs mirror is seen followed by the GaAs λ -cavity. The lower mirror is unetched except for one or two layers.

For spectroscopic investigation the samples were held at $T = 5\ \text{K}$ in an optical cryostat. An argon-ion laser was used to excite carriers across the band gap of the $\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$ quantum well. The emission was dispersed by a double monochromator and detected by a photomultiplier. Angle-resolved studies of the far field emission

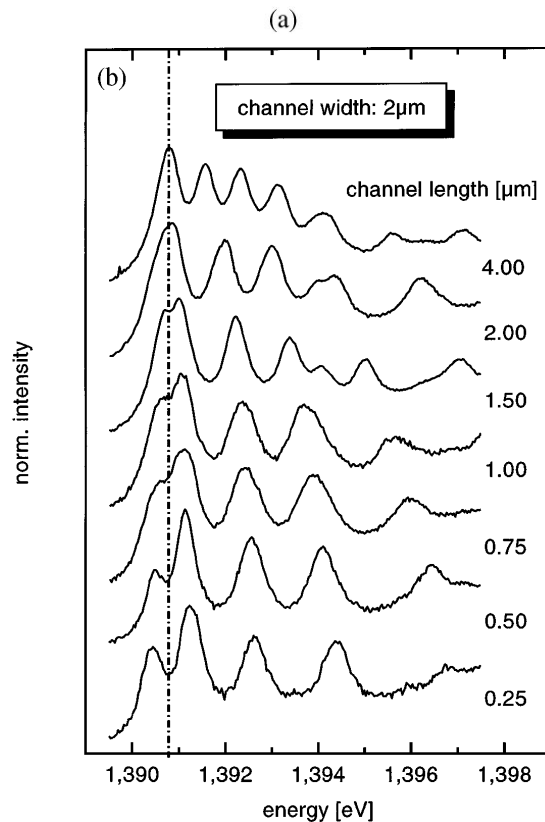
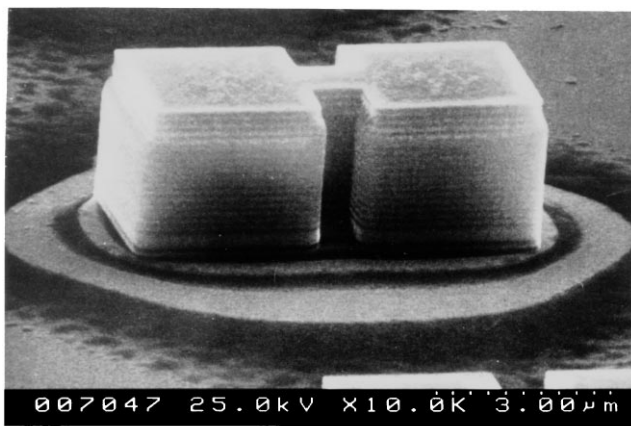


FIG. 1. (a) Scanning electron micrograph of a photonic molecule. (b) Photoluminescence spectra of photonic molecules with varying channel lengths L .

of the optical modes were performed by using an aperture providing an angle resolution of 1° for the detection.

Figure 1(b) shows photoluminescence spectra of photonic molecules with varying channel lengths but with a fixed channel width of $2 \mu\text{m}$. Each spectrum consists of several lines corresponding to different three-dimensionally confined electromagnetic modes inside the molecule. With decreasing channel length the energy splitting between the various photon modes increases, as expected from the stronger confinement in smaller molecules. Further, the ground mode splits into two emission lines. The splitting can be first resolved for a channel length of $L = 1.5 \mu\text{m}$, and it increases continuously, with decreasing L reaching about 1 meV for the smallest channel.

This splitting is analogous to that of the electron states in diatomic molecules such as H_2^+ , where the interaction of two atoms causes a splitting of the degenerate atomic levels into bonding and antibonding orbitals. In these electronic molecules the bonding strength is given by the Coulomb forces between the nuclei and the electrons. In contrast, the interaction of the photon modes in the photonic molecules is determined by the geometry of the molecules and thus can be varied by the structure design through, for example, the length or the width of the interconnecting channel.

We have used numerical calculation techniques [15] to study the confined photonic modes in these molecules. Figure 2 shows the calculated electric field distributions of the six lowest modes in the plane of a molecule with a channel length of $1 \mu\text{m}$ and a width of $2 \mu\text{m}$. The modes can be characterized by their parities P_x and P_y , either positive or negative, along the molecule axis and normal to it. Therefore the molecule modes can be labeled by n, P_x, P_y , where n is the principal number giving the order in energy of the optical modes in decoupled dots and P_x, P_y are the parities.

The electromagnetic field distributions in Fig. 2 are analogous to the bonding and antibonding orbitals in diatomic molecules, which are discussed in textbooks on quantum physics [16]. The $0++$ and the $0-+$ modes correspond to bonding and antibonding σ -orbitals formed from s -like atom states. The next two higher lying modes $1++$ and $1-+$ correspond to σ -like molecular orbitals formed from p -like atom modes oriented along the molecule axis. Finally, the $1+-$ and the $1--$ modes are analogous to π -like orbitals formed from p -modes, now oriented perpendicular to the molecule axis [17].

The energies of the emission from the optical modes are plotted against the channel width for a fixed channel length of $1 \mu\text{m}$ in Fig. 3(a). The limit of $W = 0$ corresponds to separated dots for which there are two optical modes in the energy range investigated. For

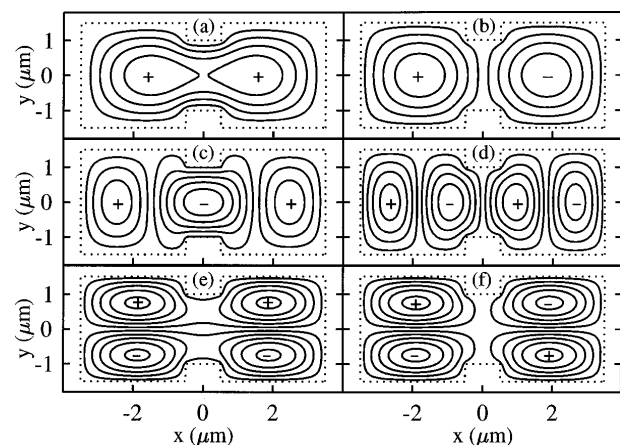


FIG. 2. Calculated electric field distributions of the six lowest confined optical modes in photonic molecules. The modes in each subfigure are (a) $0++$, (b) $0-+$, (c) $1++$, (d) $1-+$, (e) $1+-$, and (f) $1--$.

nonzero widths these modes split. The lowest lying mode of the isolated dots splits into the bonding and antibonding combinations $0++$ and $0-+$. The next higher dot mode splits into four modes as expected from its double degeneracy, where $1++$ and $1-+$ correspond to σ -like bonding in the electronic case and $1+-$ and $1--$ to π -like bonding. The first two of these four modes exhibit greater dispersion with channel width than do the other two, a behavior which we attribute to their having larger amplitude in the channel region than the other modes. The calculated mode energies (solid lines) are in good agreement with the experimental data.

In Fig. 3(b) the emission energies are shown versus channel length for a fixed channel width of $2 \mu\text{m}$. For channel length $L \rightarrow 0$ the photon modes approach those in photonic dots with a size $3 \mu\text{m} \times 6 \mu\text{m}$, which have a lower symmetry than those in the square dots. Modes such as $1-+$, $2++$ originate from photonic dot modes which are excited along the molecule axis. They have substantial weight in the channels and show greater dispersion with channel length. For large L these modes become similar to those of photonic wires in which the photons have free dispersion along the wire. Modes such as $1+-$ and $1--$ originate from excited dot modes normal to the molecule axis. They have less weight in the channels and are less affected by channel length.

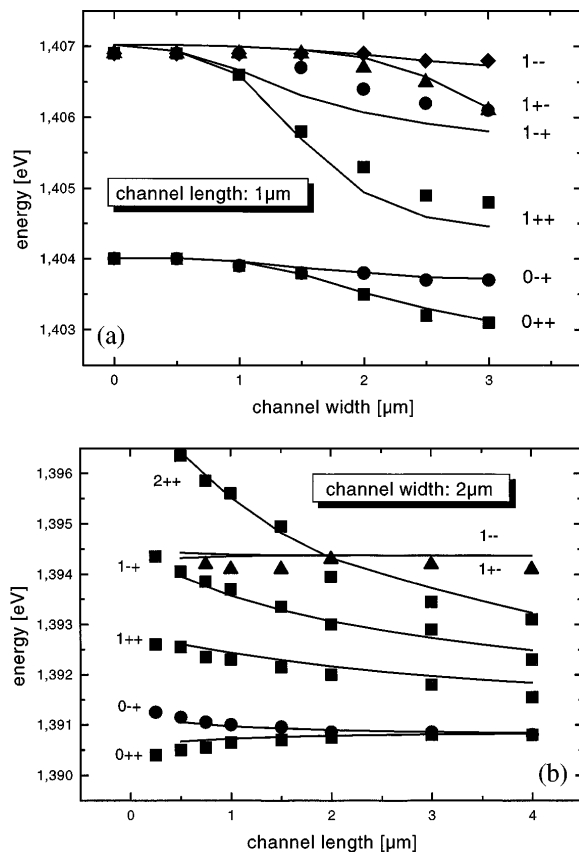


FIG. 3. Energies of the optical modes in photonic molecules plotted against channel width W for $L = 1 \mu\text{m}$ (a) and against channel length L for $W = 2 \mu\text{m}$ (b).

Additional insight into the electromagnetic field distributions in the photonic molecules can be obtained from angle-resolved photoluminescence because each field distribution in the molecule plane causes a characteristic directional dependence of the emission. In these experiments the emission is detected within a small solid angle relative to the normal of the molecule. Figure 4(a) shows the angle dependence of the luminescence spectra of photonic molecules with a channel length of $0.25 \mu\text{m}$ and a channel width of $1.5 \mu\text{m}$. The angle of detection ϑ was varied in the plane defined by the molecule axis and the normal to the molecule. The $0++$ emission intensity is maximum at $\vartheta = 0$ and then drops continuously to zero at about $\vartheta = 10^\circ$. In contrast, the $0-+$ mode is not observed at $\vartheta = 0$. For larger angles its emission intensity increases, has a maximum for $\vartheta = 7^\circ$, and then drops again to zero. The angle variation of the emission intensities of the excited modes $1++$ and $1+-$ with ϑ is stronger than for the ground modes reflecting the higher complexity of their field distributions in the cavity plane in Fig. 2. The $1++$ mode shows weak emission for $\vartheta = 0$. With increasing ϑ its intensity then drops to zero, increases again, has a maximum for $\vartheta = 11^\circ$, and finally drops again to zero. The emission intensity of the $1-+$ mode is zero for $\vartheta = 0$, has a first small peak for ϑ about 3° , drops almost to zero for $\vartheta \approx 7^\circ$, and then becomes maximum at about $\vartheta = 14^\circ$ [18].

The data from angle-resolved spectroscopy provide information on the internal electric field distribution in the molecules. Figure 4(b) shows measured (symbols) and calculated (lines) emission intensities for the two split ground photon modes versus ϑ . The far-field emission intensity I as a function of ϑ is calculated from the in-plane field $e(x, y)$ by a Fourier transform [19]. For the directions of detection used here, it is given by

$$I(\vartheta, \varphi) = \left| \int e(x, y) \exp\left(i \frac{E}{\hbar c} \sin \vartheta x\right) dx dy \right|^2, \quad (1)$$

where E is the mode energy. As shown in Fig. 4(b), experiment and theory are in good agreement. Thus angle-resolved studies furnish a quantitative description of the modes and confirm directly that coherent photon modes are formed in the coupled structures with moleculelike field distributions.

Very recently, coupled electronic quantum dots have also attracted interest both in transport [20] and in optical studies [21]. In these systems, unlike the present photonic structures, a quantitative description of the confined levels is often complicated by many particle effects from electron-electron interaction or by uncertainties in the confinement potential. In addition, there is no direct experimental access to the confined carrier wave functions as there is from angle-resolved studies in the photonic case.

In summary, we have investigated the optical modes in photonic molecules fabricated by connecting two photonic dots. These structures can be considered as prototypes for more complex systems formed from interacting

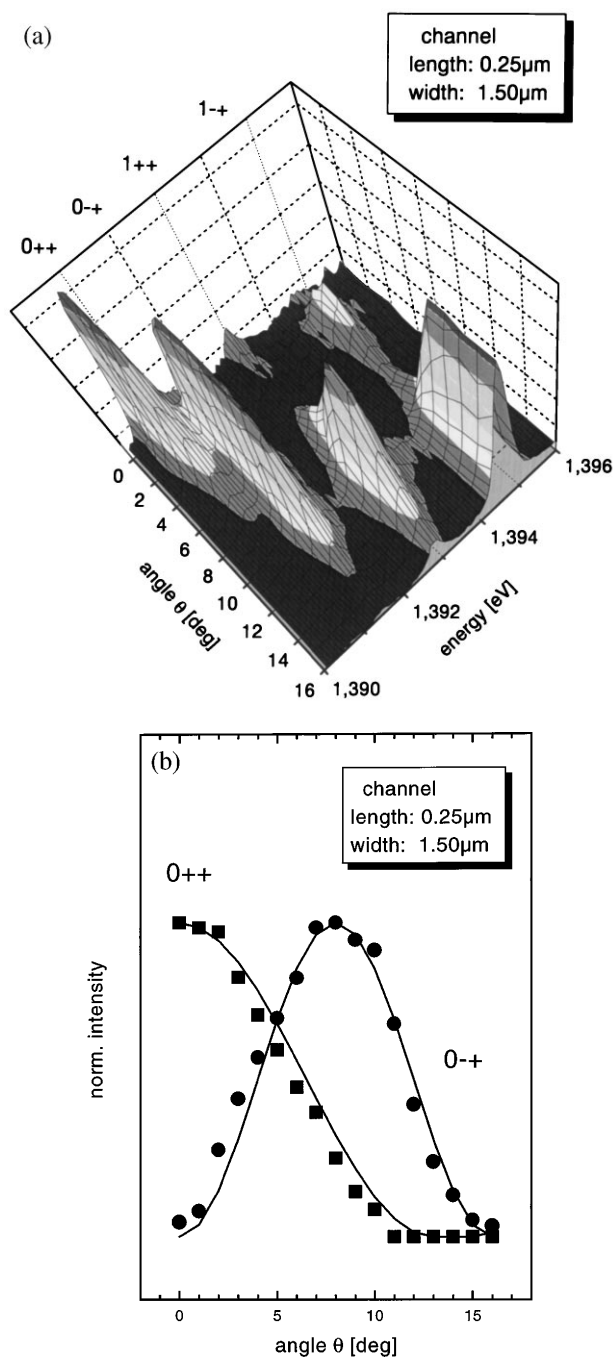


FIG. 4. (a) Three-dimensional plot of angle-resolved spectra of photonic molecules versus detection angle and energy. (b) Measured and calculated emission intensities for the two ground photon modes $0++$ and $0-+$ versus ϑ .

dots. By combining larger numbers of dots, photonic molecules with complicated geometries (e.g., triangles, squares, etc.) could be obtained. Photonic crystals can be fabricated by connecting photonic dots in periodic arrays. Suitably designed molecule structures might also be used to modify the optical selection rules by the cavity geometry [6].

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