Isomeric photonic molecules formed from coupled microresonators

G. Guttroff, M. Bayer, and A. Forchel
Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

P. A. Knipp
Christopher Newport University, Newport News, Virginia 23606

T. L. Reinecke
Naval Research Laboratory, Washington, DC 20375

Isomeric photonic molecules were formed by connecting four identical cavities in different geometries: a chain, a square, and a T shape. The optical mode spectrum in these structures exhibits three-dimensionally confined photonic states, which have been studied by photoluminescence spectroscopy. The energies of the optical modes depend strongly on the molecule geometry. The experimental data are in good agreement with detailed calculations of the fields in the cavities.

During the last few years microresonators with three-dimensional confinement of light have attracted considerable attention [1,2]. The density of the optical modes in these structures is dominated by sharp, discrete resonances. It has been shown that a pair of such resonators can be coupled to a ''photonic molecule,'' showing, for example, a splitting of the resonator ground photon mode into symmetric and antisymmetric modes [3]. This splitting is in close analogy to the bonding and antibonding electronic orbitals in diatomic molecules. It has been pointed out that these cavities may be also used as building blocks for constructing molecules of higher complexity or photonic crystals [4–6]. In particular, the process of coupling artificial photonic atoms to form molecules is extended here to cases which do not have a direct electronic analogy in nature, for example involving different symmetries.

These structures therefore might be considered realizations of systems of coupled oscillators, for which the coupling strength between them can be tailored through the resonator geometry. Many different interacting systems in nature can be described by a picture of coupled oscillators. Examples are atoms in a resonator interacting strongly with a confined light field, which leads to the normal mode splitting known as vacuum Rabi splitting. In solid state systems, examples are polaritons resulting from strong exciton-photon or phonon-photon interactions, or magnetic excitations resulting from spin-spin interactions. Restricting oneself to coupling between optical resonators, there have been a number of reports, for example, on cleaved coupled cavity lasers [7], arrays of coupled vertical cavity surface emitting lasers [8,9] or microwave filters based on periodic arrays of coupled cavities [10]. In coupled lasers, geometry induced symmetries and symmetry breakings have been used to obtain laser operation on optical ''supermodes'' [8,9]. Another example of exploiting symmetries in cavities are waveguide couplers operating in the microwave range, so-called magic T's [10,11].

Here we spectroscopically study coupled photonic cavities having different geometries, which we call ''photonic isomers,'' and compare the experimental results to detailed numerical calculations. The molecule structures were fabricated by coupling four identical resonators, which were arranged geometrically in different ways. The different arrangements result in characteristic optical mode spectra. In particular, the symmetry of the molecular structure leads to degeneracies among the optical modes.

The photonic molecules for our studies were fabricated from planar semiconductor microcavities containing a GaAs resonator layer with a width of one light wavelength. This GaAs layer was embedded between highly reflecting GaAs/AlAs Bragg mirror stacks with 21 mirror pairs placed at the bottom and 19 at the top. A 7-nm-wide $In_{0.14}Ga_{0.86}As$ quantum well was placed at the center of the cavity as the optically active medium. The photonic molecule structures were patterned using lithography and etching. Only the upper Bragg mirror stack and the cavity were patterned keeping the bottom mirror essentially unetched [12]. Figure 1 shows scanning electron micrographs of the three different isomeric molecule types fabricated. In Fig. 1(a) a linear arrangement of the resonators is shown, in Fig. 1(b) a square arrangement,
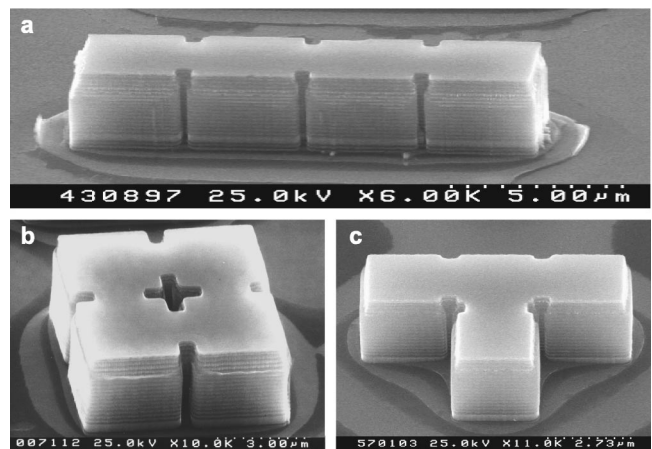

FIG. 1. Scanning electron micrographs of linear (a), square (b) and T-shaped (c) isomeric photonic molecules.
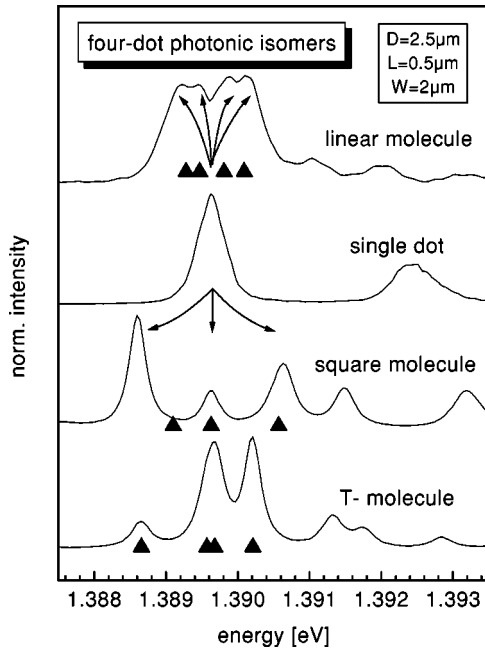
FIG. 2. Angle integrated spectra of different photonic molecules in comparison with the spectrum of a single photonic dot. Triangles give calculated energies.

FIG. 3. Calculated electric field distributions of the optical modes in a linear molecule.

and in Fig. 1(c) a T-shaped arrangement. The lateral resonator size in each case in Fig. 1 is $3 \times 3 \mu m^2$. The dimensions of each channel connecting two resonators are 2-μm width by 0.5-μm length.

The square shaped molecule has a higher symmetry than the linear one. Both structures are invariant under rotations by 180° around an axis normal to the molecule plane (C_2 symmetry). The square molecule is also invariant under rotations of 90° around this axis (C_4 symmetry). The T-shaped structure can be considered as a molecule with a weakly broken C_3 symmetry. An unbroken C_3 symmetry would be obtained if three photonic dots were placed symmetrically around a center cavity and the angle between the three interconnecting channels in the molecule plane would be 120° (triangular molecule). The T-shaped molecule is distorted from this symmetry, with one of the in-plane angles being increased to 180° and the other two reduced to 90°.

For optical studies the samples were held in a helium cryostat at $T = 2$ K, and the structures were excited by an Ar-ion laser ($\lambda = 514.5$ nm). The photoluminescence signal was collected either within a solid angle of about 10° or with a high angular resolution. In the latter case the only emission detected was that which passed through a small aperture, providing an angular resolution of 1°. The aperture could be moved parallel to the cavity plane. The luminescence was analyzed by a double monochromator with a focal length of 1 m, and detected by a Peltier-cooled GaAs photomultiplier interfaced with a photon counting system. The optical setup provides a spectral resolution of 50 μeV.

Figure 2 shows angle-integrated photoluminescence spectra of linear, square, and T-shaped photonic molecules in comparison with the spectrum of a single photonic dot. In order to make mode splittings more easily observable, the
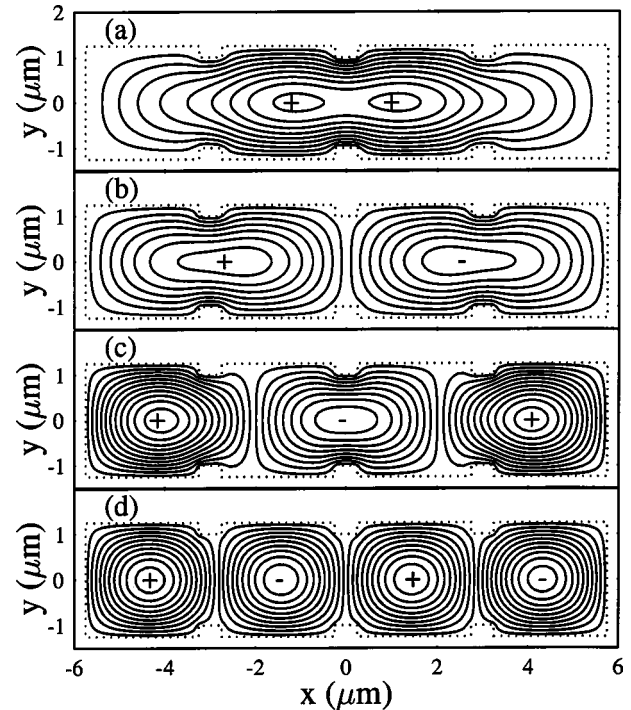
cavity sizes for the dots in Fig. 2 were reduced to 2.5 $\times 2.5$ μm^2, while the dimensions of the channels were kept the same as in Fig. 1 (2-μm width by 0.5-μm length). Due to the coupling between the dots, the optical modes in the molecules show a splitting which is characteristic of the molecule shape. For simplicity, here we will discuss only the lowest lying photon modes in the isomers. For the linear molecule (top trace) a set of four closely spaced spectral lines (indicated by arrows) is observed, which is located in the energy range around the single ground photon mode in an isolated dot (the second trace from the top). In contrast, for the square shaped molecules a set of spectral lines is observed in this energy range that consists of only three different features (the second trace from the bottom), which are about equidistantly spaced. The energy splittings between them are much larger than those in the linear arrangement. The spectrum of the T-shaped molecule (bottom trace) also consists of three lines, but the energy splittings between them are smaller than in the square molecule, and they are no longer equidistantly spaced.

Generally a splitting of each single dot mode into four modes is expected from the coupling of four photonic dots. Due to symmetry, however, degeneracies might occur in the mode spectrum. In order to obtain a quantitative understanding, we have made detailed numerical calculations of the optical modes in the isomeric molecules by using the boundary element method for solving Maxwell's equations [13,3].

Figure 3 shows the electrical field distributions of the optical modes in the linear molecule which originate from splitting of the ground photon mode due to coupling between the dots [14]. A splitting into four nondegenerate photon modes is found. The lowest energy mode (a) is symmetric under
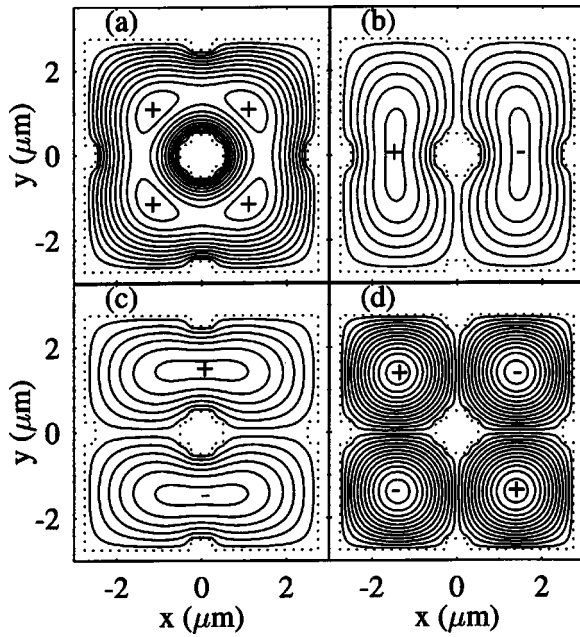
FIG. 4. Same as Fig. 3, but for a square molecule.

reflection at the symmetry plane of the chain, while the first excited mode (b) is antisymmetric for this reflection and has a node at the center of the chain. The second excited mode (c) with two nodes is symmetric and has an antinode in its center. The fourth mode (d) is antisymmetric and has nodes in each channel. The calculated energies of the modes are shown by triangles in Fig. 2, and are in good accord with the experimental data.

The four photon modes in the square molecule are plotted in Fig. 4. Here the modes can be characterized by their parities along the sides of the molecules that are determined by reflections at the corresponding symmetry planes: The ground mode (a) is symmetric along both directions. The two next higher lying modes [(b) and (c)] are symmetric along one of these directions, but antisymmetric along the other direction. They are degenerate because they can be transformed into one another by rotations of $90°$. The fourth mode (d) is located at higher energy, and is antisymmetric along both directions. The energies of these modes are shown in Fig. 2 by triangles, from which less good agreement with the experimental data can be seen. In particular, the mode energies in the calculations are not equidistantly spaced as in the experiment. This difference most likely arises from the etching depth in the hole at the center of the square being smaller than outside, i.e., only part of the upper mirror may be etched and not the GaAs resonator itself. This effect will lower the energy of all the states relative to that from a full etching depth. This will affect mainly the energy of the ground mode and its splitting from the first excited mode, because it is much more tightly localized to the center of the square. On the other hand, the splitting between the first and second excited modes will be less affected.

The field distributions for a T-shaped molecule are shown in Fig. 5. The ground mode (a) has no node, the next two higher lying modes [(b) and (c)] have one node each located approximately in the molecule center. The mode (d) has
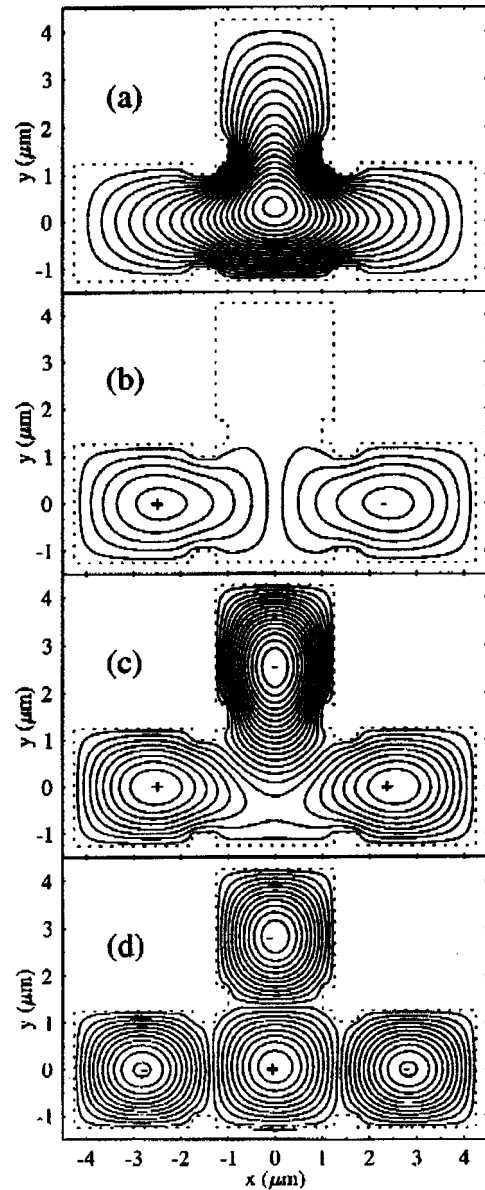

FIG. 5. Same as Fig. 3, but for a T-shaped molecule.

nodes in each interconnecting channel. For a triangular molecule with C_3 symmetry, we expect only a splitting into three modes because the mode with middle energy will be twice degenerate. The distortion from this symmetry leads to a splitting of the degenerate center mode. This splitting is rather small: From the calculations we find a splitting between the (b) and (c) modes of about 0.1 meV. In the angle integrated spectrum in Fig. 1 only three modes are observed. However, one notes that the half width of the center mode is considerably larger than that of, for example, the mode located at higher energy. This is an indication of the mode splitting as a consequence of the reduced symmetry.

Detailed insight into the optical modes in the isomers can be obtained from angle-resolved photoluminescence studies: Each mode has a characteristic field distribution in the cavity plane. Its far-field emission intensity is given by the square of the Fourier transform of this field distribution [3,15,16]. This allows us to identify the several confined modes in the
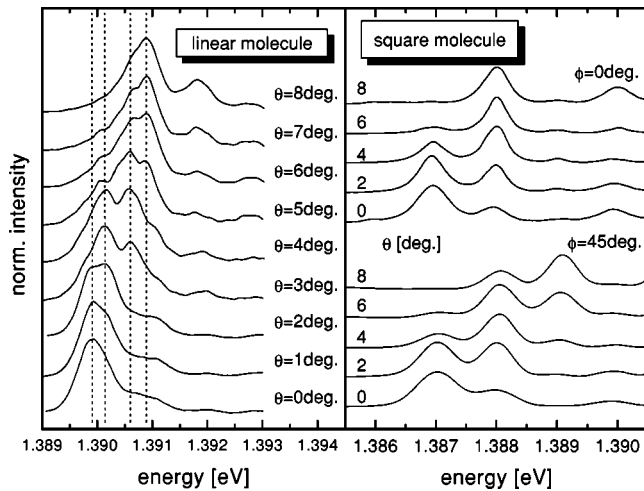
FIG. 6. Angle resolved spectra of a linear molecule (left) and of a square molecule (right).

molecules from such studies. The left panel of Fig. 6 shows angle-resolved photoluminescence spectra of a linear molecule. The angle of detection ϑ was varied along the chain. All four molecule modes are observed with increasing angle. At $\vartheta=0$, mainly emission from the ground mode is seen, while for the first excited mode, for example, destructive interference of the fields occurs in the far field [17]. When the detection direction is varied, the emission from the ground mode vanishes, and the three higher lying photon modes subsequently appear at their corresponding energetic positions.

The right panel in Fig. 6 shows angle resolved spectra of a square molecule. Here the direction of observation can be characterized by a set of two angles: The polar angle ϑ gives the direction relative to the cavity normal, and the azimuthal angle φ is the angle in the plane of the cavity. $\varphi=0$ corresponds to observation along the direction of the side of the individual cavities. From the field distribution in Fig. 4 it is clear that the highest lying of the three split modes should not be observable for $\varphi=0$, because the far field of this mode vanishes for all observation angles due to the odd parity of this mode along x and y axes. This is in agreement with the experimental data in the upper part of Fig. 6, where with increasing angle ϑ only the two lowest modes can be seen. This mode should, however, be observable, when the detection is done along the diagonal of the square for the angle $\varphi=45°$ in the lower part of Fig. 6, because the mode has even parity with respect to the diagonal. In the corresponding spectra, emission from this mode appears at a detection angle of about 6°. Thus these results of angle-resolved studies confirm the above assignments of the optical modes in the angle integrated spectra of the isomeric molecules.

[1] J.M. Gérard, D. Barrier, J.Y. Marzin, R. Kuszelewicz, L. Manin, E. Costard, V. Thierry-Mieg, and T. Rivera, Appl. Phys. Lett. **69**, 449 (1996).

[2] J.P. Reithmaier, M. Röhner, H. Zull, F. Schäfer, A. Forchel, P.A. Knipp, and T.L. Reinecke, Phys. Rev. Lett. **78**, 378 (1997).

[3] M. Bayer, T. Gutbrod, J.P. Reithmaier, A. Forchel, T.L. Reinecke, P.A. Knipp, A.A. Dremin, and V.D. Kulakovskii, Phys. Rev. Lett. **81**, 2582 (1998).

[4] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).

[5] S. John, Phys. Rev. Lett. **58**, 2486 (1987).

[6] J. Joannopoulos, R. Meade, and J. Winn, *Photonic Crystals* (Princeton University Press, Princeton, 1995); J.D. Joannopoulos, P.R. Villeneuve, and S. Fan, Nature (London) **386**, 143 (1997).

[7] See, for example, W.T. Tsang, N.A. Olsson, and R.A. Logan, Electron. Lett. **19**, 341 (1983); **19**, 488 (1983); Appl. Phys. Lett. **42**, 650 (1983); IEEE J. Quantum Electron. **11**, 1621 (1983).

[8] See, for example, M. Orenstein, E. Kapon, N.G. Stoffel, J.P. Harbison, L.T. Florez, and J. Wullert, Appl. Phys. Lett. **58**, 804 (1991); M. Orenstein, E. Kapon, J.P. Harbison, L.T. Florez, and N.G. Stoffel, *ibid.* **60**, 1535 (1992).

[9] See, for example, R.F.M. Hendriks, M.P. van Exter, J.P. Woerdman, and C.J. van der Poel, Appl. Phys. Lett. **69**, 869 (1996).

[10] Information on microwave filters and on magic T's can be found in R. E. Collin, *Foundations for Microwave Engineering*, 2nd ed. (McGraw-Hill, New York, 1992).

[11] For recent work on magic T's, see for example, C.A. Lee and G.C. Dalman, IEEE Trans. Microwave Theory Tech. **47**, 34 (1999); L. Fan, C.H. Ho, S. Kanamaluru, and K. Chang, *ibid.* **43**, 2749 (1995), and the cited references.

[12] M. Röhner, J.P. Reithmaier, A. Forchel, and H. Zull, Appl. Phys. Lett. **71**, 488 (1997).

[13] P.A. Knipp and T.L. Reinecke, Phys. Rev. B **54**, 1880 (1996); Physica E (Amsterdam) **2**, 920 (1998).

[14] The confined electric fields are predominantly polarized in the cavity plane. From the calculations we find that the energy splitting between two differently polarized modes in the plane is negligible (<50 μeV).

[15] T. Gutbrod, M. Bayer, A. Forchel, J.P. Reithmaier, T.L. Reinecke, S. Rudin, and P.A. Knipp, Phys. Rev. B **57**, 9950 (1998); T. Gutbrod, M. Bayer, A. Forchel, P.A. Knipp, T.L. Reinecke, A. Tartakovskii, V.D. Kulakovskii, N.A. Gippius, and S.G. Tikhodeev, *ibid.* **59**, 2223 (1999).

[16] A. Kuther, M. Bayer, T. Gutbrod, A. Forchel, P.A. Knipp, T.L. Reinecke, and R. Werner, Phys. Rev. B **58**, 15 744 (1998).

[17] Due to the even parity of the second excited mode, emission from it can be seen at $\vartheta=0$. With increasing ϑ the corresponding intensity first decreases, then increases again, and reaches its maximum at about 6°.