Theoretical prediction of a dramatic *Q*-factor enhancement and degeneracy removal of whispering gallery modes in symmetrical photonic molecules

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Coupled-microdisk photonic molecules with high-symmetry geometries that support nondegenerate whispering gallery modes with high quality factors are numerically designed, based on a two-dimensional model. Dramatic enhancement of calculated *Q* factors of nondegenerate modes as compared with single-microdisk whispering gallery modes of the same radial order is achieved by tuning the intercavity coupling distances. Potential applications of this work to the design of single-mode coupled-microdisk structures with large spontaneous emission factors and low threshold lasing operation and to random laser simulations are discussed. © 2006 Optical Society of America

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Semiconductor microdisk resonators supporting high-*Q* whispering gallery (WG) modes provide the performance required for the next generation of optoelectronic components such as light-emitting diodes, low-threshold microlasers, and narrow-linewidth filters.[1] Arranging several electromagnetically coupled microcavities into so-called photonic molecules[2] offers new functionalities of the devices without compromising the *Q* factors of individual cavities.[3–7] Coupled-microcavity models can also be used for interpreting the experimental spectra of random powder lasers with a powder particle size larger than or comparable to the emission wavelength.[8] Circular microdisk resonators support dense frequency-dependent TE and TM spectra of WG modes that are classified as $\mathrm{WGH(E)}_{m,n}$ modes, m being the azimuthal mode number and n the radial mode number.[1,6,9] Unlike the lowest-order modes in optical microcavities,[2] all the WG modes are double degenerate owing to the symmetry of the structure. This double degeneracy is an important issue in view of the use of such cavities as building blocks of photonic devices, as it can cause the appearance of parasitic peaks in the resonator spectra, mode hopping, polarization instabilities, and noise.[10]

Splitting of the degenerate individual cavity modes due to electromagnetic interactions of neighboring microcavities has been observed both theoretically and experimentally.[2,6,7] Previous studies of the modal spectra of double-cavity photonic molecules also showed the possibility of either increasing or suppressing the resonant WG-mode *Q* factors and controlling mode frequency splitting by changing the intercavity coupling distance.[5,6] However, in low-symmetry photonic molecule structures (such as, e.g., linear cavity chains[2–6]) all the resonant modes split into several groups of nearly degenerate modes. The number of groups is equal to the number of cavities forming a photonic molecule,[7] and the number of modes in each group depends on the individual cavity mode degeneracy[2,6,11] (e.g., two for a circular-disk WG-mode photonic molecule[6]). Such nearly degenerate modes can be indistinguishable in the photonic molecule spectra.[7] However, fabrication imperfections can cause further splitting of nearly degenerate modes within a group, revealing the fine structure of photonic molecule modes.[11]

In this Letter general design rules to build 2D WG-mode microdisk photonic molecules with a wide free spectral range and greatly enhanced *Q* factors of nondegenerate modes are established numerically by using the method of Muller boundary integral equations (MBIEs).[9] The central idea of this study is to arrange the microcavities into the configurations with high symmetry with the aim to enhance a single nondegenerate mode and simultaneously suppress all the neighboring modes considered parasitic. Two symmetrical molecule geometries are considered: an equilateral triangle possessing C_{3v} symmetry (invariant under a rotation by $2\pi/3$) and a square configuration of C_{4v} symmetry (invariant under a rotation by $\pi/2$).

Photonic molecules composed of 2D circular microcavities with diameters of 1.8 μm and an effective refractive index of $n_{\mathrm{eff}}^{\mathrm{TE}}=2.63$ are considered. Such 2D microcavities serve as models of 3D 200 nm thick GaInAsP ($n=3.37$) microdisk resonators at the wavelengths around 1.55 μm.[12,13] An isolated circular microcavity with such parameters supports a TE-polarized double-degenerate $\mathrm{WGH}_{6,1}$ mode in the vicinity of the spontaneous emission peak ($\lambda=1.547\ \mu$m, $Q=513$). TM-polarized WG modes are not included in the analysis, as the $n_{\mathrm{eff}}^{\mathrm{TM}}$ in such thin disks is too small to allow the cavity eigenmodes within the material spontaneous emission range. Corresponding eigenvalue problems are solved with the rigorous MBIE method previously developed and successfully applied to simulate optical microcavities

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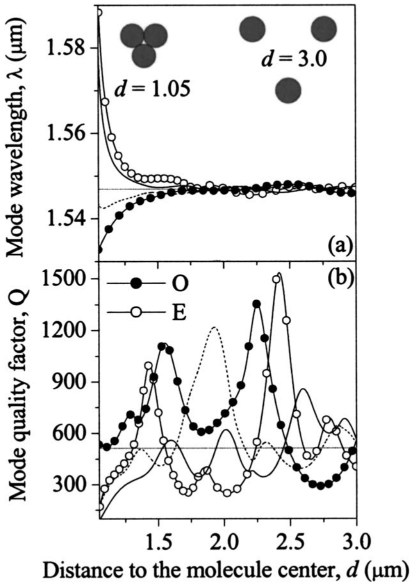

Fig. 1. Shift and splitting of wavelengths (a) and change of Q factors (b) of the $\mathrm{WGE}_{6,1}$ modes in a triangular photonic molecule as a function of the cavities' distances to the molecule's center. Corresponding single-cavity characteristics are plotted for comparison (straight line).

of various shapes for a variety of applications.[9,13] Unlike the techniques that are conventionally used to simulate the spectra of coupled microcavities (such as the coupled mode theory, tight binding approximation, and finite-difference time-domain methods) the MBIE method yields both fast and highly accurate solutions that take into account all the electromagnetic interactions in the system.

Figures 1(a) and 1(b) present the wavelength shifts and Q-factor oscillations of the split $\mathrm{WGE}_{6,1}$ modes in the triangular molecule with increasing distance between the centers of individual cavities and the center of the molecule (the inset shows the transformation of the molecule configuration). It can be seen that the double-degenerate WG modes split into four modes (two of which are again double degenerate owing to the symmetry of the structure). The nondegenerate E (even) and O (odd) modes have field patterns that are either symmetrical or antisymmetrical along all three symmetry axes [Figs. 2(a) and 2(b)]. These modes exhibit higher Q factors than the degenerate ones for certain distances d. Clearly a Q factor increase of 2–3 times in comparison with a single microcavity can be achieved in the triangular molecule.

Next, a higher C_{4v}-symmetry molecule geometry is considered [Figs. 3(a) and 3(b)]. Here the degenerate WG modes split into four (EE, EO, OE, and OO) nondegenerate modes with even–odd symmetry along the square diagonals and the x and y axes and two double-degenerate modes. The modes with the highest Q factors are the OE and OO modes [the near-field patterns are shown in Figs. 4(a) and 4(b)]. A dramatic 23-fold enhancement of the nondegenerate OE mode [Fig. 4(a)] in the optimal square-molecule configuration ($d=1.6125$ μm) is demonstrated. Note that all the other modes have significantly lower Q factors at this point. It should be pointed out that there is a direct analogy with the nondegenerate high-Q modes in square and triangular microcavities.[13] Other symmetrical molecule geometries such as hexagons and crosslike shapes can potentially offer even further Q-factor enhancements (possibly accompanied by directional light emission) and are currently under study.

Of course higher Q factors can be achieved by simply choosing a microdisk resonator of larger diameter, as the Q factors of the WG modes grow exponentially with the mode azimuthal number m.[6,9] However, to ensure a stable single-mode microdisk

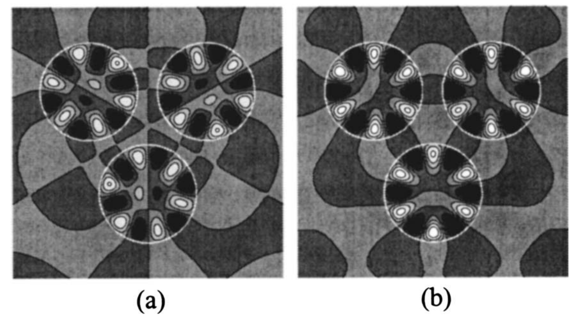

Fig. 2. Magnetic near-field portraits of the (a) O and (b) E modes in the triangular molecule with $d=1.25$ μm.

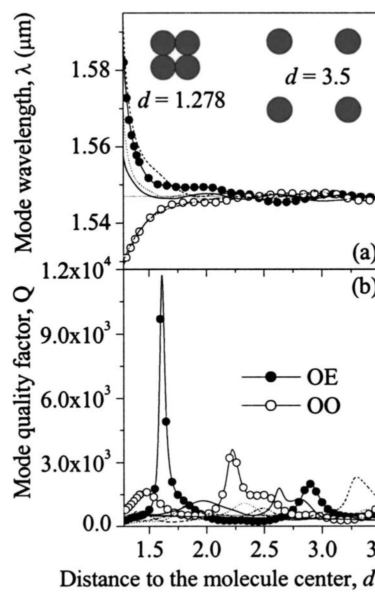

Fig. 3. Shift and splitting of wavelengths (a) and change of Q factors (b) of the $\mathrm{WGE}_{6,1}$ modes in a square photonic molecule as a function of cavities' distances to the molecule center.

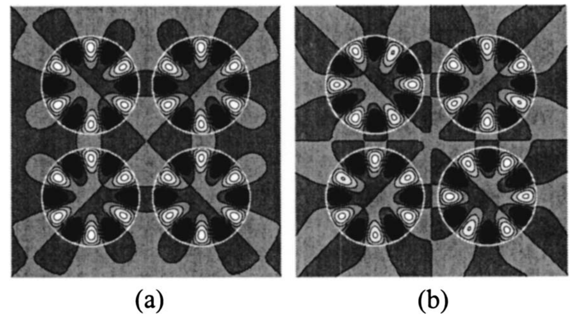

Fig. 4. Magnetic near-field portraits of the (a) OE and (b) OO modes in the square molecule with $d=1.45$ μm.

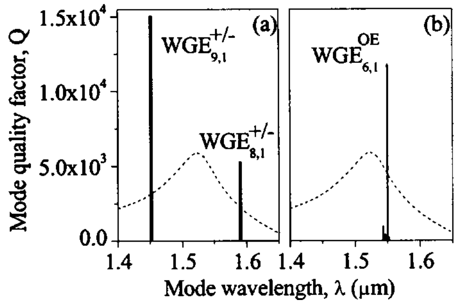

Fig. 5. Spectral lines with respective Q factors for the WG modes in (a) 2.3 μm diameter single microdisk and (b) optimally tuned ($d=1.6125$ μm) square photonic molecule composed of 1.8 μm diameter microdisks. The dotted curve is an approximation (a.u.) of the spontaneous emission spectrum in GaInAsP–InP quantum well microdisk lasers (Ref. 12).

laser operation and to increase the fraction of spontaneous emission into the lasing mode, a microcavity structure supporting only one high-Q nondegenerate mode in the spontaneous emission range is required. Figure 5 presents a comparison of the optical WG-mode spectra of a single larger-radius ($r=1.15$ μm) microdisk resonator [Fig. 5(a)] and of the optimally tuned ($d=1.6125$ μm) square photonic molecule composed of four smaller-radius ($r=0.9$ μm) microdisks [Fig. 5(b)]. It can be clearly seen that, although both structures demonstrate WG modes with comparable Q factors ($Q_{8,1}^{\text{single}}=5243$, $Q_{9,1}^{\text{single}}=15055$, and $Q_{6,1}^{\text{OE}}=11757$), there is only one high-Q nondegenerate photonic molecule mode within the spontaneous emission range [Fig. 5(b)], where there are two double-degenerate high-Q WG modes in a single microdisk [Fig. 5(a)]. This photonic molecule configuration that avoids several equally coupled WG modes may help to achieve quasi-single-mode operation of a microdisk laser. Further enhancement of the nondegenerate photonic molecule mode Q factor can be achieved by tuning the molecule geometry to spectrally align the mode wavelength with the semiconductor material gain peak.[5,14]

In summary, optical spectra of WG modes of 2D symmetrical photonic molecules composed of evanescently coupled microdisk resonators have been calculated and explained. A square photonic molecule supporting a nondegenerate WG mode with a 23-times-increased Q factor and a wide free spectral range has been demonstrated. The results and conclusions of this study are directly applicable to the design of 3D photonic molecules composed of microspheres, which currently can be fabricated and tuned with high precision by self-assembly and by optical manipulation techniques.[15] The ability to engineer and tune the spectral characteristics of microdisk photonic molecules by exploiting the molecule's symmetry paves the way for a variety of possible applications such as development of single-mode light-emitting devices with improved polarization stability and lowered thresholds.

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