Coupled microcavities as photonic molecules permit the study of confined photonic modes similar to confined electron states \([1–3]\). Recently, evanescent-coupled microdisks have attracted great attention because they can be fabricated easily by the lithographic technique. The improvement of emission performance for photonic integrated circuits and some functionality are expected in photonic molecule structures using two or more coupled microdisks. Lasing operation, mode splits due to optical coupling, and bistability were observed in coupled GaInAsP microdisks \([4,5]\). The finite-difference time-domain (FDTD) technique and the lasing eigenvalue problem method were used to investigate the mode characteristics and threshold gain of the coupled microdisks \([6,7]\). Furthermore, photonic molecules composed of several identical microdisks were investigated by the methods of the lasing eigenvalue problem and Muller boundary integral equations \([8,9]\).

However, the past investigations focused on mode coupling between the same order whispering-gallery modes (WGMs). In this Letter, we find by FDTD simulation that anticrossing mode coupling can exist between some coupled first- and second-order WGMs, which will greatly reduce the \(Q\) factor of the coupled first-order WGM. The simulated mode field patterns also verify the field distribution variation between the first-order and the second-order coupled WGMs.

A two-dimensional (2D) photonic molecule composed of two coupled microdisks with the radius \(R\) and the gap \(g\) surrounded by air, as shown in Fig. 1, is used to simulate the coupled mode characteristics by the FDTD technique. A perfect matched layer \([10]\) is used as the absorbing boundary condition with a distance \(s=0.8\ \mu m\) from the perimeters of the microdisks. To excite the transverse electric resonant modes TE\(_{m,n}\), a Gaussian modulated cosine impulse \(P(x,y,t)=\exp[-(t-t_0)^2/\tau_0^2]\cos(2\pi ft)\) is added to the magnetic field component \(H_x\) at some points inside the microdisks, where \(t_0\) and \(\tau_0\) are the times of the pulse center and the pulse half-width, respectively, and \(f\) is the center frequency of the pulse. The time variation of a selected field component at selected points inside the microdisks is recorded as a FDTD output, and the \(Q\) factors are calculated from the complex roots of the microdisk eigenequation \([13]\) are \(2.42 \times 10^4, 1.94 \times 10^5\) for WGMs TE\(_{7,1}\), TE\(_{8,1}\), and TE\(_{9,1}\), respectively, without the splitting of the WGM resonances. When the mesh size is an important parameter in modeling the microdisk by the FDTD technique \([12]\). In this Letter, we choose the mesh size based on the numerical results of a single microdisk with the radius \(R = 1\ \mu m\) and the refractive index \(n = 3.2\). Taking the mesh cell size of 10 nm (5 nm), we obtain \(Q\) factors of \(2.39 \times 10^4, 9.70 \times 10^4, 1.94 \times 10^5\) for WGMs TE\(_{7,1}\), TE\(_{8,1}\), and TE\(_{9,1}\), respectively, without the splitting of the WGM resonances. The \(Q\) factors calculated from the complex roots of the microdisk eigenequation \([13]\) are \(2.42 \times 10^4, 1.16 \times 10^5, \) and \(5.58 \times 10^5\). In the following simulation, a uniform mesh with cell size of 5 nm, a time step of the Courant limit \(\Delta t\), and 20-cell perfect matched layers are used in the FDTD simulation.

The coupled microdisks have four types of coupled modes \([6,7]\) with the symmetry marked as \([x,y] = [\pm, \pm]\), where the plus and minus symbols imply...
that the coupled mode is symmetric and antisymmetric relative to the X or Y axis, respectively. So we can simulate the coupled modes by the FDTD technique in a quarter of the coupled microdisks based on the symmetry boundaries at the X and Y axes. As the gap $g$ approaches zero, the coupled modes with symmetry of $[\pm, -]$ usually have smaller wavelengths and larger $Q$ factors than the coupled modes of $[\pm, +]$.

First, we consider the two coupled microdisks with the radius $R = 1 \mu m$ and the refractive index $n = 3.2$. We find that the $Q$ factor of the coupled first-order WGM TE$_{9,1}$ is anomalously small. Simulating the mode field distribution for the coupled disks at the gap $g = 0.1 \mu m$, using a narrow frequency excitation pulse with $t_w = 15,000 \Delta t$, $t_0 = 30,000 \Delta t$, and $f = 196.5 \text{ THz}$, we have the variation of mode field distributions over a half-period $T$ as shown in Fig. 2 with a time interval of $T/10$. Figures 2(b) and 2(c) are similar to the field distribution of the first-order WGM TE$_{9,1}$ and the second-order WGM TE$_{6,2}$, respectively. The results indicate that mode coupling exists between the coupled WGMs TE$_{9,1}$ and TE$_{6,2}$. In Fig. 3, we plot the obtained mode wavelengths and $Q$ factors for the coupled WGMs TE$_{9,1}$ and TE$_{6,2}$. The results of Fig. 3(a) show that anticrossing coupling exists between the coupled WGMs TE$_{9,1}$ and TE$_{6,2}$ at the gap $g = 0.2 \mu m$. The mode $Q$ factor of the coupled WGMs TE$_{9,1}$ in Fig. 3(b) quickly decreases with decreasing $g$ when $g$ is less than 0.8 $\mu m$. The open squares are the coupled TE$_{9,1}$ when the gap $g$ is larger than 0.2 $\mu m$ and transfer to TE$_{6,2}$ when the gap $g$ is smaller than 0.2 $\mu m$ because of the anticrossing mode coupling between them.

The coupling effect on the coupled WGM TE$_{6,2}$ is larger than that of the coupled WGM TE$_{9,1}$, and the mode wavelengths of the two coupled modes have a crossing point at about $g = 0.2 \mu m$. In Fig. 3(c), the solid curve is the intensity spectrum obtained by the Padé approximation for the strong coupling case with $g = 0.2 \mu m$, which is fitted by one and two Lorentzian peaks as the dashed curve and the dotted curves, respectively. The open squares, which agree much better with the solid curve than with the dashed curve, are the sum of the two dotted curves with the peak wavelengths corresponding to the mode wavelengths of the coupled WGMs TE$_{9,1}$ and TE$_{6,2}$. The results show that quite exact mode frequencies and $Q$ factors can be obtained for the two coupled WGMs even though they are not split far enough. It should be noted that calculations for other, lower-order, modes show similar behavior if a second-order mode with a suitable wavelength exists.

For a single microdisk with radius $R = 1 \mu m$ and $n = 2.8$, the wavelengths (the $Q$ factors) of TE$_{9,1}$ and TE$_{6,2}$ are 1340 nm and 1344.9 nm (54,433 and 58), respectively. The mode wavelength of TE$_{6,2}$ is 4.9 nm larger than that of TE$_{9,1}$, so the mode wavelengths of coupled WGMs TE$_{9,1}$ and TE$_{6,2}$ antisymmetric to the Y axis may have a crossing point. Mode $Q$ factors for the coupled modes with the symmetry of $[+, -]$ are calculated for two coupled microdisks with radius
$R = 1/\mu m$ and refractive index $n = 2.8$. The obtained $Q$ factor of the coupled WGM TE$_{9,1}$ decreases with the gap $g$ much quicker than for the coupled WGMs TE$_{7,1}$ and TE$_{8,1}$. To verify the reason for the anomalously small $Q$ factor for the coupled WGM TE$_{9,1}$, we also simulate the mode field pattern for the coupled WGM TE$_{9,1}$ by taking the excitation pulse covering the frequency range of one first-order WGM with $t_w = 15,000\Delta t$, $t_0 = 30,000\Delta t$, and $f = 223.97$ THz at the gap $g = 0.3/\mu m$. The obtained mode field distribution variations over a half-period $T$ are plotted in Fig. 4 with a time interval of $T/10$. The field distribution patterns in Figs. 4(a) and 4(c)–4(f) are the distributions of WGM TE$_{9,1}$, but that of Fig. 4(b) is similar to that of the second-order WGM TE$_{6,2}$. The mode wavelengths and $Q$ factors of the coupled WGMs TE$_{9,1}$ and TE$_{6,2}$ are plotted in Fig. 5 as functions of the gap $g$. The two mode wavelengths nearly cross at the gap $g$ of about 0.75/\mu m. The results show that the coupling with the second-order WGM greatly decreases the mode $Q$ factor for the coupled WGM TE$_{9,1}$ when the gap is smaller than 0.75/\mu m.

In conclusion, we investigated the mode coupling characteristics for two coupled microdisks by FDTD simulation. In addition to the well-known mode coupling between same order WGMs, we have found that mode coupling between the first- and the second-order coupled WGMs can happen as the coupling induces the anticrossing of their mode wavelengths, which greatly reduces the mode $Q$ factor of the first-order coupled WGMs and will increases the threshold gain of such a coupled microdisk laser.

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References