Vertically coupled photonic molecule microdisk laser

Xin Tu, Yi-Kuei Wu, and L. Jay Guo

A photonic molecule microdisk laser consisting of three vertically coupled disks shows a large spontaneous emission factor and strong intercoupling.

Photonic molecule (PM) microcavities have been widely employed in microlasers, signal processing, and chip-scale integrated sensing applications. The vertically coupled semiconductor microdisk laser is a potential candidate for future photonic circuit and cavity quantum electrodynamics systems owing to several advantages. First, it is compact and easy to fabricate for multilayered integration. Second, addressing different quantum dots in a single microcavity is challenging, and the microdisk laser constitutes an effective strategy for realizing multiple quantum-bit operations. Finally, the overlap of evanescent waves around the entire perimeter of neighboring disks provides much stronger coupling strength than laterally coupled resonators relying on a single interaction point.

Recently we reported that vertically coupled microdisks achieve lasing and greatly enhanced spontaneous emission coupling efficiency in wavelength-scale cavities. We have also developed a triple-stacked PM microdisk laser containing self-assembled indium arsenide (InAs) quantum dots as a gain medium and reported observed mode splitting due to strong coherent coupling between the disks.

Figure 1(a) shows a schematic for our proposed vertically coupled PM microdisk laser. The diameters of the three gallium arsenide (GaAs) disks are about 1.4\(\mu\)m. The thickness of each disk and the gap between adjacent ones is both 300nm. The undercut of the \(Al_{0.75}Ga_{0.25}As\) layer is large enough to confine the whispering gallery modes (WGMs) in the GaAs disks, and we set the dimension of the pedestal to reduce light leakage to the GaAs substrate while maintaining the proper heat sink for the sample. Figure 1(b) shows a scanning electron microscope (SEM) image of the sample.

Figure 2(a) shows the quasi-transverse electric (TE) polarized (having an electric field mostly in the cavity plane) emission spectra of the PM microdisk laser. At a low pump level, the spontaneous emission in the wavelength range of 1080~1100nm is collected through the monochromator. When we increase the pump level, three peaks emerge sequentially above the baseline. These three peaks are located at the wavelengths \(\lambda_A = 1089.1\)nm,

Continued on next page
\begin{align*}
\lambda_B &= 1091.2 \text{nm}, \quad \lambda_C &= 1093.3 \text{nm},
\end{align*}
which correspond to the splitted TE_{8,1} supermodes. Figure 3 shows the mode distributions of the magnetic profile (Hz) of three supermodes in the cross-section of the disks. We see that mode A is an antibonding mode with opposite polarities, which has the highest energy (shortest resonant wavelength). Mode C is a bonding mode with identical polarities, which has the lowest energy (longest resonant wavelength).

Figure 2(b) shows the dependence of the emission intensities on the pump power for each supermode, respectively (filled squares, circles, and triangles). All three lasing peaks exhibit a standard S-shape curve with different knee features and slopes. Note that the turn-on of mode B without a pronounced knee indicates a large spontaneous emission coupling factor. This is because the vertical stacks suppress all the unwanted modes and enhance the spontaneous emission coupled to the WGM. To quantitatively analyze the emissions, we solved the rate equations and fit the experimental data to estimate \( \beta \). The fitted, colored curves are in good agreement with the experimental data with the result of \( \beta_A = 0.09, \beta_B = 0.72, \) and \( \beta_C = 0.01 \), respectively. \( \beta_B \) is the largest because its confinement factor is twice that of the other two modes, while its average mode volume is just about half that of the other two modes. Both of these factors contribute to mode B having not only the strongest gain but also the highest Purcell factor, and many more spontaneously emitted photons are coupled into this mode. Since the mode coupling in our PM structure via evanescent coupling along the whole perimeter of the microdisk is very different from previous side-coupled microcavities, we expect that much higher coupling coefficients can be achieved using this new scheme.

Finally, we analyzed the intercoupling characteristics between the different disks and the PM in terms of coupled microcavities using coupled mode theory. We fit the experimental spectra and found the coupling strength between the adjacent disks to be 0.39THz, which is at least one order of magnitude higher than the dot-cavity coupling strength (10–30GHz).

In summary, the vertically coupled PM microdisk laser has the clear potential to realize long-distance coupling between two quantum dots in different locations. We expect that vertically coupled PM microdisks will be helpful in some functional devices in quantum electrodynamics, such as logical gates, and highly dense photonic integrated circuits. We hope to improve the coupled PM microdisk structure to enhance the spontaneous emission coupling factor and optical coupling strength.

We also acknowledge instrument support from the Electron Microbeam Analysis Laboratory and the Lurie Nanofabrication Facility at the University of Michigan, Ann Arbor. Xin Tu is supported by the China Scholarship Council (grant 2010610047) and by the University of Michigan.

Author Information

Xin Tu
Fudan University
Shanghai, China

Xin Tu is a PhD candidate working on microcavity lasers.

Yi-Kuei Wu and L. Jay Guo
Department of Electrical Engineering and Computer Science Center for Nanophotonics and Spintronics University of Michigan
Ann Arbor, MI

Yi-Kuei Wu is a PhD candidate working on plasmonics and microcavities.

L. Jay Guo is a professor.

References