Highly directional output from long-lived resonances in optical microcavity

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We report a simple and robust mechanism that can result in highly directional emission from long-lived resonances in microcavities. By placing a nanoparticle (NP) into the evanescent wave region of microcavities, highly directional outputs with divergence angle $\sim 1.9^{\circ}$ -10° can be obtained in single or double directions. The perturbation of NP on evanescent waves preserves the high-quality (*Q*) factors, and the collimation of microcavities generates the highly directional outputs. Our numerical simulations show that this mechanism is very robust to the size of NP and the refractive index/separation distance/size of microcavities. © 2011 Optical Society of America *OCIS codes:* 140.3945, 230.3900.

Microdisk lasers, regarded as candidates for optical sources for hybrid optoelectronic circuits, have triggered intense basic and applied research interests in physics over the past decade [1,2]. Basically, such researches can be categorized in two groups. The first is high-quality (Q) microdisks, which promise microdisk lasers to operate with very low energy cost [1]. The second group is deformed cavities [3], which can produce directional outputs by tailoring cavity boundaries. However, in real applications, those two groups are significantly restricted by uniform output and Q spoiling, respectively. A Limacon-shaped cavity, which combines high Q and unidirectional output, has been proposed [4] and experimentally realized [5] recently. However, its divergence angle $(\sim 40^{\circ})$ [4–6] is too broad.

Another approach to produce directional output without serious Q spoiling has been proposed by placing scatters into a circular disk [7–9]. However, after the scatters are placed inside the resonator, the resonances can be separated into high-Q modes (HQMs) and low-Q modes (LQMs). HQMs are away from scatter and result in an isotropic far-field pattern (FFP). LQMs are strongly scattered and can form directional outputs in FFPs [7–9]. But their Q factors are not the highest and will not be excited easily in experiment. Applying level crossing between HQM and LQM, the superstates can provide high-Q and unidirectional emission simultaneously [7]. But the experimental results will also be destroyed by the degeneracy with other nondirectional emission HQMs [4]. Therefore, seeking a mechanism for both high-Q and highly directional emission is very challenging and is essential. In this Letter, we demonstrate one possible approach to achieve this goal.

The key of our finding is based on the focusing effect of dielectric microcavities [10]. As shown in Fig. 1(a), when plane waves illuminate a dielectric microcylinder, they will be focused to a bright spot (approximately half wavelength in width and several wavelengths in length), referred to as nanojet (NJ) [10,11]. Considering the time-reversal property of the focusing effect, light from a point source at the position of NJ can also be collected and then collimated to a narrow beam. In microcavity re-

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search, we replace the point source with a nanoparticle (NP), which can scatter the resonant modes of the microdisk. Because the scattering loss is much larger than tunneling at the boundary, this NJ becomes the main leaky channel of microcavity and therefore works like a point source. The scattered light is then collimated by the microcavity into a highly directional beam. According to the previous research on the NJ [10,11], the focusing effect can be observed over a wide range of cavity size and refractive index. Thus its time-reversal process of highly directional emission should be also very robust.



Fig. 1. (Color online) (a) Plane wave is focused into a nanojet by a microcavity with $R = 5 \ \mu m$. (b) Eigenvalues in microcavity with a nanoparticle. The radius of NP is ~250 nm away from the cavity edge with $R_2 = 250$ nm. (c) Far-field angular distribution of total emission with $\text{Re}(kR) \simeq 25.198$ (d) FFPs $\log(|E_z|)$ of symmetric (left) and antisymmetric modes (right). *z* direction is vertical to the plane. The scale bar in left panel is 10 μ m, which is valid for all of the other field patterns.

Meanwhile, as the NP is placed outside the resonator, only the evanescent waves are slightly scattered. High-Q factors of long-lived resonances will be preserved in this design. Therefore, placing a NP in the evanescent wave region of microcavity will be an effective and robust way to obtain highly directional outputs and high-Q factors.

The simple mechanism analyzed above is then tested with numerical computation (Comsol Multiphysics (3.5a) [6,12]. Here microcavity is considered as a twodimensional system. The refractive index is set as 1.757 (for Sapphire) and polarization is TM (E is perpendicular to plane). An NP with a radius of about 125 nm is placed 125 nm (edge to edge) away from a microcavity with $R = 2.5 \ \mu m$. Figure 1(b) shows the eigenvalues inside such a resonator around $kR \sim 24$, where k is the wave vector and R is the microcavity radius. Many resonances with different azimuthal number (m) and radial number (n) can be observed. Here we are focusing on the highest Q modes (n = 1) above the dashed line, because they are the typical lasing modes in actual experiments. As the Q factors are orders of magnitude lower than cavity without scatter ($\sim 9 \times 10^8$), the scattering loss from NP is dominant here. Figure 1(c) shows FFP of one HQM at kR = 25.198, which corresponds to operation wavelength ~624 nm. This FFP and all of the FFP below include the angular distributions from both symmetric and antisymmetric modes. Highly directional output with divergence angle $\sim 5^{\circ}$ can be observed in the opposite direction of the incident plane wave in Fig. 1(a). This is almost the same as our above qualitative analysis. The high Q mode is slightly scattered by NP and the scattered light is collimated by microcavity. Figure 1(d)shows the field pattern of $\log |E_z|$ with different symmetries. Highly directional emission can also be directly observed from the field pattern at 40 μ m away from the cavity. Meanwhile, high-Q factors in Fig. 1(b) can be understood from the localization as whispering-gallery modes.

However, besides the collimated beam along $\theta = 180^{\circ}$, there are strong emissions along other directions. The integrated intensity inside the collimated beam [calculated with $U = \sum \int_{-\theta_i}^{\theta_i} I(\theta_i) d(\theta_i) / \int_{-\pi}^{\pi} I(\theta) d(\theta)$, where θ_i is the divergence angle of each beam] is only ~14%, as is clearly shown in Figs. 1(c) and 1(d), where significant field distribution can be observed within $-90^{\circ} \le \theta \le 90^{\circ}$.

To increase the collection efficiency of emitted energy, we place another microcavity next to the NP. As shown in Fig. 2(a), the second microcavity has radius $R_3 = R +$ $0.01 = 2.51 \ \mu m$. The separation distance between two microcavities is 2d = 500 nm, and the size of NP is $R_2 = 125$ nm. The refractive index (n) is kept at 1.757. While the twin coupled cavities structure, sometimes referred to as the photonic molecule structure, is a popular topic, here we select two cavities of different sizes to avoid possible coupling, for more general cases. Figure 2(b) shows the FFP of such a design. In addition to the beam at $\theta = 180^{\circ}$, highly directional emission can also be observed at $\theta = 0^{\circ}$, which is formed by the collimition of emission in other directions in Fig. 1(c). As only 14% light can be collected by single cavity in Fig. 1(c), the intensity of beam at $\theta = 0^{\circ}$ is much larger and its divergence angle is $\sim 8.8^\circ$. We also calculated



Fig. 2. (Color online) (a) Schematic picture of two cavities with a NP. (b) FFP from the same resonant mode in Fig. 1. (c), (d) Field patterns $\log |E_z|$ of symmetric and antisymmetric modes. Highly directional beams can be observed even 40 μ m away from cavities.

the collection efficiency of two cavities, which is greatly increased to 56%. This means that more than half scattered light are collected and collimated here. Such a high collection ratio can also be estimated from the log scale field patterns in Figs. 2(c) and 2(d), where two highly directional beams can be observed in each figure.

In conclusion, we want to discuss the robustness of our mechanism. As we have mentioned in the qualitative analysis, with the selected cavity size, particle size, refractive index, etc., our design should be very robust. Here we numerically verify this hypothesis. Figures 3(a) and 3(b) show the dependence of FFPs on the refractive index (*n*) and cavity size (*R*). Here all the settings are kept the same as Fig. 2 (including $R_3 - R = 0.01 \ \mu$ m) except the varying parameters. From the results in



Fig. 3. (Color online) (a), (b) Dependence of divergent angles on refractive index (*n*) and cavity size (*R*). Other parameters are same as in Figs. 1 and 2. (c), (d) Dependence of divergence angle on separation distance between cavities (d) with $R_2 =$ 125 nm and the size of NP (R_2) with d = 550 nm. Other parameters in (c), (d) are set as: n = 1.757, $R = 5 \ \mu m$, $R_3 = 5.01 \ \mu m$.

Figs. 3(a) and 3(b), we can clearly see that highly directional emissions with divergence angle below 10° can be obtained over a wide range of refractive index and cavity size. We have also tested the tolerance of directional output on the separation distance and size of NP. The results are shown in Figs. 3(c) and 3(d). Here n, R are kept at 1.757, and 5 μ m and $R_2 = 125$ nm for Fig. 3(c), d = 550 nm for Fig. 3(d), respectively. Highly directional emission can still be obtained from different separation distances and sizes of NP. Therefore, we can conclude that our designs are very robust in experimental conditions and should be feasible in many types of materials, ranging from glass and polymer to sapphire.

The variation of divergence angle in Fig. 3 is caused by the relative position between focus point of circular cavity and the scatter. Changing the radius of the circular cavity can slightly vary the focus point to, and then away from, the scatter and results in a minimum divergence at R = 4 m in Fig. 3(b). Meanwhile, the scatter will be partially out of the focus and generate a larger divergence angle when its size is gradually increased in Fig. 3(d). In our simulation, the best obtained divergence angle is $\sim 1.9^{\circ}$ in Fig. 3(d). The inset in Fig. 3(b) shows the FFPs at some points. Clear unidirectional output with divergence angle $\sim 5.5^{\circ}$ can be observed. This unidirectional output is generated because the collection ratio is greatly increased by the collection of the second cavity, making the intensity along $\theta = 0^{\circ}$ about six times (86%:14%) larger than it is along $\theta = 180^{\circ}$. The inset in Fig. 3(c) shows the corresponding changes in Q with the separation distance. With increased separation distance, the NP is further away from the cavity. Considering the exponential decrease in amplitude of the evanescent waves, the scattering of NP is greatly increased. Thus a dramatic increase of Q factors, from $\sim 7 \times 10^4$ to more than 100 million, is obtained. Furthermore, the parameters simulated in Fig. 3 are only used to show the robustness and do not indicate the limits of our mechanism, which can be pushed further. And our mechanism is also not limited in TM only.

Highly directional outputs from microcavities have been reported from specially designed shapes, such as stadium [13,14] and peanut [15]. Directional emission with divergence angles of several degrees has been demonstrated [13–15], but they either have a very low Qof several hundred [13,15,16] or work only for particular resonant modes [14]. In our current design, highly directional emission can be obtained from very high-*Q* modes. And the output directions can be controlled to unidirectional or bidirectional emission, which is also different from their multidirectional emissions [13–15].

In summary, we have proposed a simple mechanism for both highly directional emission in single or two directions from ultra-high-Q modes in microcavity. Our simulation shows that this mechanism is very robust on cavity size and refractive index. The divergence angles of emission beam can be as narrow as ~1.9°-10°. However, in actual experiments, three-dimensional structures will have an additional loss in the third dimension, which will slightly decrease the collection ratio and cavity Qfactors [17,18].

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