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Whispering gallery mode of modified octagonal quasiperiodic photonic crystal single-defect microcavity and its side-mode reduction

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Single-mode lasing action is obtained from a modified octagonal quasiperiodic photonic crystal single-defect microcavity which supports a well-confined whispering gallery mode with ultralow threshold and high-quality factor. Side-mode reduction is achieved by inserting a central air-hole in the cavity region. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2203943]

In the past few years, photonic crystals have served as the mirrors of the microcavities[1] which aim for high-quality (Q) factor,[2,3] ultralow threshold,[4] ultrasmall mode volume,[5] etc. Although lots of cavity designs and modifications have been investigated and demonstrated by optical pumping, lack of proper electrical injection structure is still the main difficulty towards real applications. One promising result is reported by Park *et al.*[6] A central post under the cavity region is used as a current injection wire without disturbing the lasing mode. However, its fabrication process is complex and the hexapole lasing mode is quite sensitive to the size of the central post. In fact, the idea of a central post structure originates from microdisk lasers. As a result, whispering gallery mode (WGM) in microdisk lasers would be a more suitable lasing mode for this approach. The bottleneck of microdisk lasers is that when the cavity size decreases to the diffraction limit of the lasing wavelength, the Q factor of WGM decreases dramatically and WGM cannot be sustained in the cavity anymore. Here we propose a cavity structure that supports WGM with the cavity size smaller than the diffraction-limited size in microdisk lasers.

It has been reported that the anisotropy of photonic band gap is caused by the low-symmetry level of Brillouin zone in photonic crystals.[7,8] The highest symmetry level of Brillouin zone in photonic crystals is 6. To achieve higher symmetry level, the concept of quasicrystal in solid state physics is applied. Large band gaps have been found in various quasiperiodic photonic crystals (QPCs) in recent years.[9,10] QPCs serving as the mirrors of microcavities have very good potential and have good fusions with microdisk lasers.[11,12] By this fusion, high-Q WGM could be sustained in microcavity which is smaller than the diffraction limitation. In this letter, we report a single-defect microcavity design with a highly confined WGM by shifting eight nearest-neighbor air holes in octagonal (eightfold symmetry) quasiperiodic photonic crystals (OQPCs). The WGM with its field distribution along the cavity boundary is less affected by adding a central post than the hexapole mode and the cavity size is smaller than that of microdisk lasers. Using this design, we observe single-mode lasing for a large wavelength range and identify the lasing mode as WGM from the well-fabricated devices. We further add a central air hole in the cavity region to increase the side-mode suppression ratio (SMSR).

There are two main reasons for fusing QPCs with microdisk cavities. First, the shape of QPC microcavity is similar with that of microdisk and the uniform symmetry is beneficial for sustaining WGM. Second, WGM in the QPC microcavity is sustained not only by total internal reflection (TIR) effect but also by the photonic band gap (PBG) effect. Thus, the problem of Q factor decreasing in microdisk laser when minimizing the cavity size could be solved. This kind of fusion for dodecagonal (12-fold symmetry) QPC (DQPC) microcavities formed by seven missing air holes has been investigated and demonstrated.[11–13] In fact, a good fusion can also be achieved in OQPCs by only a single missing air hole. We design a modified single-defect OQPC microcavity with cavity size smaller than the diffraction limitation. In our simulations, the mode profile is calculated by finite-difference time-domain (FDTD) method with an approximated refractive index of 2.7. Originally, the single-defect OQPC cavity supports a dipole mode. In order to obtain the well-confined WGM, the constructive interference condition has to be satisfied at the cavity boundary and the standing wave should be formed in the gears formed by the nearest air holes of the microcavity. Therefore, the eight nearest-neighbor air holes are shifted outward from position A to position B until the distance between two air holes is equal to the lattice constant, as shown in Fig. 1(a). The well-confined WGM profile in magnetic field with azimuthal number 4 of the modified microcavity is obtained and shown in Fig. 1(b). The number of lobes matches with the number of gears. The high-Q factor and large central node with zero field distribution of WGM are very promising and suitable for electrical injection structure used in microdisk lasers.

In fabrication, the epitaxial structure consisting of four 10 nm compressively strained InGaAsP multi-quantum-wells (MQWs) as the active layer with 1550 nm central wavelength under photoluminescence is prepared. First, the 140 nm silicon nitride (SiN_x) layer serving as hard mask for latter etching process is deposited on the epitaxial wafer by plasma-enhanced chemical vapor deposition (PECVD) system. And the polymethylmethacrylate (PMMA) layer is spin coated on the SiN_x layer. The QPC patterns are defined on the PMMA layer by electron-beam lithography and transferred to the SiN_x layer by reactive-ion etch (RIE) process with CHF_3/O_2 mixed gas. Then the patterns are further transferred to MQWs by inductively coupled plasma (ICP) dry etching with $CH_4/Cl_2/H_2$ mixed gas at 150 °C. At last, the membrane structure is formed by selective wet etching

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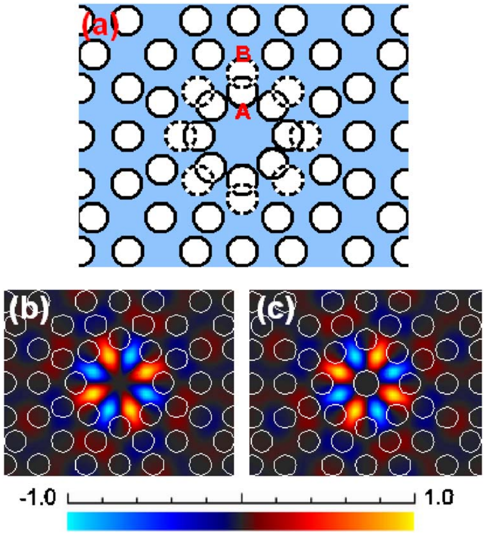

FIG. 1. (Color online) (a) Schematic of a modified OQPC single-defect microcavity. Well-confined WGM profile in modified OQPC single-defect microcavity (b) without and (c) with a central air hole.

with the mixture of HCl and H_2O at 0 °C. The top view scanning-electron-microscope (SEM) picture of the modified OQPC single-defect microcavity is shown in Fig. 2(a). The fabricated air-hole radius (r) over lattice constant (a) ratio is 0.28. The cavity size is about 1.2 μm in diameter, which is smaller than the diffraction-limited size of microdisk lasers.

In characterization, the microcavity is optically pumped by an 845 nm laser diode with focused pump spot size 1.5 μm in diameter. To avoid the thermal problems, the pump condition is set at 0.5% duty cycle with 200 KHz repetition rate. The emitted light is collected by a multimode fiber and its spectrum is detected by an optical spectrum analyzer (OSA) with 0.05 nm spectrum resolution. The light-in light-out curve (*L-L* curve) and the typical lasing spectrum at room temperature of a modified OQPC single-defect microcavity with 0.28 r/a ratio are shown in Figs. 3(a) and 3(b). The threshold can be estimated as low as 0.3 mW. The central lasing wavelength is 1534.4 nm with full width at half maximum (FWHM) 0.15 nm and 25 dB SMSR. Its Q factor is about 7500, which is estimated from the measured linewidth near the transparency pump power. In order to identify the lasing mode, we fabricate various devices with different r/a ratios from 0.25 to 0.34. The measured wavelengths of the lasing mode quite agree with the calculated resonant frequencies of WGM. Hence, we can identify the lasing mode as WGM.

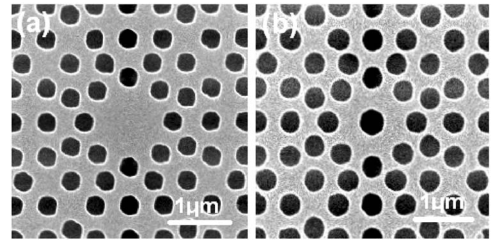

FIG. 2. Top view SEM pictures of modified OQPC single-defect microcavity (a) without and (b) with a central air hole.

Instinctively, one can add a central post or a central air hole in the cavity region without disturbing the WGM. In addition, the side mode can be reduced or destroyed due to this extra central post or central air hole. At first, we perform the FDTD simulation of the modified single-defect OQPC microcavity with a central air hole. The ratio of central air-hole radius (r') over lattice constant (a) is as large as 0.4. The well-confined WGM is still sustained in the cavity region as shown in Fig. 1(c). The top view SEM of fabricated cavity with a central air hole is shown in Fig. 2(b). In measurement, the WGM is not affected significantly as predicted and the estimated Q factor is 6800 which is only a little smaller than that without a central air hole. This further proves that the lasing mode is WGM. From the fabrication point of view, the larger central air hole or central post implies larger fabrication tolerance and less sensitivity of the WGM to the central air hole or central post. In addition, in the central post case, with larger post size, there would be lower electrical resistance and faster thermal transition compared with the smaller one. Thus, lower threshold voltage and better heat dissipation can be expected.

We also compare the lasing spectra with and without the central air hole. We fabricate two devices with similar lattice parameters, one is with the central air hole and the other without. The measured lasing spectra in decibel scale are shown in Fig. 4. One can see that the side mode is greatly reduced and the SMSR increases from 25 to larger than 30 dB after adding a central air hole. Besides, also shown in

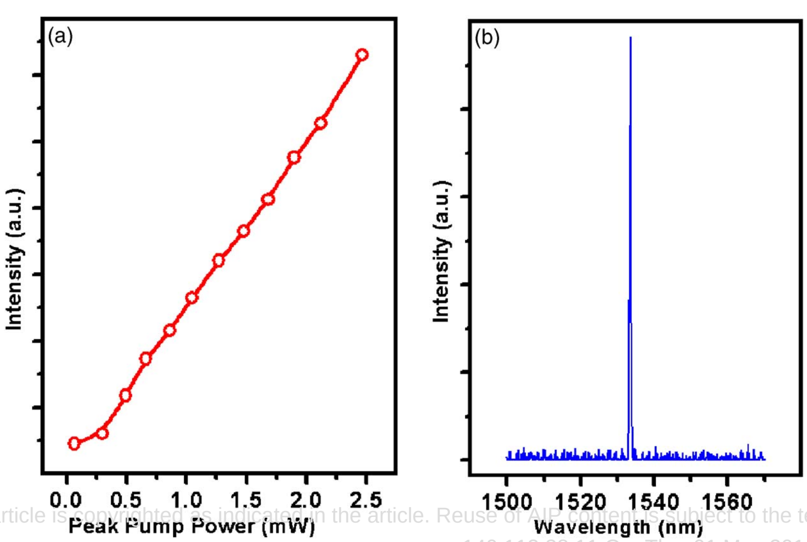

FIG. 3. (Color online) (a) *L-L* curve with threshold as low as 0.3 mW. (b) Lasing spectrum at 1534.4 nm with 0.15 nm FWHM.

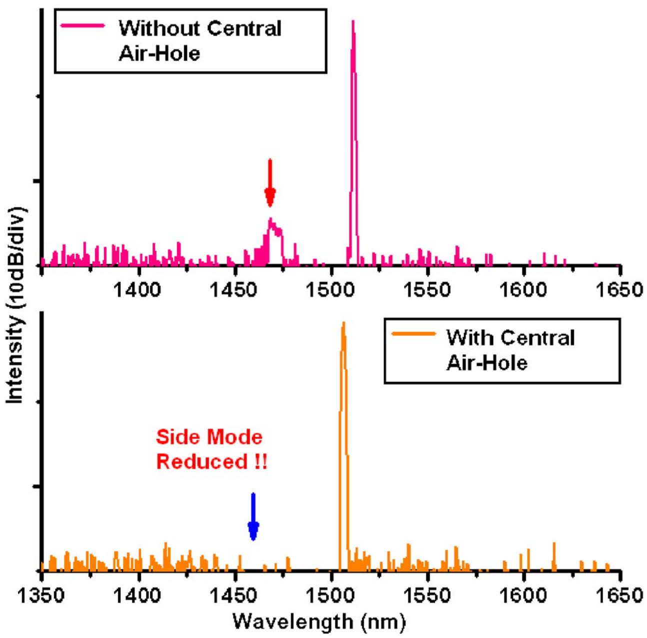

FIG. 4. (Color online) Lasing spectra in decible scale without (top) and with (bottom) a central air hole. The side mode is greatly reduced by inserting the central air hole.

Fig. 4, the lasing mode is not affected significantly by the added central air hole, which agrees with our simulation results quite well. We believe that similar results can be obtained for the central post case. This implies that this modified OQPC single-defect microcavity design is a promising structure for electrical injection with larger central post size tolerance.

In conclusion, we propose a new single-defect microcavity design in OQPC and the well-confined WGM with zero field distribution at the cavity center is obtained. We observe lasing action with an ultralow threshold of 0.3 mW and a high-Q factor of 7500 from the well-fabricated device. We also add a central air hole in the cavity region to reduce the side modes. Improved SMSR over 30 dB is obtained from the real devices.

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