HTML ABSTRACT + LINKS

Photonic quasicrystal single-cell cavity mode

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We propose and realize the photonic quasicrystal (PQC) single-cell resonator based on a InP-InGaAsP freestanding slab. A well-defined hexapole-like localized state following a $C_{6\nu}$ symmetry is identified from the PQC single-cell resonator. In this type of hexapole mode, the electromagnetic energy is strongly concentrated on the dielectric region, in contrast to that in a triangular lattice photonic crystal. By tailoring the structural parameters, the hexapole mode shows a maximum theoretical quality factor of ~20 000. The PQC single-cell resonator lases in a single hexapole mode with a threshold of ~0.6 mW at room temperature. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1852716]

The periodicity is the main keynote of the photonic crystal. Based on this simple feature, one can define Brillouin zones, draw the dispersion curves along their edges, and sometimes find photonic band gaps. The photonic crystal enables us to confine light in the small space comparable to its wavelength, exploiting the photonic band gap or anomalous dispersion characteristics that cannot be found in bulk materials.

A *quasi*crystal is a structure that cannot be indexed to any Bravais lattice and can be regarded as an intermediate state between the crystal and the amorphous states.[1] From the viewpoint of symmetry, the photonic quasicrystal (PQC) can be placed in a class between the periodic photonic crystal and the random lattice structure. Recently, it was reported that the photonic quasicrystal without any definite translational periodicity could also have a substantial photonic band gap in which very low transmission is observed.[2–4] In particular, Chan *et al.* proved the existence of a photonic band gap in an octagonal tiling structure by looking into the density of states.[2] The PQC has distinctive characteristics by insensitivity to the propagation direction and the long coherent-interaction-range order. These features have been utilized to make bent waveguides with low losses,[4,5] light-emitting diodes with high extraction efficiency,[6] and a new type of band-edge laser.[7]

However, up to date, few experimental efforts dealing with localized states in the PQC structure have been reported, except that Baba *et al.* have recently reported a whispering gallery-type laser (a seven-hole-missing cavity) based on a QPC, although the employed structure is represented by the triangular lattice on a large unit cell.[8] In this letter, we introduce a unique two-dimensional PQC single-cell resonator structure and study the characteristics of the localized states existing in the PQC single-cell cavity.

The PQC [the inset of Fig. 1(b)] can be classified as a *dodecagonal* structure constructed by combining equilateral triangles and squares, keeping 12-fold rotational symmetry as a whole.[9] Thus, the distance (a) between every two closest neighboring points is identical. A Fourier transform of this real structure confirms the 12-fold rotational symmetry, as depicted in Fig. 1(a). Twelve white spots appear in the reciprocal space and the distance between each point in the first circle indicates the basic reciprocal vector $2\pi/a$. In order to identify the existence of the low-transmission region, we investigated the transmission spectrum through the PQC slab structure by using the three-dimensional finite-difference time-domain (FDTD) simulation.[3,9] In this computation, the air-hole radius of the PQC (r) is $0.25a$ and the slab thickness (t) is $0.7a$. The refractive index of the slab is 3.4, the same as that of the InGaAsP material used in the experiment. Dipole sources (TE) covering omnidirectional wave vectors whose center-normalized frequency (a/λ) varies from 0.1 to 0.9 were imposed on the left, inside the slab, as shown in the inset of Fig. 1(b). The transmission spectrum was recorded at the multiple points on the opposite side, and then summed. Electromagnetic waves excited from the sources can tunnel the PQC structure only if they are coupled to the guided modes available in the PQC structure. In the transmittance spectrum [Fig. 1(b)], we can find the very low transmission region at the normalized frequency between 0.23 and 0.61, where light barely penetrates through the PQC. Note the transmittance is less than −30 dB.

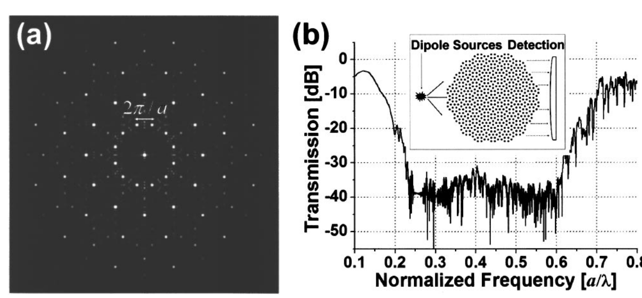

FIG. 1. (a) A Fourier representation of a dodecagonal structure. Twelve white spots are visible around the origin of the reciprocal space. The distance of two closest neighboring spots in the first circle indicates the basic reciprocal vector $(2\pi/a)$. (b) The transmittance spectrum of the dodecagonal structure with the radius of air holes (r) of $0.25a$ obtained by using the three-dimensional FDTD method. The refractive index and the slab thickness are 3.4 and $0.7a$, respectively.

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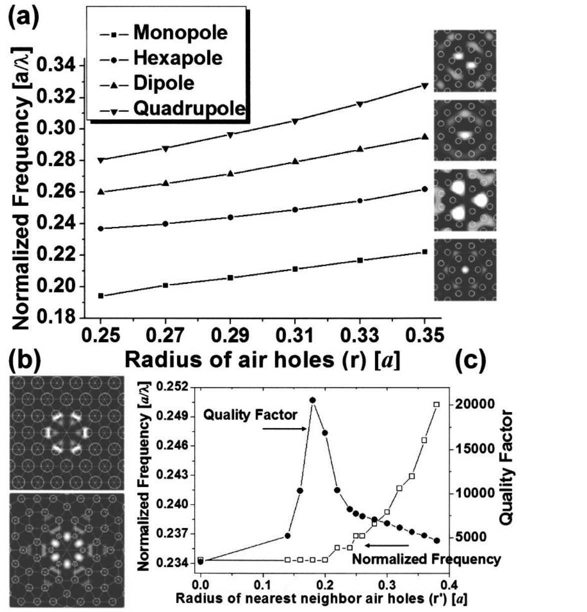

FIG. 2. (a) Plot of the normalized frequencies (a/λ) of all elementary modes in a PQC single cavity versus the radius of air holes (r) and their magnetic-field profiles (on the right). (b) Typical intensity profiles of the hexapole mode of a triangular photonic crystal lattice (on the top) and a dodecagonal PQC (on the bottom). (c) Plot of the resonant normalized frequency (a/λ) and the quality factor of the PQC hexapole mode versus the radius of nearest-neighbor air holes (r').

In general, the PQC resonator can support distinctive localized modes depending on the location of a filled single air hole, because all points are distinguishable owing to their nonperiodicity.[2] Taking advantage of the highest symmetry of the PQC structures, we place the single cell at their center to obtain the well-confined modes near the cavity. Note that the central point in the PQC structure is a unique position to obtain 12-fold symmetry. In designing the single cell, we tune the two parameters: the radius of the nearest-neighbor air holes (r') and the rest air holes (r).

In the PQC single-cell cavity, all the elementary localized modes (monopole, hexapole, quadrupole, and dipole) maintaining $C_{6\nu}$ symmetry showed up as in the triangular lattice photonic crystal single-cell cavity by varying the radius of air holes (r) [Fig. 2(a)].[10] This implies that the PQC single-cell cavity with 12-fold symmetry (except for the first layer with sixfold symmetry) can support the localized states similar to those of the triangular lattice structure. It is worth mentioning that the spectral distances between any adjacent elementary modes are much larger than those of the triangular lattice photonic crystal.[10] Thus, it is much easier to excite a pure single resonant mode within the bandwidth of a typical photoluminescence spectrum. The well-isolated mode is generally advantageous to achieve a high spontaneous emission factor. This relatively larger spectral separation results partly from the mode profile spread out effectively to the third layer that allows distinctive dielectric filling factors for different modes.

Among all localized modes found in the simulation, we paid special attention to the hexapole mode with three node lines. The hexapole mode is known to have smaller vertical losses than other elementary modes in the triangular lattice photonic crystal.[11] This is ascribed mostly to the destructive interference of electric fields with alternating phases. It is important to note that the intensity profile of the electric field of the hexapole mode in the PQC single cell is rotated by 30° relative to that of the triangular lattice photonic crystal [Fig. 2(b)]. Generally, a single-cell cavity mode originates from an extended state at a band-edge point, so that their profiles are identical to each other, except for the degree of confinement. Thus, the hexapole mode in the PQC (triangular lattice photonic crystal) single-cell cavity can be considered to reflect a dielectric-band (air-band) profile. The intensity profile of the electric field of this PQC hexapole is concentrated strongly on the dielectric region between the nearest-neighbor holes. According to our computation, the overlap factor of the electric-field intensity and the dielectric region in the PQC hexapole mode is about 99%. For comparison, for the hexapole mode in a triangular lattice or the whispering gallery mode in a square lattice,[12] the overlap factor is about 50%. Since the high-intensity region is away from the semiconductor/air interface, the mode is much profitable to obtain the gain. Furthermore, the good overlap factor is essentially necessary in cavity quantum electrodynamics experiments to observe very low power photon sources.

Fixed at $r=0.25a$ and $t=0.7a$, we investigated the resonant frequency and the quality factor of the hexapole mode as we varied r'. As depicted in Fig. 2(c), the resonant frequency remains nearly unchanged when r' is less than $0.20a$, because the electric field of the hexapole mode hardly overlaps with the air-hole region. This is the other consequence of the high concentration of the hexapole-mode electric-field intensity on the dielectric region. However, the quality factor changes continuously in the range where the resonant frequency is nearly fixed. In fact, the quality factor depends strongly on r', and it has a maximum value of 20 000 when $r'=0.18a$. This implies that the whispering gallery-type hexapole mode with an angular momentum number of 6 undergoes little scattering loss when the total one-round-trip length reaches 3λ at specific condition. The quality factor of other localized modes of the PQC single cell is smaller by one order of magnitude than this value. When the quality factor of the hexapole mode has the highest value ($r'=0.18a$), the effective mode volume was 2.8 $(\lambda/n)^3$ (Here, n is the refractive index of the slab.). The mode volume is relatively larger than that of the triangular lattice photonic crystal hexapole mode.[11] With this quality factor and effective mode volume, the Purcell factor was estimated to be 560.[11]

Experimentally, we fabricated the PQC single-cell resonators on InP-InGaAsP freestanding slabs, targeting to excite the hexapole mode. In the middle of the slab, six pairs of InGaAsP quantum wells emitting near 1.55 μm were used as the active material and the thickness of the quantum wells is

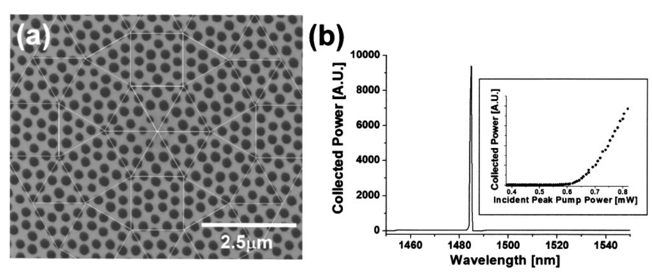

FIG. 3. (a) A scanning electron microscope image of the final processed PQC with a distance (a) of 370 nm, the radius of air holes (r) of $0.33a$, and the radius of nearest-neighbor air holes (r') of $0.27a$. (b) A typical spectrum and *L-L* curve from photoluminescence experiments.

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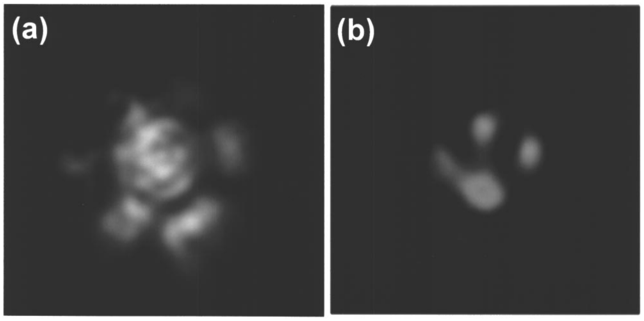

FIG. 4. By adjusting the distance of the lens and the sample, the far-field image (a) and the near-field image (b) were recorded by a CCD camera.

282 nm. The dodecagonal PQC patterns were defined on the poly(methylmethacrylate) (PMMA) deposited on the InP sacrifice layer and the air holes were perforated by Ar/Cl_2 chemically assisted ion-beam etching using the PMMA mask.[13] The InP layer at the bottom of the InGaAsP quantum well was then selectively dissolved with a dilute HCl solution to form a freestanding structure.

Figure 3(a) shows the scanning electron microscope image of a final processed PQC structure. We tried several different lattice spacings (a) from 350 to 400 nm and varied both r and r'. The fabricated sample was pulse-pumped by an external 980 nm laser diode. The pulse width was 10 ns and the duty cycle was set to be 0.5% to avoid thermal heating. Figure 3(b) shows the measured spectrum of the PQC laser operating in a single mode and the threshold was about 0.6 mW at room temperature from the *L*-*L* curve (collected laser output power versus incident peak pump power), shown in the inset of Fig. 3(b).

In order to identify the lasing mode, the focused and the slightly defocused image (close to a far-field image) were recorded, using a 50× objective lens and a CCD camera. By adjusting the distance between the objective lens and the sample near the focal point of the lens, we took the far- and the near-field images, as shown in Figs. 4(a) and 4(b), respectively. First, in the slightly defocused image [Fig. 4(a)], the six bright lobes around the center of the sample were observed. This is one of the signatures of the hexapole mode with sixfold symmetry. Figure 4(b) represents the near-field image, and the dashed white line in the figure indicates the portion of the fabricated PQC structure. In accordance with the central node of the hexapole mode, the near-field intensity was hardly concentrated upon the center of the single cell. However, six distinct spots are not clearly resolved on account of the limited resolution of the lens. From the spectrum near the transparency condition, we can estimate the experimental quality factor from the spectral line width. The spectrometer-limited quality factor (∼2000) was smaller than the theoretical value.

In summary, we investigated the localized modes in the dodecagonal PQC single-cell cavity. Inside the low transmission region of the PQC, four types of localized modes with large spectral separation were identified in the vicinity of the single cells. By tailoring the structural parameters ($r=0.25a$, and $r'=0.18a$), the theoretical quality factor of the hexapole mode can be tuned up to ∼20 000. In the experiment, the PQC single-cell cavity was fabricated on the two-dimensional InGaAsP-InP freestanding slab. This resonator lased in a single mode with a threshold of about 0.6 mW at room temperature. From the CCD images representing six lobes and the central node, the lasing mode was confirmed to correspond to the hexapole mode. Considering the high concentration of the electromagnetic field energy on the dielectric region, the central intensity node, the large separation from other modes, the high Purcell factor, this PQC hexapole mode will be of potential use for quantum optics applications in addition to low-threshold light sources.

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