Nondegenerate monopole-mode two-dimensional photonic band gap laser

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We propose and demonstrate photonic band gap lasing action from a nondegenerate monopole-mode, high-quality factor cavity. By optical pumping at room temperature, the monopole-mode laser is realized and identified from its mode shape, spectrum, and polarization. The monopole-mode laser shows nondegeneracy and genuine two-dimensional oscillation with incident threshold pump power less than 0.3 mW. This laser mode has a small modal volume of \( \sim 4.5(\lambda/2n_{\text{slab}})^3 \) and shows a quality factor of larger than 1900, estimated from the spectral linewidth below threshold. © 2001 American Institute of Physics. [DOI: 10.1063/1.1416163]

The photonic crystal is an artificial material whose optical properties can be engineered to the taste of the designer.1–3 Specifically, the concept of photonic band gap (PBG) opens up the possibility of the active control of photons1–3 and attracts hope for the ultimate zero-threshold laser. To realize the ultimate laser, the resonant cavity should meet two requirements: the size of the cavity should be an order of wavelength and the quality factor \( Q \) factor of the optical cavity should be high.6 The physical dimension of the cavity determines the number of photon modes available for a given cavity. It can easily be argued that the best choice is the cavity allowing just one single mode. Then, all the photons generated inside the cavity are forced to funnel through this single mode to come outside. However, just the small cavity does not guarantee the true single mode condition. When a single defect cavity is formed in the photonic crystal, doubly degenerate dipole modes are commonly observed.7,8 Here, we propose and demonstrate the nondegenerate monopole-mode two-dimensional (2D) PBG laser having a high-\( Q \) factor, emitting 1540 nm at room temperature. This truly nondegenerate monopole-mode remains single mode even under asymmetric structural perturbation and is expected to have a large spontaneous emission factor. The monopole-mode laser has the modal volume of \( \sim 4.5(\lambda/2n_{\text{slab}})^3 \), where \( n_{\text{slab}} \) is the refractive index of the slab material, and shows unambiguous 2D lasing oscillation with low threshold.

For our PBG lasers, free-standing 2D triangular photonic crystal slab structures are employed.7,8 In the slab structure, photons are confined in lateral and vertical directions, respectively, by PBG of periodic triangular photonic crystals and total internal reflection between air and the slab. A simple way to make a small single defect cavity is by removing one hole in otherwise regular photonic crystals. This simple single defect cavity supports only dipole modes that are doubly degenerate. The Caltech group introduced intentional asymmetry to lift this degeneracy and reported demonstration of lasing action.9 However, splitting of this mode by any asymmetry increases optical losses and thereby decreases the \( Q \) factor of the resonant mode.8 On the other hand, it is known that by modifying the properties of the defect, four different resonant modes (monopole, dipole, quadrupole, hexapole modes) can be generated.5 Among these four modes, the monopole mode draws our attention since the hexagonal symmetry of this mode indicates the nondegeneracy. In routine single defect structures, the monopole mode is buried in the air band. Therefore, we try to tune the resonant frequency of this mode to the middle of the PBG where photon confinement should be efficient. If one decreases the size of nearest neighbor air holes, the effective size of the cavity is slightly enlarged. Accordingly, initially in the air band the monopole mode can be pulled down into the band gap. Experimentally, as shown in Fig. 1, we reduce and push away the nearest neighbor holes around the defect. The intensity profile of this localized mode is plotted in Figs. 2(a) and 2(c) by the three-dimensional (3D) finite difference time domain (FDTD) method.10 Note that the monopole-mode profile has good overlap with the defect region where

FIG. 1. The SEM image of a fabricated sample. By reducing and pushing away the nearest neighbor holes around the defect, the monopole mode is pulled down into the band gap. In this picture, lattice constant \( a \) and hole sizes \( (r, r') \) are as follows: \( a = 0.57 \mu \text{m} \), \( r = 0.33 a \), and \( r' = 0.22 a \). Slab thickness is \( 0.35 a \).

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gain is generated. This property is advantageous to the lasing action.

To fabricate the monopole-mode laser experimentally, indium gallium arsenic phosphide (InGaAsP) quantum wells are used as an active material whose photoluminescence peak is located at 1.55 \( \mu \text{m} \). The fabrication process of the PBG laser cavity is as follows. Polymethylmethacrylate (PMMA) is coated on the laser structure and triangular PBG patterns are written by electron-beam lithography. \( \text{Ar/Cl}_2 \) chemically assisted ion beam etching is performed to drill down to the waveguiding region. After PMMA is totally removed, chemical wet etching completes the slab. The scanning electron microscope (SEM) image of the top view of the finished structure is shown in Fig. 1. Various lattice constants and hole sizes are tried following the guidance of the 3D FDTD calculations. The lattice constant, \( a \) varies around 0.55 \( \mu \text{m} \). The hole sizes, \( r \) (regular holes) and \( r' \) (nearest neighbor holes) are changed around 0.35 \( a \) and 0.225 \( a \), respectively. The actual size of the hole is estimated by averaging several holes adjacent to the center.

The PBG lasers are tested by optical pumping at room temperature. A 980 nm laser diode is used as a pumping source with \( \sim 10 \) ns pulses of \( \sim 1\% \) duty cycle. A \( \times 50 \) microscope objective lens is used to focus the pump beam to \( \sim 3.5 \) \( \mu \text{m} \) and to collect output light coming out of the slab structure. Rich PBG lasing modes are observed from various samples that have different lattice constants and hole sizes. Experimentally observed frequencies of lasing modes are summarized and compared with the calculated values in Fig. 3. Dot symbols represent the experimental values and lines are the calculated results obtained from 3D FDTD calculations using parameters taken from the samples used for the experiment. Circular dots follow the frequency dependence of the monopole mode and square dots seem to follow that of the split quadrupole modes.

The monopole mode has several characteristics inherent to it. As shown in Fig. 2(b), the mode profile has hexagonal symmetry with an intensity node at the center. The dim hexagon around the donut-shaped light signifies these characteristics visually and compares well with the mode profile shown in Fig. 2(a). This genuine 2D transverse electric-like mode oscillates radially in the plane of the slab with respect to the center of the cavity utilizing the full 2D PBG. And the direction of polarization varies with the angle of propagation in the plane of the slab waveguide and is perpendicular to the propagating direction as shown in Fig. 2(d). Therefore, when observed from the top, the resultant output beam is measured unpolarized as verified in Fig. 4(a). The noncircular shape of the polarization data is attributed to the asymmetry introduced during fabrication processes of PBG patterns and polarization-dependent optical components used in the measurement. In the case of the quadrupole mode, the polarization data shows a minimum along a certain direction.

Experimentally, the monopole mode is observed to retain its nondegeneracy over a broad frequency range in spite of unavoidable asymmetric PBG patterns. This fact ensures more efficient coupling into the solely available mode and thereby provides the larger spontaneous emission factor as compared to the other degenerate modes. In addition, spatially adjacent modes are located farther than the spectral width of the photoluminescence of the InGaAsP quantum wells. Therefore, most of the spontaneous emission will be
effectively coupled into this one nondegenerate monopole mode. As one can witness from the inset of Fig. 4(b), no other resonant mode is observed when the monopole mode is lasing.

The $Q$ factor is a good criterion to check optical losses of a resonant cavity. The $Q$ factor of the monopole mode is measured and compared with the value calculated by the 3D FDTD method. With the radius of regular air holes and slab thickness fixed to $r = 0.35 \text{ a}$ and $t = 0.35 \text{ a}$, respectively, resultant total $Q$ factors are calculated as a function of the radius of the nearest neighbor holes (Fig. 5). The vertical and the in-plane $Q$ factor are shown separately to compare optical losses into the vertical and the in-plane directions. The in-plane $Q$ factor should increase monotonically as one enlarges the calculation domain. Therefore, the total $Q$ factors are to be limited by the vertical losses.\(^\text{8,11}\) Here it is shown that total $Q$ factor of the monopole mode is over 1500 which is larger than that of the dipole mode. The maximum vertical $Q$ factor of the monopole mode ($\sim 3700$) is found to be larger than that of the dipole mode as well as the in-plane $Q$ factor. In fact, the $Q$ factor can be made even larger by adjusting the position and size of the nearest holes. For the monopole mode, the electric field is well confined vertically within the slab as shown in Fig. 2(c), indicating smaller coupling into the vertical direction. Experimentally, the below-threshold linewidth of the monopole resonance is $\sim 0.8 \text{ nm}$, which sets the lower bound of the total $Q$ factor as $\sim 1900$. This value compares reasonably with the calculated $Q$ factor considering the resolution of the spectrometer of $0.8 \text{ nm}$.

In Fig. 4(b), the collected power at the lasing wavelength is plotted as a function of the peak pump power incident on the sample. About 10% of the incident beam is absorbed to generate carriers. The peak threshold pump power is less than 0.3 mW. Considering our pumping conditions, the threshold power of the monopole mode is smaller than those of the other modes.\(^\text{12}\) This reduction of the threshold is attributed to the nondegeneracy, the high-$Q$ factor and the good overlap of optical mode with the gain medium.

The fact that the monopole mode has an intensity minimum at the center can be used preferably for electrical current pumping. In fact, the introduction of a post of small radius at the central node hardly affects the characteristics of the monopole mode. We found that the $Q$ factor of the monopole mode with a post is not degraded noticeably. Moreover, the other resonant modes will be discouraged by the additional loss originating from the central post. Therefore, this structure might be advantageous for single mode lasing action by electrical pumping in the near future.

Here, we propose and demonstrate the PBG lasing action from a nondegenerate monopole-mode, high-$Q$ factor PBG cavity. The monopole-mode laser has the modal volume of $\sim 4.5(\lambda/2d_{\text{slab}})^3$ and shows unambiguous 2D lasing oscillation with low threshold. We believe this monopole-mode PBG laser is a strong candidate for the ultimate zero-threshold laser.

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