Small, low-loss heterogeneous photonic bandedge laser

Soon-Hong Kwon, Se-Heon Kim, Sun-Kyung Kim, and Yong-Hee Lee

Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, 305-701 Korea
soonhong.kwon@gmail.com

Sung-Bock Kim

Telecommunication Basic Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon 305-600, Korea

Abstract: We have demonstrated the operation of a new type of heterogeneous photonic crystal laser, a five-lattice-constant large photonic bandedge laser assisted by a photonic bandgap, in a triangular lattice at room temperature. When the air hole radius of the surrounding photonic crystal (PC) is slightly smaller than that of the bandedge mode region, most in-plane losses of the first K point bandedge mode in the central region are suppressed and the quality factor of the mode is greatly enhanced to 50000. We identified the photonic bandgap-bandedge (PBG-BE) lasing modes through the spectral position, near-field pattern, and the state of polarization, which correspond well with the results of the three-dimensional (3D) finite-difference time-domain (FDTD) method computation. The two-dimensional (2D) feedback mechanism of the first K bandedge was verified through the Fourier analysis. Low threshold incident peak pump power of ~ 0.24 mW is achieved owing to the low optical loss of the PBG-BE mode.

OCIS codes: (230.5750) Resonators; (140.5960) Semiconductor lasers.

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1. Introduction

Since Yablonovitch and John firstly demonstrated the concept of photonic bandgap (PBG) materials in 1987 [1,2], these materials have attracted much attention as new building blocks in photonics, primarily owing to the capacity to control photons at the scale of wavelength. In particular, various photonic crystal (PC) lasers have been studied by many groups worldwide owing to demand for submicron sized coherent sources for photonic integrated circuits. In order to fulfill the conditions for efficient small sources, i.e., high quality factor, low threshold, and high coupling ratio with waveguides, various types of cavity structures such as single defect [3], ring type [4], stick type [5], slab edge [6], and coupled cavities [7] have been proposed and studied. In most PC lasers, the PC functions as a mirror. Several groups have meanwhile taken notice of the possibility that the flat dispersion curve near the photonic bandedge in the band structure can be used for lasing operation [8-14]. The group velocity near the bandedge is zero because of coupling between the Bloch waves. Photons in the PC can then interact with an active material for a lengthy period, which results in lasing operation. Recently, photonic bandedge lasers have been realized in organic material [13] and semiconductor quantum wells [8-11]. Both our research team and Monat *et al.* have shown lasing operation of the photonic bandedge mode in a sample with a small active area ~ (10×10 μm) using a two-dimensional (2D) slab structure [9-11]. However, in a real sample, the group velocity of the bandedge mode becomes nonzero due to the finite size of the PC pattern [14] and consequently in-plane loss, i.e., propagation of the mode out of the pattern through the slab, is unavoidable. On the other hand, the bandedge mode below the light line is vertically well guided inside the slab. Therefore, if the in-plane loss can be reduced, the bandedge mode would have very low loss.

In this paper, we propose a new heterogeneous photonic crystal cavity structure based on the bandedge mode. In order to prevent in-plane loss, the outer photonic bandgap region is introduced to contain the central bandedge mode. In other words, the resonant frequency of the central bandedge mode lies within the photonic bandgap of the surrounding PC structure, and then the in-plane loss of the bandedge mode will be minimized. In general, a PC pattern can be modified by changing several parameters such as lattice constant, air hole radius, and lattice geometry. Here, we changed the air hole radii of the surrounding PC structure and investigated the characteristics of heterogeneous photonic crystal bandedge lasers in free-standing slab triangular lattice structures at room temperature. Because the photonic bandgap assists the lasing of the bandedge mode, we call this type of laser a photonic bandgap-bandedge (PBG-BE) laser. We identified the lasing mode from the spectral position and polarization characteristics, and compared them with theoretical calculations based on the three-dimensional (3D) finite-difference time-domain (FDTD) method.

2. Design and Fabrication

Six pairs of InGaAsP quantum wells with an emission peak at 1.55 μm are embedded in the center of the slab. We constructed triangular lattice structures by electron beam lithography and Cl_2-assisted Ar-beam etching techniques. The InP sacrificial layer below the slab was removed using a diluted $HCl:H_2O$ (4:1) solution through the etched air holes to form free-standing slabs. The thickness of the slab is 282.5 nm, which supports only the fundamental

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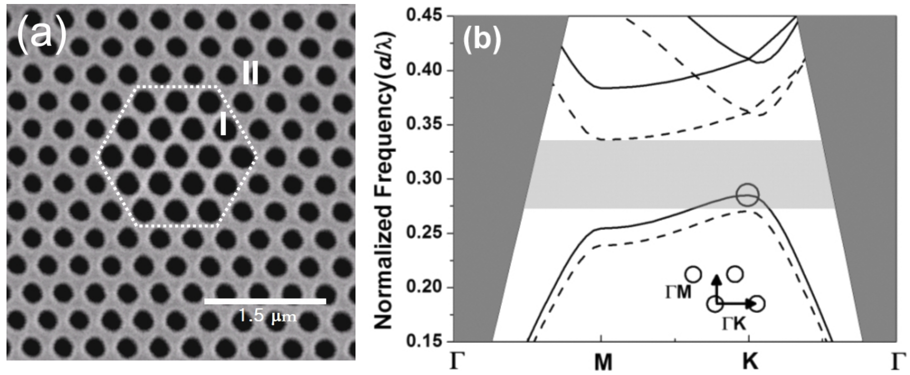

Fig. 1. (a) Top-view scanning electron microscope (SEM) image of a fabricated PBG-BE laser. The lattice constant is 390 nm. The air hole radius of the central hexagon region (I) with five holes along the ΓK direction, and that of surrounding region (II) are 137 nm (0.35*a*) and 117 nm (0.30*a*), respectively. The dotted white hexagon indicates the boundaries of the central region. (b) The band structures calculated by the 2D plane-wave expansion method. X-axis indicates wavevector. The solid lines and the dashed lines correspond to a band structure of air hole radius 0.35*a* and 0.30*a*. The regions above the light line are filled by dark gray, in which modes are leaky. The transparent gray region indicates the photonic bandgap of a band structure with a radius of 0.30*a*. The circle corresponds to the first K point of the band structure with larger air holes, which is the operating point of our PBG-BE laser.

transverse electric (TE)-like mode. Air holes in the central region of the pattern have slightly larger radii (0.35*a*) than that of the surrounding air holes (0.30*a*). This cavity structure has a hexagon with five larger holes along the ΓK directions, as shown in Fig. 1(a). The overall shape of this cavity looks similar to the graded photonic crystal cavity with defects [15]. Since the normalized frequency of the band structure increases with the air hole radius, the frequency of the K point bandedge mode operating in the central region can be placed within the photonic bandgap of the outside region, as shown in Fig. 1(b). Here, the normalized frequency is defined as a ratio of lattice constant to wavelength. In the experiments, the air hole radii of the central region were designed to be in the range of 0.26*a* ~ 0.38*a* and the radii of the outside holes were designed such that they were 0.05*a* smaller than those of the central region. Outside of the central region is filled with 11 layers of smaller air holes. The lattice constants ranged from 325 nm to 414 nm with about 20 nm steps to match the gain region of the InGaAsP quantum wells into the first K point bandedge. The fabricated samples with various parameters were pulse-pumped using a 980 nm laser diode at room temperature. The pulse width was 7.5 ns and the duty cycle was 0.1 % to avoid thermal heating effect. The pumping beam was focused with a ×50 microscope objective lens (numerical aperture=0.85) and light emitted from the sample was collected in an infrared camera and a monochromator with the same lens positioned vertically to the sample surface. The pumping spot diameter was approximately 3.5 μm as a FWHM (full-width at half-maximum).

3. Results and discussion

A typical PBG-BE mode pattern in the lasing sample was captured by an infrared camera, as shown in Fig. 2(a). In contrast to that the mode pattern of the normal bandedge laser spreads over the PC region larger than the pump spot [11], the mode was located near the central region having larger air holes. The measured mode size was 2 μm (FWHM), which is smaller than the pump spot size, showing the bandgap effect of the surrounding region. In addition, the state of polarization was measured to confirm that the lasing mode originated from the first K point bandedge mode. The oscillation of the first K point bandedge mode results from the coupling several nonparallel wave vectors [13]. The Fourier-space electric-field intensity profile of the PBG-BE mode is obtained from the Fourier transform of real-space electric-field components calculated by FDTD, as shown in Fig. 2(b). Here, the lattice spacing *a* is

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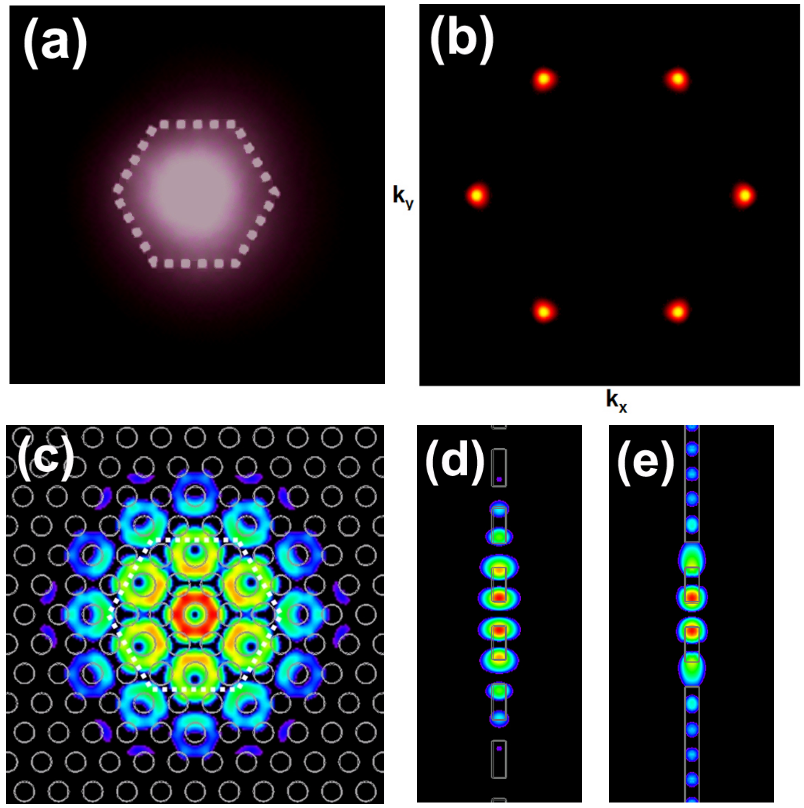

Fig. 2. (a) Typical mode pattern images of PBG-BE lasers taken by an infrared camera. The dotted white hexagon represents the boundaries of the photonic bandedge mode region, which is same with the central region (I) of the SEM image. (b) Fourier space field pattern of the PBG-BE mode. (c) Top-view and (d) side-view of the calculated electric-field intensity profile of the PBG-BE mode. The dotted white hexagon indicates the boundary of the bandedge mode region. (e) side-view of the first K point bandedge mode operating at the finite PC pattern with no surrounding air hole. The intensity is indicated by a logarithm scale.

dicretized to 20 mesh points for FDTD calculations. Note that the wave vectors are localized at the six K points in the Fourier space and these six unparallel wave vectors construct the mode simultaneously. This shows the 2D feedback mechanisms of the first K point bandedge mode. Therefore, the mode is expected to be unpolarized. In fact, the measured lasing mode displays no definite polarization direction, as shown in the inset of Fig. 3. In comparison, the one-dimensional (1D) distributed feedback (DFB) bandedge modes [11] such as the second X and second M points consists of a pair of anti-parallel wave vectors, hence the polarizations become linear.

To further understand the effect of the surrounding PBG, we theoretically compare the PBG-BE mode with the 'conventional' bandedge mode that exists in a sample with no surrounding air hole using 3D FDTD simulation, which does not contain the material absorption losses. For the structure used in this calculation, the air hole radius of central region and that of outside region were 0.35*a* and 0.30*a*, respectively. In the top-view and the side-view of the intensity profile of Fig. 2(c) and (d), the electric fields of the PBG-BE mode are well localized at the central region. On the other hand, in the case of the conventional bandedge mode below the light line, significant photon energy leakage out of the PC pattern is easily noticeable in Fig. 2(e). In terms of optical loss mechanisms, the role of the surrounding

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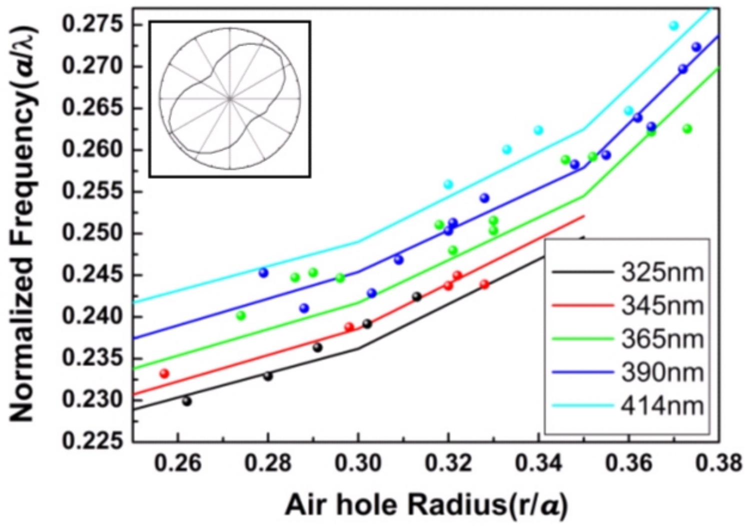

Fig. 3. The normalized frequency of the PBG-BE laser as a function of air-hole radius (r/a) for each lattice constant, a, 325 nm 345 nm, 365nm, 390 nm, 414 nm, which are indicated by black, red, green blue, and cyan, respectively. The dots and the solid lines represent the measured lasing positions and the calculated ones by the 3D FDTD method. The inset is the measured polarization states of the laser.

PC becomes clearer. In the conventional PC pattern having 21 air holes along the ΓK direction, the vertical and horizontal quality factors of the conventional bandedge mode are 37000 and 1200, respectively, i.e. the in-plane loss is dominant for the mode with total quality factor of 1160 [14]. Here, the quality factor Q is defined as follows.

$$Q = \frac{2\pi(\text{stored energy})}{\text{energy loss per cycle}} . \qquad (1)$$

For comparison, the PBG-BE mode with five larger air holes shows a much larger total quality factor of 50000. The vertical and horizontal quality factors are 55000 and 550000, respectively, showing the suppression of the in-plane loss. We decided to compare this PBG-BE mode with the resonant modes of a conventional large defect cavity with five-missing holes along the ΓK direction. The proposed hetero-structure can also be viewed as a modified large defect cavity structure. The quality factors of the modes at the unmodified large defect cavity are found to be only a few thousands, which are orders of magnitude smaller than that of the PBG-BE mode. The relatively large group velocity and the mode mismatch at the boundary of the central defect are partly responsible to this small quality value of the unmodified PC defect cavity modes compared with the PBG-BE mode of the hetero-structure.

In order to further identify the lasing mode, the measure normalized frequencies (plotted as dots) for each lattice constant are compared with the calculated frequencies (plotted as lines) as a function of air hole radius in the central region, as shown in Fig. 3. The normalized frequency of the lasing mode differs slightly from that of the first K point bandedge due to the wave vector uncertainty stemming from the finiteness of the central region [14]. Thus, the plane-wave-expansion (PWE) method cannot be used and hence the resonant frequencies in Fig. 3 are obtained through the 3D FDTD method. The measured spectral positions agree well with the theoretical predictions over a broad range of air hole radius for each lattice constant. The difference between simulations and experiments is less than 1 % of the normalized frequency, which correspond to an error of ~ 0.01a for the air hole radius measurement.

A typical output characteristic is shown in Fig. 4(a). The threshold pump power was measured to be 0.24 mW. In order to estimate the cold cavity quality factor, the slightly-below-threshold linewidth was taken with pump power of 0.22 mW, which makes the pumped

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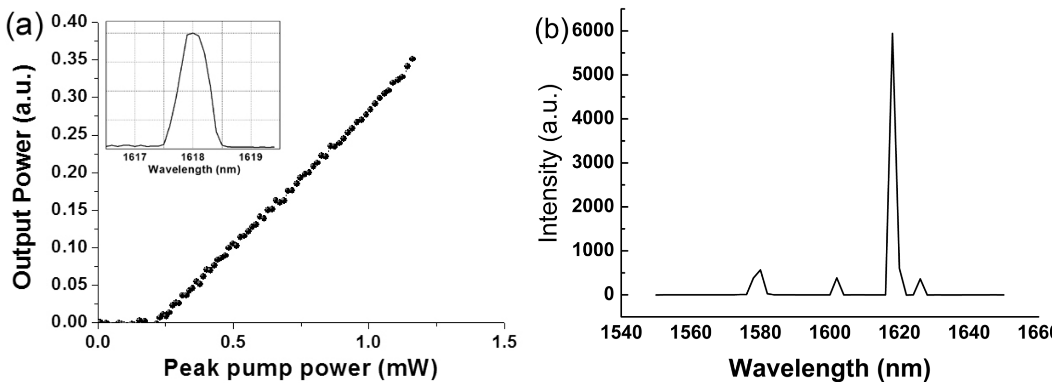

Fig. 4. Collected output power at the lasing wavelength is plotted for peak pump power. The threshold incident pump power is ~ 0.24 mW. The inset is the spectrum of the laser at the pumping power ~ 0.22mW. (b) The spectrum of the PBG-BE lasing mode at peak pump power of 0.35 mW.

PC region transparent. The spectrometer-limited linewidth of $\Delta\lambda$ ~ 0.6 nm was obtained, indicating the lower bound of the quality factor of 2700. This high quality factor is partly responsible for the low threshold. On the other hand, several small peaks were observed in the spectrum, as shown in Fig. 4(b). The peaks spread spectrally over 40 nm near the PBG-BE resonance. Thus, there may be two possibilities of small peaks. If a mode satisfies the resonant conditions of the five unit-cell cavity and experiences a flat dispersion curve near the bandedge, then the mode is allowed by the cavity. Another possibility is that other resonant peaks near the bandedge are created by small amount of deformation or imperfection in the real sample.

4. Summary

In summary, we have realized a new type of heterogeneous photonic crystal bandedge laser surrounded by a photonic bandgap near 1.55 μm. When the first K point bandedge mode operates in the central region, the surrounding photonic bandgap region suppresses the in-plane loss, which is dominant in the bandedge mode. Therefore, the quality factor of the mode becomes relatively high value of 50000. In fact, the lasing mode was confined in the central region, as shown in the near-field pattern, and the spectral positions of the lasers agreed well with the theoretical predictions. In addition, the polarization shows no definite direction, which originates from that the first K point bandedge mode are constructed by the 2D DFB mechanism. This is confirmed through the 2D Fourier field pattern of the mode. The heterogeneous laser has low threshold incident peak pump power of ~0.24 mW because of the low optical loss of the PBG-BE mode.

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