High-peak-power efficient edge-emitting photonic crystal nanocavity lasers

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Record-high edge-emitted peak power was collected from L3 and finite-waveguide two-dimensional photonic crystal nanocavity quantum well membrane lasers at room temperature under single-mode operations. Peak power levels of 230 μW and 540 μW were collected from L3 and finite-waveguide edge-emitters, and their quantum differential efficiencies are 11% and 27%, respectively, limited by their collection efficiencies in free space. © 2009 Optical Society of America

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As an on-chip source candidate, to our knowledge the two-dimensional photonic crystal (PhC) defect laser is so far the smallest laser that is capable of electrical injection [1], room temperature cw operation [2], and high bandwidth modulation [3]. To fill this role, sufficient in-plane output power is required for an on-chip receiver to operate at high speed and low bit-error rate, and more power is also preferred for having more functionalities on the planar lightwave circuit. We have previously reported 120 μW edge-emitted peak power from an optically pumped photonic crystal double-heterostructure (DH) nanocavity quantum-well membrane laser [4,5]. The estimated quantum differential efficiency (η_d) of this device is 7%, where η_d is defined as the number of photons collected per electrons injected (through optical pumping) above threshold. In this Letter, we report 230 μW peak power collected from an edge-emitting L3 nanocavity laser, whose η_d is 11%, and 540 μW peak power from a finite-waveguide (WG) laser, whose η_d is 27%. These data represent record peak-power levels collected from PhC defect mode lasers and PhC WG cavity lasers.

DH and L3 [6] high-quality-factor (Q) nanocavities are excellent choices for designing small-footprint in-plane lasers for their low out-of-plane losses ($Q_{\text{out-of-plane}} > 100{,}000$) and tiny mode volumes ($\sim(\lambda/n)^3$). By decreasing the number of cladding periods on one side, we experimentally increase their in-plane losses to surpass the out-of-plane loss. For the L3 cavity, we choose to open up its PhC mirrors in the direction in which the high-Q mode is most extended in space, which is 30 deg away from the line defect direction. This is an attempt to obtain a more directional emission pattern in the far field, so that the collection efficiency can be improved. This approach is also in accordance with the optimization result in the cavity-WG coupling design [7].

The fabrication and measurement setup are the same as those in [5]. The sample substrate is in thermal contact with a thermoelectric cooler set to be 20°C–21°C. An array of devices was made in which the number of PhC periods between the defect cavity and output port was varied. Figure 1(a) is a scanning electron microscope (SEM) image of the number 5 de-

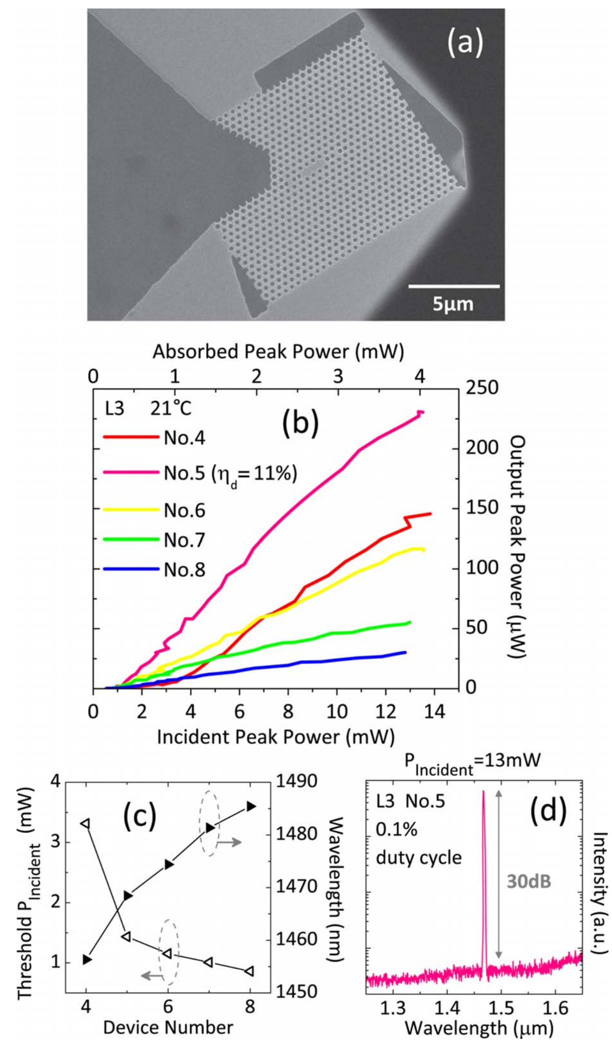

Fig. 1. (Color online) (a) Top-view SEM image of a fabricated PhC L3 cavity with five PC cladding periods on the facet side (number 5 device). (b) L-L curves of number 4, 5, 6, 7, and 8 devices. (c) Threshold and lasing wavelength behaviors versus device numbers. (d) Lasing spectrum of the number 5 laser.

vice, where the device number represents the number of cladding periods on the facet side of the defect. The lattice constant is 410 nm and the r/a (radius over lattice constant) value is 0.29. Light-in–light-out (L-L) curves of the laser array, ranging from device number 4 to number 8, are plotted in Fig. 1(b). The trends of their lasing wavelengths and thresholds are shown in Fig. 1(c). As the number of cladding periods decreases, the lasing wavelength blueshifts, since the average index of the mode decreases. Both the thresholds and slope efficiencies increase due to the increasing optical loss toward the facets when more PhC mirror periods are removed. The number 4 cavity is the device lasing with the least number of facet cladding periods. The highest peak power (230 μW) was collected from the number 5 laser. This lasing spectrum is shown in Fig. 1(d). The estimated η_d is 11%.

Recent studies have shown that a PhC single-line-defect WG laser might be an efficient edge-emitter with reasonable footprint [8,9]. We also fabricated an array of single-line finite-WG cavities with different defect lengths. Figure 2(a) shows an SEM image of the number 10 device with 410 nm lattice constant and 0.30 r/a, where the device number represents the number of defect periods of the finite-WG cavity. L-L curves of the number 8, 9, and 10 lasers are plotted in Fig. 2(b), and their lasing spectra are plotted in Fig. 2(c). Cavities shorter than eight periods did not lase, and cavities longer than ten periods suffered from multimode lasing. The number 10 laser, having the lowest threshold and highest slope efficiency, output 540 μW in peak power. The estimated η_d is 27%.

The number 10 finite-WG laser has a mode volume about twice as large as that of the L3 cavity [9]. Both types of edge-emitters operated at room temperature under single-mode operation. Low duty cycle pumping of 0.1% was used to alleviate device heating. The highest collected peak power was limited by the maximum output power from the 852 nm pumping laser.

Three-dimensional finite-difference time-domain calculations were done to study these two devices further using the same methodology described in [5]. Structural information used in the simulation of the L3 cavity was directly obtained from the top view SEM image in Fig. 1(a) through edge detection. The r/a of the PhC lattice shown in Fig. 2(c) is uniform, but the complete structural information of the finite-WG cavity couldn't be extracted from this top-view SEM image owing to the reflection of the electron beam off the underneath substrate on the right half of the device. Thus perfect lattice was drawn in the calculation. Passive Q and collection efficiencies were evaluated for these two cavities. The NA (NA=0.65) used for calculating the collection efficiencies is the same as that of the collection lens in the experiment. The L3 cavity is shown to have a passive Q of 3500, and 17% of its optical power can be collected in the experiment; the finite-WG cavity has a 1600 passive Q and a 35% collection efficiency. The difference in collection efficiency explains the difference in collected power levels.

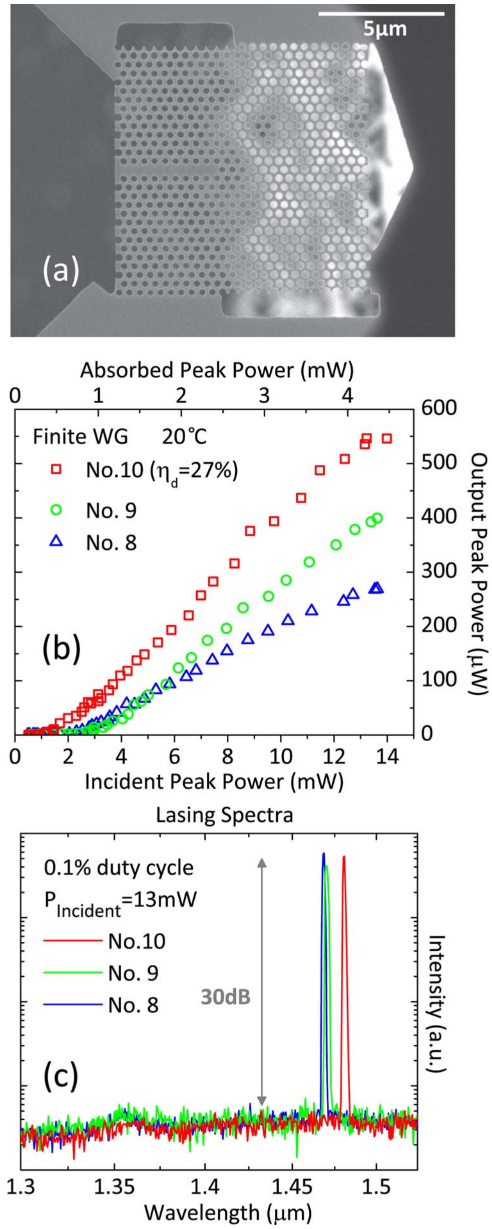

Fig. 2. (Color online) (a) Top-view SEM image of a fabricated ten-period-long PhC finite-WG cavity (number 10 device). (b) L-L curves of number 8, 9, and 10 devices. (c) Lasing spectra of the number 8, 9, and 10 lasers.

The mode profiles are shown in Fig. 3. They indicate that both laser modes couple to the surface modes existing at the device facets where the PhC lattice is terminated. They carry power away from the laser and, for the finite-WG cavity, the amount of power flowing along the facet is about 6% each in the up and down directions. However, the surface waves might be also responsible for the directional emission pattern in-plane (x–y plane) in Fig. 3(c), which is an interesting direction to collimate the laser beam emitting from a subwavelength aperture [10].

For our 2D PhC membrane structures, the collimation can be achieved only in plane. Along the z direction, the 240-nm-thick membrane diffracts the beam in wide angles and limits the collection efficiency as in the case of the number 10 finite-WG laser. In the

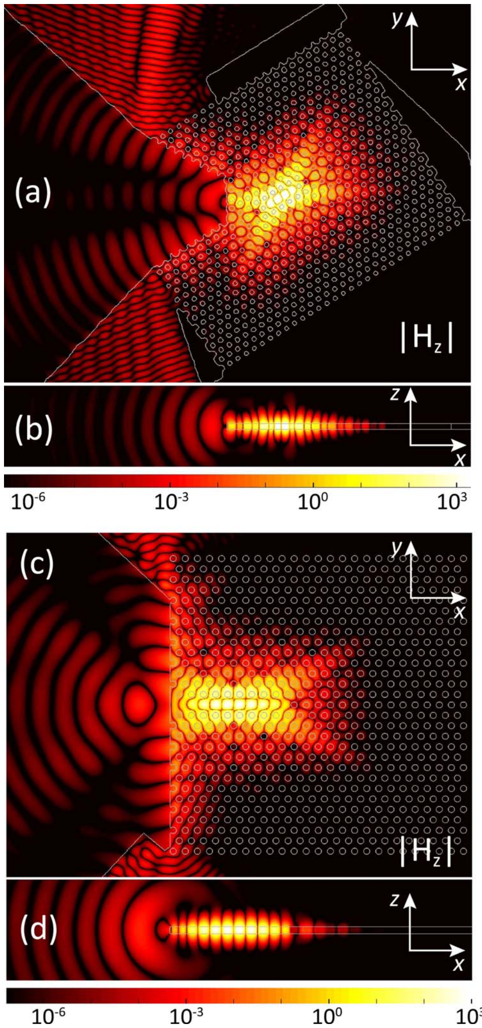

Fig. 3. (Color online) H_z field profiles of the lasing modes of the number 5 L3 edge-emitter (a), (b) and the number 10 finite-WG edge-emitter (c), (d). (a), (c) Field distribution in the *x*–*y* plane at the center of the membrane. (b), (d) Field distribution in the *x*–*z* plane through the device center. Index profiles of the device are outlined in gray.

integrated form enabled by quantum-well intermixing (QWI) [11] or regrowth [8,12], the laser power will be coupled into an adjacent WG in plane. This coupling efficiency can be engineered to be above 90% while maintaining a reasonable cavity Q (a few thousand) for low threshold operation [7,12]. We might expect to obtain 1.4 mW of peak power coupled into the WG and η_d of 70%, inferred from the finite-WG data.

Our results show that small lasers can potentially be as efficient as large ones and can provide sufficient in-plane output power for on-chip communications if their temperatures are kept low.

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