

## 120 $\mu\text{W}$ peak output power from edge-emitting photonic crystal double-heterostructure nanocavity lasers

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As an attempt to collect more in-plane emission power out of wavelength size two-dimensional photonic crystal defect lasers, edge-emitting photonic crystal double-heterostructure quantum well membrane lasers were fabricated by shortening the number of cladding periods on one side. 120  $\mu\text{W}$  peak output power was collected from the facet of the single mode laser at room temperature. Laser efficiencies were analyzed and agree very well with three-dimensional finite-difference time-domain modeling. © 2009 American Institute of Physics.

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The physical size of semiconductor lasers has been shrinking down to the wavelength<sup>1</sup> or even subwavelength scale,<sup>2</sup> which greatly increases the potential for dense photonic integration. However, the laser output power scales with its mode volume. As one of the smallest lasers that is capable of electrical injection<sup>3</sup> and continuous wave operation at room temperature,<sup>4–10</sup> two-dimensional (2D) photonic crystal (PC) defect lasers have not been shown to have sufficient collected output power ( $>50 \mu\text{W}$ ) for current on-chip optical receivers to operate at high bandwidth (10 GHz) and low bit-error rate ( $10^{-12}$ ).<sup>11</sup> In addition, most 2D PC defect lasers emit vertically instead of in-plane, which is the preferred direction for planar lightwave circuits. Their dominant out-of-plane loss has always been a bottleneck in engineering the direction of laser emission. Recently, the double-heterostructure (DH) cavity<sup>12,13</sup> was realized on 2D PC membranes with a quality factor ( $Q$ ) of more than 100 000 and mode volume as small as  $\sim(\lambda/n)^3$ , where  $n$  is the refractive index of the semiconductor membrane. This cavity's ultrahigh  $Q$  gives us the luxury to intentionally increase the in-plane optical loss by orders of magnitude so that it is much greater than its vertical loss and still be able to achieve lasing.<sup>14</sup> This was done by shortening the waveguide cladding on one side of the cavity, following up on the previous demonstration by Yang *et al.*<sup>15</sup> in which a DH nanocavity laser was demonstrated to edge-emit into a planar integrated PC waveguide. We expect that this approach will result in a single-sided edge-emitter with the potential for high collection efficiency at the output facet without going to a larger mode volume structure.<sup>16</sup>

To demonstrate this idea, DH cavities with an InGaAsP quantum well (QW) active region were fabricated in which each cavity had a different number of PC periods cladding one side of the central heterostructure. Their waveguide cores were aligned along  $\langle 01\bar{1} \rangle$  direction on a (100) InP substrate in order to open up the facet from etch stop planes in the final HCl undercut.<sup>17</sup> Fabrication of these devices followed the same procedures as in Ref. 18 with the addition that the sample was diced very near the end of the cavities in

order to facilitate the collection of the edge-emitted laser radiation.

Figure 1 is a scanning electron microscope (SEM) image of the number 5 device where the device number represents the number of cladding periods on the facet side of the heterostructure. All devices have 14 cladding periods on the other side and 14 periods in the direction perpendicular to the waveguide except the heterostructure region where more periods were added to ease identification. The lattice constant is 441 nm along the waveguide core only in the heterostructure region and 420 nm everywhere else. The  $r/a$  (radius over lattice constant) value is 0.306. The standard deviation is less than 2% in lattice constant and is about 3% in  $r/a$ . It is obtained from image analysis of Fig. 1 where the lattice is defined by the centers of mass of the air holes identified by an edge-detection algorithm.

These cavities were optically pumped by an 852 nm diode laser at normal incidence through a 100 $\times$  infrared-corrected objective lens at 21 °C substrate temperature. The pulse duration was 8 ns with 0.1% duty cycle. The size of the pump spot overlapping the field-confining heterostructure region was about 2  $\mu\text{m}$  in diameter. The output power was collected from the facet by a 60 $\times$  anti-reflection-coated aspheric lens with 0.65 numerical aperture (NA) and detected by an InGaAs photodiode. A piece of double-side-polished

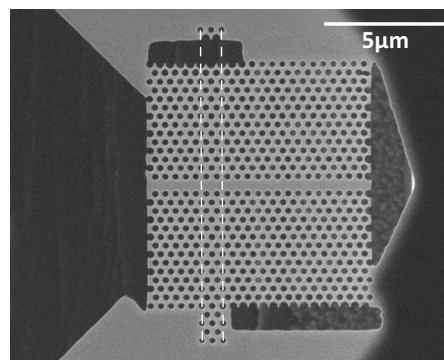


FIG. 1. Top view SEM image of a fabricated PC DH cavity with five PC cladding periods on the left. The heterostructure region is delineated with white dotted lines.

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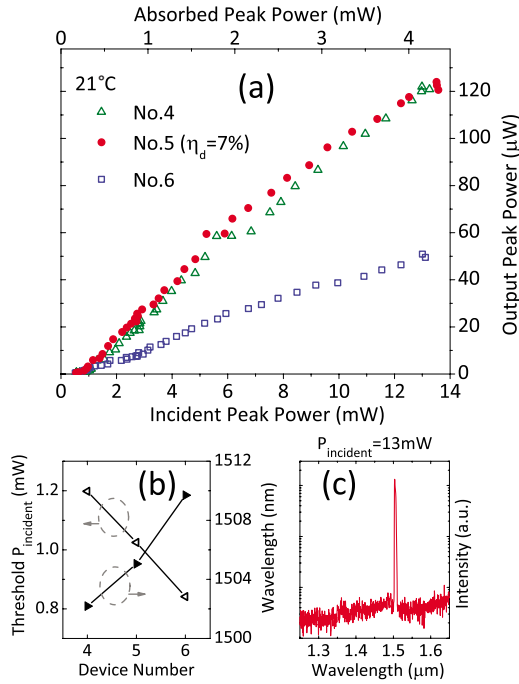


FIG. 2. (Color online) (a) L-L curves of number 4, 5, and 6 devices. (b) Threshold and lasing wavelength behaviors versus device numbers. (c) Lasing spectrum of the number 5 laser.

silicon wafer was used as a filter to verify that light from the pumping laser was not collected.

Light-in-light-out (L-L) curves of number 4, 5, and 6 lasers are shown in Fig. 2(a). Number 4 cavity is the device lasing with the least number of facet cladding periods. The trends of their lasing wavelengths and thresholds are plotted in Fig. 2(b). As the number of cladding periods decreases, lasing wavelength blueshifts since the average index of the mode decreases. Both their thresholds and slope efficiencies increase due to the increasing optical loss toward the facets when more PC mirror periods are removed. Number 4 and 5 devices output similar powers of 120  $\mu$ W at the highest pumping level. Number 5 laser has a lower threshold and its lasing spectrum is shown in Fig. 2(c).

This 120  $\mu$ W peak output power is much higher than that of any other PC defect mode lasers reported to date.<sup>14,19</sup> This number is edge-emitted power from a single cavity of small mode volume under single mode operation at room temperature. No optimization was done to engineer the far field or improve the coupling, and no disordering was done to the cladding mirror to reduce the QW absorption loss.<sup>20</sup>

The self-written codes<sup>21</sup> of three-dimensional finite-difference time-domain (3D FDTD) method was used to model the number 5 device.<sup>13,22</sup> The time step, spatial resolution, and semiconductor refractive index were 0.035 fs, 22 nm, and 3.4. The mode profile was obtained by discrete time filtering after broadband initial excitation. The filter was implemented as a Blackman window with 130 000 time steps convolution. The dielectric structure in calculation is directly taken from the top view SEM image in Fig. 1, in order to get an estimation of the passive quality factor ( $Q_{\text{passive}}$ ) of the fabricated device. The result is 4000 for  $Q_{\text{passive}}$  and the mode profiles are plotted in Fig. 3, which clearly shows a dominant facet emission. To calculate the radiated power, a time average of one oscillation period of the Poynting vectors is performed. Integrating the averaged Poynting vectors

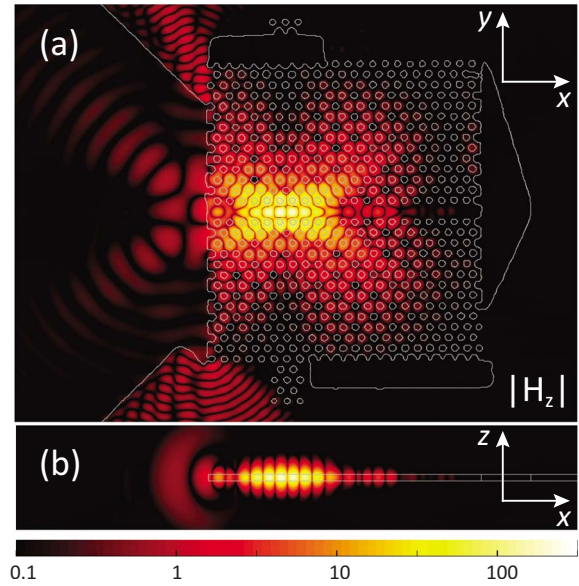


FIG. 3. (Color online) Mode profile of the number 5 edge-emitter, calculated by 3D FDTD using the structure information from its top-view SEM image. (a) Intensity plot of the vertical magnetic field ( $H_z$ ) distribution in  $x$ - $y$  plane at the center of the membrane. (b)  $H_z$  field profile in the  $x$ - $z$  plane through the center of its waveguide core. Index profiles of the device are outlined in both plots in gray.

over a conical area set by the NA of the collecting lens and dividing it by the integral over a closed surface containing the whole DH mode, we get 18% for collection efficiency ( $\eta_{\text{collection}}$ ). Poynting's theorem is numerically verified along with this calculation and the accuracy is within 1%.

The differential quantum efficiency ( $\eta_d$ )<sup>23</sup> of the number 5 device at low pumping level is 7%, calculated by dividing the collected photon number by the total number of electrons injected in the semiconductor slab.  $\eta_d$  is expressed as

$$\eta_d = \eta_{\text{collection}} \eta_{\text{internal}} \frac{\alpha_{\text{passive}}}{\alpha_{\text{passive}} + \alpha_{\text{absorption}}}, \quad (1)$$

where  $\alpha_{\text{passive}}$  and  $\alpha_{\text{absorption}}$  are passive optical loss of the resonator and optical absorption loss from the QW in the mirror region where carrier density is below transparency. The ratio between these two loss terms can be determined by their corresponding  $Q$  values (which is inversely proportional to loss). From Ref. 20, we have an equivalent  $Q_{\text{absorption}}$  of 5600 for DH laser at its threshold, which gives a value of 60% for the  $\alpha_{\text{passive}}/(\alpha_{\text{passive}} + \alpha_{\text{absorption}})$  term using the  $Q_{\text{passive}}$  result from 3D FDTD. The internal quantum efficiency ( $\eta_{\text{internal}}$ ) is taken to be 80%,<sup>24</sup> which is the fraction of the absorbed carrier being captured by the QWs. Then the only unknown term  $\eta_{\text{collection}}$  in Eq. (1) can be extracted to be 15%, which agrees well with the calculated number above.

There is plenty of room to improve  $\eta_d$ . A well engineered facet termination<sup>16,25</sup> and cavity-waveguide coupling<sup>14,15,26,27</sup> increase  $\eta_{\text{collection}}$ , photopumping with a longer wavelength light can reduce device heating due to phonon relaxation, and QW intermixing has already been demonstrated to be able to eliminate most of the absorption loss, leading to both increased slope efficiency and lower threshold.<sup>20</sup> A 80%  $\eta_{\text{collection}}$  and our intermixing result can improve the  $\eta_d$  to be 43% and a power level approaching 1 mW.

In conclusion, we have reported 120  $\mu\text{W}$  record room temperature edge-emitting output peak power from QW membrane single mode PC defect lasers with wavelength-cubed  $[\sim(\lambda/n)^3]$  mode volume, formed by shortening the number of cladding periods on one side of a DH nanocavity. Output power of those devices can still be greatly enhanced to improve their efficiencies. This result is promising for ultrasmall semiconductor laser applications toward on-chip light sources and single photon emitters.<sup>28</sup>

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