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

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(Received 23 October 2008; accepted 26 January 2009; published online 16 March 2009)

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 $\mu$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*.
[DOI: 10.1063/1.3097278]

The physical size of semiconductor lasers has been shrinking down to the wavelength[1] or even subwavelength scale,[2] 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[3] and continuous wave operation at room temperature,[4–10] two-dimensional (2D) photonic crystal (PC) defect lasers have not been shown to have sufficient collected output power (>50 $\mu$W) for current on-chip optical receivers to operate at high bandwidth (10 GHz) and low bit-error rate ($10^{-12}$).[11] 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[12,13] 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.[14] This was done by shortening the waveguide cladding on one side of the cavity, following up on the previous demonstration by Yang *et al.*[15] 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.[16]

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.[17] 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× 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 $\mu$m in diameter. The output power was collected from the facet by a 60× anti-reflection-coated aspheric lens with 0.65 numerical aperture (NA) and detected by an InGaAs photodiode. A piece of double-side-polished

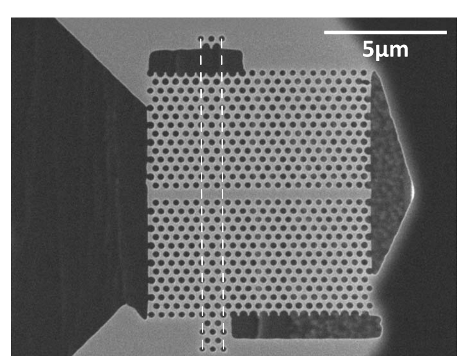


FIG. 1. Top view SEM image of a fabricated PC DH cavity with five PC cladding periods on the left. The heterostructure region is delineated with white dotted lines.

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