Identification of modes and single mode operation of sapphire-bonded photonic crystal lasers under continuous-wave room temperature operation

M. H. Shih, Mahmood Bagheri, Adam Mock, S. J. Choi, J. D. O’Brien, and P. D. Dapkus
Department of Electrical Engineering-Electrophysics, University of Southern California,
Powell Hall of Engineering, 3737 Watt Way, Los Angeles, California 90089-0271

Wan Kuang
Department of Electrical & Computer Engineering, Boise State University, 1910 University Drive,
Boise, Idaho 83725

(Received 7 September 2006; accepted 16 February 2007; published online 21 March 2007)

Sapphire-bonded photonic crystal laser cavities were fabricated and characterized under room temperature continuous-wave operation, and the single mode lasing with a side-mode-suppression ratio of 28 dB was observed. The lasing modes of the photonic crystal cavities were characterized and compared to calculated spectra from the three-dimensional finite-difference time-domain method. © 2007 American Institute of Physics. [DOI: 10.1063/1.2715107]

Two-dimensional photonic crystal defect lasers are a developing technology that may have promise as light sources in dense chip-scale optical systems. There are many reports for photonic crystal defect cavities formed in a suspended membrane however, this type of laser cavity can only operate under pulsed pumping conditions because of the poor heat dissipation of this device geometry. Compact, room temperature continuous-wave (cw) sources will be necessary elements in photonic integrated circuits. There are only few demonstrations of photonic crystal defect lasers on a sapphire substrate or AlOx substrate which are capable of operating under cw conditions at room temperature. Here we report on single mode cw lasers with a high side-mode-suppression ratio (SMSR). This photonic crystal microcavity, bonded to a sapphire substrate, is the smallest laser capable of room temperature cw operation reported to date. By comparing the cw lasing spectrum to the calculated result from a three-dimensional (3D) finite-difference time-domain (FDTD) calculation, we have also been able to identify the optical modes of this photonic crystal cavity under a broader range of conditions.

These devices were fabricated in a 240 nm thick InGaAsP layer containing four InGaAsP strained quantum wells designed to emit near 1.55 μm at room temperature. These InGaAsP layers were deposited by metal-organic chemical-vapor deposition (MOCVD) on an InP substrate. The wafer was then bonded to a 320 μm thick sapphire substrate and annealed in a H2 chamber at 500 °C. The InP substrate was removed by a wet etching procedure with HCl solution. After the wafer bonding step, the photonic crystal cavities were fabricated in the InGaAsP layer. A silicon nitride mask was deposited by plasma-enhanced chemical-vapor deposition and 3% polymethylmethacrylate resist was spin coated on top of the mask. The photonic crystal cavities were defined using electron beam lithography, and the photonic crystal patterns were transferred into the silicon nitride mask using a reactive ion etch. The pattern was transferred into the InGaAsP layer using an electron cyclotron etch. The mask was removed at the end of the fabrication.

The photonic crystal laser cavities were formed by a defect in a triangular photonic crystal lattice in which 37 holes were missing (D4 cavity). We label this cavity D4 because the 37 missing holes correspond to a hexagon with a “radius” of four lattice constants. These cavities are approximately 3.2 μm in diameter and are surrounded by 11 periods of photonic crystal lattice cladding. In this work, we fabricated cavities with lattice constants between 360 and 420 nm for the purpose of fine-tuning the lasing wavelength. All of the laser cavities were optically pumped at room temperature using an 850 nm diode laser at normal incidence. The pump spot was focused by a 100× objective lens to a spot approximately 2.5 μm in diameter. The output power was collected from the top of the cavities by a multimode fiber that was connected to an optical spectrum analyzer. Figure 1 is a scanning electron microscope (SEM) image of a D4 photonic crystal laser cavity with a lattice constant of 400 nm taken from a 30° angle view.

Figure 2(a) shows a lasing spectrum of a sapphire-bonded photonic crystal cavity pumped at two times of threshold under room temperature cw conditions. The lasing wavelength is 1589 nm and the nearest resonance occurs around a wavelength of 1560 nm. The SMSR of this lasing

FIG. 1. Scanning electron microscope (SEM) image of a sapphire-bonded photonic crystal laser cavity from a 30° angle view. The lattice constant of the cavity is 400 nm.
mode is more than 28 dB. Changing the collective fiber position changes the total power collected instead of the SMSR value. We also note that most of the power radiated from this cavity is not collected from the top but is instead radiated into the substrate. There is 19 dB of optical loss in the optics so we only collected tens of nanowatts of power from the laser. We expect that the power emitted from this laser is much larger than this value. Figure 2(b) is the comparison of a lasing spectrum and the gain spectrum of the quantum wells. The gray spectrum is the measured photoluminance (PL) from the sample without the photonic crystal patterns and the black is the lasing spectrum of Fig. 2(a) on a linear scale. The high SMSR was obtained because the lasing mode is well aligned to the gain peak of the quantum wells. Figure 2(c) shows the output power versus input power lasing data of a D4 laser cavity with 11 periods of photonic crystal. The lasing threshold of this cavity occurred at 0.4 mW of incident power.

To engineer the optical modes of these photonic crystal defect cavities, we have characterized the operating modes of the D4 cavity. More than 50 cavities with different lattice constants were fabricated on the same sample. Each of these cavities was optically pumped and the lasing wavelengths were recorded. Figure 3 shows the lasing wavelengths versus photonic crystal lattice constant of the lasing cavities. The lasing wavelength varied nearly linearly with the lattice constant of the photonic crystal indicating that the same mode was being observed in each cavity. In the set of these cavities we observed two modes, labeled as A and B in Fig. 3. The normalized frequencies of groups A and B are approximately 0.252 and 0.263, respectively. The lasing spectrum of the D4 cavity shown in Fig. 2(a) shows operation at mode A.

In order to better understand these data, a 3D FDTD theoretical model for the lasing modes of the D4 sapphire-bonded photonic crystal cavity was used to simulate this cavity. Figure 4 shows the calculated quality factor $Q$ of the optical modes of the cavity versus the normalized frequency. Since the index contrast between the core semiconductor layer and the sapphire cladding layer is reduced at the bottom of the cavity compared to a suspended membrane device, we expect to obtain resonance modes which have a $Q$ value that is less than the $Q$ value of the corresponding suspended membrane D4 cavity. In this case there are only a few modes with calculated $Q$ values over 1000. The solid-line spectrum in Fig. 4 is a measured lasing spectrum from a cavity pumped slightly above threshold under cw conditions. The two highest $Q$ modes within the simulated region, labeled A and B, correspond to the lasing modes A and B in Fig. 3. The lasing spectrum in Fig. 4 shows the lasing at mode B. Good agreement between the measured spectrum and the calculated $Q$ spectrum was obtained not only at las-
In summary, we have demonstrated a sapphire-bonded photonic crystal laser under room temperature cw operating conditions. A SMSR of 28 dB was reached for this D4 laser. The wavelengths of the lasing modes of an array of these lasers were observed and identified by comparing the measured lasing spectrum and 3D FDTD simulation results. Good agreement between measurement and theory was obtained.

This study is based on research supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. F49620-02-1-0403 and by the National Science Foundation under Grant No. ECS-0094020. Computation for the work described in this letter was, in part, supported by the University of Southern California Center for High Performance Computing and Communications.