Photonic Crystal Microcavity Lasers

Department of Electrical Engineering-Electrophysics, University of Southern California
e-mail: jdobrien@usc.edu

ABSTRACT
Photonic crystal lasers will be discussed with particular emphasis on devices capable of room temperature CW operation and devices with quantum dot active regions. CW lasers have -3 dB modulation bandwidths over 10 GHz with approximately 30 dB of side mode suppression. An analysis of the modulation response and the linewidth of microcavity lasers suggests that gain nonlinearity and microcavity effects may be playing an important role in these device characteristics. The photonic crystal lasers with quantum dot active regions have absorbed powers at threshold of under 15 μW. The presentation will also describe approaches to increasing the output power obtained from these lasers illustrated with data showing 100 μW of pulsed output power from a microcavity photonic crystal laser

Keywords: intensity modulation, gain compression, quantum dot, integrated optics.

1. INTRODUCTION
Progress in the development of photonic crystal lasers continues to be made, but there are also significant research challenges remaining. If these lasers are to function as transducers in high bandwidth communication systems in planar integrated optics platforms, then devices capable of room temperature, electrically pumped, CW operation with modulation bandwidths in excess of 10 GHz and producing many tens of microwatts of output power are needed. This paper reviews some of the progress we have made in characterizing the dynamics and modulation response of photonic crystal lasers including their linewidth and small signal intensity modulation response. In addition, we discuss our progress in obtaining higher output powers from these microcavity devices and in incorporating quantum dot active regions.

2. OPTICAL CHARACTERIZATION OF MICROCAVITY LASERS
The microcavity lasers in this study were formed in 240 nm thick InGaAsP membranes wafer-bonded to a sapphire substrate. The membranes contain four layers of compressively-strained quantum wells designed to emit at 1550 nm. The sapphire substrate allows room temperature CW lasing in microcavities with minimum required quality factors. The cavities are formed by removing 37 holes out of a hexagonal photonic lattice (D4). The details of the device fabrication can be found elsewhere [1]. Figure 1(a) shows an SEM image of a fabricated D4 cavity on sapphire.

In operation, the devices were optically pumped with an edge-emitting Fabry-Perot laser at 850 nm focused on the device surface with an objective lens. The out-of-plane emission from the devices was collected through the same objective lens and then coupled to an optical fiber for further analysis. Figure 2(b) shows the measured lasing spectrum of a typical D4 cavity showing 30 dB side-mode-suppression.

![Figure 1. (a) SEM image of a fabricated D4 photonic crystal defect laser on sapphire. (b) The lasing spectrum taken on an optical spectrum analyzer showing 30dB of side-mode suppression under CW operation at room temperature with L-L curve as inset.](image)
2.1 Small signal intensity modulation response measurement

The small-signal intensity modulation response of these devices was measured by spatially overlapping the laser emission from a modulated VCSEL operating at 850 nm with the emission of the edge-emitting CW diode pump laser. The out-of-plane emission of the photonic crystal cavities was collected using a microscope objective lens and then coupled into an optical fiber. The collected light was then amplified using an EDFA. To improve the signal-to-noise ratio the ASE noise from the EDFA was suppressed using an optical bandpass filter with an approximate bandwidth of 360 pm. The optical signal was then detected using a fast InGaAs photodetector and followed by a microwave electrical amplifier. The resulting signal was displayed and analyzed using a network analyzer. By measuring the small-signal intensity modulation response of the microcavities, S21, as shown in Fig. 2, and applying curve fits to the measured curves, we extracted the relaxation oscillation frequency and damping term of these devices at different bias points.

Figure 2. Measured small-signal intensity modulation response of photonic crystal laser cavity with an applied curve fit.

Figure 3(a) shows the measured relaxation oscillation frequency squared, $f_R^2$, behaviour versus the output power of a typical D4 laser cavity. The nonlinear behaviour of this curve indicates the presence of gain nonlinearities [2]. The presence of gain nonlinearities limits the maximum modulation bandwidths of these devices by decreasing the relaxation oscillation frequency and increasing damping. The presence of gain nonlinearities, and the minimum optical power required for noise-free communication in an optical links, limits the maximum acceptable quality factor of microcavity lasers for practical applications. Figure 3(b) shows the extracted damping term versus the relaxation oscillation frequency squared behaviour. The slope of this curve indicates a maximum possible -3 dB modulation bandwidth of 30 GHz for these structures. This bandwidth is possible when the devices are biased about 10 times threshold. However, in practice, the output power of these devices starts to roll off due to heating at less than five times threshold and we are unable to pump these devices at ten times threshold.

Figure 3. (a) Extracted relaxation oscillation frequency squared ($f_R^2$) versus the collected output power, (b) the behaviour of the damping term versus the relaxation oscillation frequency squared.
2.2 Laser linewidth

The linewidth of photonic crystal lasers was also characterized to investigate the noise properties of the microcavity lasers using the self-delayed optical homodyne technique [3]. The linewidth of the lasers above threshold is expected to decrease linearly as a function of the inverse output power. Figure 4(a) shows the behaviour of the laser linewidth against the inverse of the output power. The measured laser linewidth shows the expected linear dependence over a range of output power until the linewidth starts to rebroaden at higher output powers. The saturation and rebroadening of the semiconductor laser linewidth are attributed to gain nonlinearities in the active medium.

Figure 4. (a) Photonic crystal laser linewidth against the collected output power inverse, (b) laser linewidth behaviour close to threshold.

Figure 4(b) shows the measured laser linewidth behaviour close to threshold. At low output powers, close to lasing threshold, photonic crystal lasers show an increase in the laser spectral width. This effect is due to the effective coupling of phase and intensity noise above and below threshold. Coupling between phase and amplitude does not contribute to the spectral width of lasers below threshold, while as the laser is pumped farther above threshold, this contribution saturates and the laser linewidth behaves as the normal single mode laser models predict. Because of the increased spontaneous emission coupling into these microcavity lasers, the transition between below and above threshold is a soft transition, resulting in the increase being more pronounced in this transition region [4, 5].

3. EDGE-EMITTING LASERS

We have also been working to improve the output power of photonic crystal lasers. Two-dimensional photonic crystal (PC) microcavity lasers would be a more promising source candidate for photonic integrated circuits if they were capable of in-plane emission at higher collected output power. We have recently taken advantage of the high quality factors (Q) demonstrated in double-heterostructure (DH) cavities, [6, 7], to obtain waveguide-coupled power from a heterostructure laser by loading the resonant cavity with a nearby output waveguide [8, 9]. Here we report high output powers obtained from devices with quantum well active regions. Fabrication of these devices followed the same procedure as in [9], with the addition that the sample was diced very near the end of the cavities in order to facilitate collection of the edge-emitted laser radiation. The cavities were optically pumped under pulsed conditions with an 8 ns pulse width at a 0.1% duty cycle.

Figure 5. Input pump power versus the output power for the asymmetric heterostructure laser cavities.
Figure 5 is the light-in-light-out curve under two different substrate temperature conditions. 118 µW of peak output power was obtained from a device that had three waveguide periods cladding the central heterostructure on one side at a temperature slightly below room temperature. More than 50 µW of peak output power was obtained just above room temperature. The largest side-mode-suppression ratio obtained from this device was 26 dB under pulsed pumping conditions.

4. QUANTUM DOTS

We have also demonstrated photonic crystal double heterostructure lasers with quantum dot active regions. In one particular demonstration the laser was butt-coupled to a photonic crystal waveguide. The devices reported here were fabricated in a 220 nm thick GaAs membrane that was embedded with five layers of InAs QDs as the active material. The QD density per layer is $2 \times 10^{10}$ cm$^{-2}$ and the emission was designed to be near 1.3 µm. The epitaxial growth of these devices was performed by Professor Dennis Deppe’s group. The details of the sample growth and fabrication are similar to that found in [10]. The double-heterostructure cavity had a lattice constant $a = 343$ nm in the cavity, and 335 nm in the mirrors. The photonic crystal hole radius $r$ was measured to be approximately 0.3$a$ everywhere. The length of the cavity was 2$a$. On one side of the cavity the confining layers extended for a distance of 13$a$. An output waveguide was butt coupled to the mirror with the fewer number of periods. This waveguide had $a = 351$ nm in order to position the lasing wavelength within the low-transmission-loss wavelength range of the waveguide. No effort was made at this stage of the research to optimize the output coupling. The devices were optically pumped with a semiconductor laser diode at 850 nm with typical pump conditions of 16 ns pulse widths at a 1% duty cycle. The pump beam was focused by a microscope objective to a spot size of 1 – 1.5 μm and was normally incident onto the sample. Light scattered vertically out from the devices was collected by the same microscope objective and focused into a multi-mode fiber. The peak pump power absorbed by the cavity at threshold is estimated to be 12 µW.

REFERENCES