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Photonic crystal microcavity lasers

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Abstract
We report on our progress made in developing microcavity photonic crystal lasers. Both suspended membrane devices and devices formed in membranes bonded to sapphire are described.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Two-dimensional photonic crystal microcavity lasers in which the resonant cavity is formed at a defect in a triangular lattice photonic crystal were first demonstrated in 1999 [1]. Since then much progress has been made [2–7], but these devices are still very immature. Only one group has reported electrically pumped operation of these lasers [8] and there are very few reports of optically pumped room temperature continuous-wave (CW) operation [5, 9, 10]. However, a great deal of progress has been made in understanding and controlling the modes of these lasers.

In this work we report on two different photonic crystal microcavity laser geometries: devices formed by defects in photonic crystals patterned in suspended semiconductor membranes, and devices formed by defects in photonic crystals patterned into semiconductor membranes bonded to a sapphire substrate. Figure 1(a) shows an electron micrograph of four suspended membrane lasers in a row, and figure 1(b) shows an electron micrograph of a sapphire-bonded laser cavity. The suspended membrane geometry photonic crystal microcavity lasers were demonstrated first. Research on these devices demonstrated an ability to numerically model and lithographically control their optical modes in microscopic detail. The poor heat dissipation in these lasers limits their usefulness, however. Sapphire-bonded photonic crystal microcavity lasers share with their suspended membrane counterparts the ability to manipulate the optical modes on subwavelength scales while also possessing much better thermal conductivity allowing other laser properties such as the dynamics to be investigated. This paper sketches the progress made in our lab in these directions.

After this short introduction to the paper, the first section gives a short overview of the implementation of a numerical three-dimensional finite-difference time-domain algorithm used to solve Maxwell’s equations and model the optical properties of these devices. The rest of the paper is divided into two parts. The first part treats the suspended membrane devices. Here, a basic approach to fabricating these devices is described. This is followed by a longer discussion of the modal characteristics of these lasers and a discussion of the lithographic tuning of these modal properties. Finally, the main drawback of these lasers, their poor thermal properties, is discussed. The second main section of this work describes the cavities formed in a membrane bonded to sapphire. These devices are capable of room temperature CW operation. This section again begins with a description of a basic approach used to fabricate these devices. Then again the demonstrated modal behaviour of these devices is described. This is followed by a description of work done to characterize the optical losses in these cavities. Finally, the section concludes with a description of the progress made in our efforts to understand and characterize the dynamic properties of these lasers.

2. Three-dimensional finite-difference model of microcavity photonic crystal lasers

In this section, we describe the numerical approach to calculating the resonant frequencies and quality factors of the modes in photonic crystal microcavities and demonstrate excellent agreement between our numerical predictions and the observed modes. A three-dimensional finite-difference time-domain (FDTD) simulation was implemented to model these devices. The dielectric constants of all the materials were taken to be real and constant in the simulation. Therefore, the model is limited to predicting the cold cavity behaviour of these devices. Initially, the cavities are excited and the FDTD routine propagates this energy in the cavities in the time domain. The frequency response of the cavity is calculated from the Fourier transform of the time-dependent field recorded in the cavity at low-symmetry locations. Small defect photonic crystal
microcavities studied in this review can support as many as 40 resonant modes. The frequency resolution of the temporal Fourier transform is proportional to the number of time steps in the recorded time sequence and inversely proportional to the total number of samples used in the Fourier transform. This resolution can be made far smaller than the mode spacing. The quality factor, $Q$, of each mode can be calculated from the ratio of full width at the half magnitude of the cavity resonance in the frequency domain to the centre frequency. The inherent challenge of this approach is to obtain sufficient frequency resolution. The smallest identifiable spectral width usually cannot resolve a quality factor higher than a few hundred. Distortion to the spectrum is also introduced because the numerical simulation terminates before the impulse response is fully evolved. This has the effect of viewing the true time-domain response through a rectangular window, which translates mathematically into the convolution of the true spectrum with a sinc function. Using a Padé interpolation of the frequency response addresses the problem by extrapolating the electromagnetic field in the time domain beyond the actual simulation window [11]. The discrete Fourier transform (DFT) series $P(\omega_k)$ is interpolated with a Padé function, which is the ratio of an order $I$ and an order $J$ polynomials $Q_I$ and $D_J$,

$$P(\omega_k) = \frac{\sum_{i=0}^{I} \alpha_i (\omega_k)^i}{\sum_{j=0}^{J} \beta_j (\omega_k)^j}.$$

(1)

Taking $\beta_0$ to be unity, coefficients $\alpha_i$ and $\beta_j$ in equation (1) can be solved with $I + J + 1$ Fourier transform samples and a continuous Padé function interpolating the Fourier spectrum is derived. The accuracy of the frequency response is significantly improved beyond the frequency resolution of the DFT. By combining a Padé approximation with the DFT, the quality factors of all the modes in the cavity can be determined with just one FDTD simulation. Figure 2 shows the calculated TE$_z$-like (even) resonance mode frequencies and their quality factors for a triangular lattice photonic crystal defect microcavity, where the $z$ direction is the epitaxial growth direction [12]. The cavity is created in a dielectric membrane suspended in the air. The membrane has a refractive index, $n$, of 3.4 and a thickness, $d$, of 0.45 in units of the lattice constant $a$. The cavity is formed by a defect in the lattice in the form of holes missing from the lattice. In this case 19 holes are missing from the triangular lattice which corresponds to a hexagonal ‘radius’ of 3 holes. A cavity of this type is denoted by $D_3$. The air holes have a normalized radius of $r/a = 0.33$ in the simulation except those immediately adjacent to the cavity defect, which have a slightly smaller radius of $r/a = 0.3$. For the purpose of comparison, the photoluminescence (PL) spectrum of an actual photonic crystal defect cavity pumped below threshold is superimposed on the calculated $Q$ spectrum in figure 2. The left and bottom axes are for the calculated quality factors and resonance frequencies, while the right and top axes are for the measured optical intensity and frequencies. The horizontal axes of the two plots are intentionally shifted by less than 1%, or 16 nm in wavelength in order to better illustrate the agreement between the two. The peaks in the PL spectrum

Figure 1. (a) Electron micrograph of a row of suspended membrane lasers. (b) Electron micrograph of a sapphire-bonded photonic crystal laser cavity from a 30° angle view.

Figure 2. Calculated resonance mode frequencies and their quality factors for a suspended membrane $D_3$ photonic crystal defect cavity (bars) with a membrane thickness of $d/a = 0.45$ and hole radius of $r/a = 0.33$ except the inner holes around the defect which have slightly smaller $r/a = 0.3$. It is compared with the measured photoluminescent spectrum of cavity with similar dimensions (curve). The left and bottom axes are for the calculation, whereas the right and top axes are for the measurement curve. The difference of frequency is within 0.0035 in normalized scale, or about 16 nm in free space wavelength. Resonant modes with a quality factor of over 1000 in the material gain region are also labelled with their corresponding irreducible representation in the $C_{6v}$ point symmetry group [12].
3. Suspended membrane photonic crystal lasers

This section describes the fabrication of photonic crystal lasers formed in a suspended semiconductor membrane into which the laser cavity had been patterned. Historically these cavities were the first to be demonstrated because of the relative simplicity of their design. This design was simplified by the strong optical confinement of the optical mode to the membrane provided by the semiconductor/air interfaces at the top and bottom of the membrane.

3.1. Fabrication

These lasers were formed in an InGaAsP membrane. These InGaAsP layers were deposited by metal organic chemical vapour deposition (MOCVD) on an InP substrate. The epitaxially grown layers were 224 nm thick and contained four compressively strained InGaAsP quantum wells separated by 23 nm of unstrained InGaAsP barrier layers. The PL spectrum of these quantum wells shows emission between 1420 and 1630 nm and is peaked at 1.5 µm at room temperature. On top of the last barrier layer, a 60 nm thick InP cap layer was grown to protect the quantum wells during the dry etching steps. The InP cap layer was subsequently removed at the end of the device processing.

After the epitaxial growth, an etch mask was deposited on the sample. This mask consisted of a 160 nm thick silicon nitride layer deposited byPECVD followed by 5 nm thick Cr and 45 nm thick Au layers deposited by e-beam evaporation. Finally, a 100 nm thick 2% polymethylmethacrylate (PMMA) layer was spin coated on the mask.

The photonic crystal pattern was defined in the resist by electron beam lithography. After lithography, the pattern was transferred into the Cr/Au metal layer by Ar⁺ milling in an ion beam etching (IBE) system. The patterned Cr/Au layer was then used as a mask to pattern the silicon nitride layer by CF₄ dry etching in a reactive ion etching (RIE) system. The pattern was then transferred 400 nm deep into the semiconductor using an electron cyclotron resonance (ECR) etch. The gas mixture used in this etch was CH₂/He/Ar. By the time the ECR etching was completed, the metal layer had been completely removed. During this process, we used an RIE oxygen plasma etch to clean the excessive polymer on the sample that was generated by CH₄ chemistry after every 200 s of ECR etching. After the metal layer was removed, the sample was then etched again by RIE to completely remove the silicon nitride mask using the CF₄ plasma. The final step was a wet chemical etching that undercut the membrane and stripped the 60 nm InP cap layer to achieve a smooth surface. This wet etching was done at 0 °C in a HCl: H₂O = 4:1 mixture. This wet etching is anisotropic and has important consequences in the fabrication of undercut photonic crystal membranes.

The consequences of this anisotropy can be seen in figures 4(a) and (b), i.e. the chemical etch stops at certain
slow etching planes for HCl: H2O = 4:1 at 0°C. The etching results in a wedge-shaped profile for a square pattern. More details on these etch-stop planes can be found in [14, 15]. To facilitate the membrane undercut, we formed large openings at the ends of the pattern merging into the edges of the PC along the <0, 1, −1> orientation. Owing to their dramatically different physical dimensions compared with the photonic crystal holes and their asymmetric shape, these opening windows prevent the etch-stop planes from forming. Two top view scanning electron microscope (SEM) images of fabricated photonic crystal $D_3$ and $D_2$ microcavities are shown in figure 5.

3.2. Characterization

These suspended membrane structures operate as microcavity lasers under pulsed optical pumping conditions at room temperature. A suspended membrane $D_3$ photonic crystal cavity contains one dominant high $Q$ mode that has a predicted cold cavity $Q$ value over 10 000. The calculation also indicates that more than 95% of the in-plane energy density overlaps with the gain medium. Because of the high quality and in-plane confinement factors, this $D_3$ cavity has a low lasing threshold. Under 8 ns pulse width, 1% duty cycle, room temperature optical pumping conditions and incident threshold pumping power as low as 0.5 mW have been achieved with this cavity. This incident power level corresponds to about 0.15 mW of absorbed pumping power at threshold considering the finite absorption of the 224 nm thick InGaAsP membrane and the reflection at the interface between semiconductor and air. Additionally, resonances within approximately 50 nm of this lasing mode have quality factors that are lower by nearly an order of magnitude compared with that of the lasing mode. Experimentally, we observed no mode-hopping above threshold.

3.3. Lithographic tuning

One of the advantages of photonic crystal lasers is the ability to define their operating wavelength lithographically. In this section we describe a study of the lithographic tuning of the lasing wavelength in these devices. In this experiment, an array of 31 $D_3$ suspended membrane laser cavities were fabricated with the lattice constant varying in 2 nm increments between 490 and 550 nm across the elements of the array. The $r/a$ ratios of the lasers in the array were kept approximately constant at 0.28. Figure 6 shows an array of these laser cavities. The 2 nm increments in lattice constant between the elements are near the resolution limits of our lithography at our standard beam writing magnification and resist dosage conditions.

The lasers were optically pumped at room temperature by a semiconductor laser operating at 860 nm. The pulse width was fixed at 20 ns with a 1% duty cycle. A plot of the lasing wavelengths of all 31 lasers in an array is shown in figure 7(b), and figure 7(a) shows the calculated $Q$ spectrum of one such $D_3$ laser. The data in figure 7(b) show that as one resonant wavelength tunes past the gain region of the quantum wells the lasing mode hops to a shorter wavelength mode, which also tunes with the lattice constant. From the three-dimensional FDTD calculations, it is expected that the photonic band gap for the even guided modes of the slab ranges from about 1250 to 1850 nm. This 600 nm photonic crystal bandgap is much larger than the spectral width of the gain spectrum. There are 4 modes evident in the array spectra. In each spectrum, however, we observe single mode behaviour. Several modes can be seen in each device in the sub-threshold spectra, and we use these sub-threshold spectra to identify the modes lasing in the array to be the four modes with the highest calculated $Q$ as indicated in the figure. The tuning in the lasing wavelength between adjacent devices is small compared with the wavelength spacing between different resonances. In the lattice constant range in which the lasers are operating in the highest $Q$ mode, we observed 18 devices lasing with an average spacing in their lasing wavelength of 4 nm. The relationship between the lasing wavelength and the photonic lattice constant shown in figure 7(b) is not precisely linear.
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Maxwell’s equations yield scaled eigenfrequencies when the spatial extent of the dielectric is scaled. Here, we have scaled the lattice constant with a fixed value of \( r/a \). However, since all of these lasers are fabricated in the same epitaxial layers, the membrane thickness, \( d \), is not scaled correspondingly. In addition, slight variations in the fabricated \( r/a \) across the array as well as the index dispersion of the material lead to a nonlinearity in the measured wavelength versus lattice constant characteristic. We expect that a large component of this wavelength shift can be attributed to an increase in the temperature of the cavity associated with poor heat dissipation of the suspended membrane resulting from the low thermal conductivity of air. It should also be noted that the lasing wavelengths are much longer than the room temperature PL peak. This is attributed to an increase in temperature of the cavity associated with poor heat dissipation of the suspended membrane resulting from the low thermal conductivity of air. This issue is examined further in the following sections.

The discussion above covers the fine-tuning of the lasing wavelength that can be achieved in these devices. In this section we utilize this fine-tuning ability to investigate the dependence of the threshold pumping power on the spectral alignment between the gain peak and the cavity resonance. We investigate this near room temperature. The same type of laser arrays described above was used in this study. The photonic crystal lasers were optically pumped with an 850 nm edge-emitting diode laser at normal incidence. The pumping condition used was a 4 ns pulse width with a 0.5% duty cycle. Of the 31 laser elements in the array, 17 elements operate as lasers in the same mode, which is tuned across the gain spectrum as the lattice constant varies. These 17 elements were part of 23 adjacent elements in the array. Six cavities in this series of 23 elements operated in different modes, which were more than 50 nm away from the mode of interest. Here we focus on the 17 lasers operating in the same mode. Each element shows single mode lasing with at least a 20 dB side mode suppression. Figure 8 shows the lasing wavelengths of the elements in the array as a function of lattice constant.

The average lasing wavelength spacing between elements in the array is 4.2 nm. It is also important to note that, based on our numerical simulation results, the quality factor of the mode that is lasing in the array does not change appreciably over a wide range of lattice parameters.

Figure 9 shows the threshold pumping powers and lasing wavelengths of each laser in the array at substrate temperatures of 22 and 30 °C. Because we believe that the cold cavity \( Q \) of this mode does not change from one cavity to another in the array, the approximately parabolic profile in lasing thresholds is attributed to the changing spectral alignment between the gain peak of the quantum well and the high \( Q \) mode of each cavity. Similar behaviour of the threshold condition has been observed in vertical cavity surface emitting lasers (VCSELs)
The minimum threshold pumping power in figure 9 occurs near 1670 nm, which corresponds to the point where the optical gain peak is aligned with the lasing mode. The threshold pumping power at 1670 nm is more than a factor of 7 lower than that at the low-wavelength end of the spectrum. We expect that a substrate temperature increase in a few degrees will cause a shift in the lasing wavelength of only a few Angstroms. According to the data in figure 9, a lasing wavelength shift of a few Angstroms should cause only a slight change in the threshold pumping power. However, the threshold pumping powers of the devices near 1670 nm increase by almost a factor of 2 with the 8 °C increase in temperature. We associate this result to a small $T_0$ of the InGaAsP suspended membrane photonic crystal cavity. We note that even though there is a strong threshold dependence on the spectral alignment between the gain peak and the cavity resonance, this effect does not dominate the temperature dependence of the lasers, owing to the small value of $T_0$.

3.4. Thermal tuning

One of the obstacles of achieving CW operation of membrane-type photonic crystal microcavity lasers at room temperature is the heating of the gain region due to the poor thermal conductivity of the surrounding air claddings. We used the finite-element method (FEM) to estimate the heat transfer and temperature distribution of a photonic crystal microcavity. This thermal analysis simulated a photonic crystal single-defect microcavity laser pumped with 10 ns long optical pulses and 7 mW incident power at 4% duty cycle and 3.5 μm pump spot size. The temperature distribution is shown in figure 10, which indicates a 112 °C increase in the temperature in the defect region above the substrate temperature. One of the approaches to achieve CW lasing operation is to replace the air cladding by material with a higher thermal conductivity than air. For example, a sapphire substrate has a thermal conductivity that is 2000 times larger than that of air at room temperature. A similar FEM thermal analysis on microcavities on a sapphire substrate showed a temperature increase of about 5 °C under the same pulsed pumping conditions. The photonic crystal lasers on sapphire allow room temperature CW operation and are discussed below.

To investigate the thermal properties of these suspended membrane lasers, we demonstrated lasing action above room temperature by mounting the lasers on a thermal electric cooler (TEC) to control the substrate temperature. Temperatures from 20 to 50 °C in increments of 5 °C were investigated. Lasing action for substrate temperatures up to 50 °C was obtained. The lasing wavelength shifted to the red as a function of increasing substrate temperature at a rate of 0.05 nm K$^{-1}$ as shown in figure 11(a) [3]. This redshift is mainly ascribed to
the change in the refractive index as a function of temperature instead of the relatively small cavity thermal expansion. As shown in figure 11(b), we also obtained the light-in-light-out (L–L) curves at the substrate temperatures 20 °C, 35 °C, and 50 °C, which correspond to threshold pump powers 3.2 mW, 5.3 mW and 7.4 mW, respectively. By fitting this data with the exponential threshold dependence on temperature, a characteristic temperature $T_0$ of 37.7 K was obtained.

4. Sapphire-bonded lasers

In this section sapphire-bonded photonic crystal lasers are discussed. In this work the laser cavities were formed by defects in a triangular lattice photonic crystal that was patterned into an InGaAsP membrane that had been wafer-bonded to a sapphire (alpha-Al$_2$O$_3$) substrate. This substrate greatly improves the performance of these photonic crystal lasers compared with the suspended membrane devices discussed above. The sapphire substrate functioned both as a heat sink and as a low refractive index cladding layer [18]. Since the thermal conductivity of sapphire is about 0.5 W cm$^{-1}$ K$^{-1}$, which is much larger than the thermal conductivity of air, $2.5 \times 10^{-5}$ W cm$^{-1}$ K$^{-1}$, the devices were able to be pumped above threshold continuously at room temperature without overheating.

4.1. Fabrication

The basic approach to fabricating these devices consisted of bonding an epitaxial layer structure containing an active region in a waveguide epitaxial side down to a sapphire substrate. The substrate was subsequently removed and the photonic crystal devices were then patterned. Here the epitaxial layer structure was a 240 nm thick InGaAsP layer containing four InGaAsP strained quantum wells designed to emit near 1.55 µm. This was deposited by MOCVD on an InP substrate. The bonding was done to a 240 µm thick sapphire substrate. The bonding an epitaxial layer structure containing an active region in a waveguide epitaxial side down to a sapphire substrate. The bonding was done to a 240 µm thick sapphire substrate. The bonding was done to a 240 µm thick sapphire substrate.

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Figure 12. The lasing wavelengths of the characterized cavities versus the lattice constants of the cavities. There are two groups of these lasing wavelengths, which are grouped as A and B.

4.2. Modal properties

To understand the modal properties of these lasers, finite-difference time-domain simulations were undertaken, and arrays of these sapphire-bonded devices were fabricated and tested in which the lattice constant was tuned lithographically. All of the laser cavities described in this section were optically pumped at room temperature using an 850 nm diode laser at normal incidence. The pump spot was focused by a 100x objective lens to a spot about 2.5 µm in diameter. The output power was collected by a multi-mode fibre and connected to an optical spectrum analyzer. More than 50 cavities were characterized, and the lattice constant and lasing wavelength of each cavity were recorded. Figure 12 shows this data. The lasing wavelength varied approximately linearly with the changing lattice constant. From the data shown, two modes are lasing in these devices, both of which tune as expected with the changing lattice constant. We label the two modes as A and B. The normalized frequencies of groups A and B are approximately 0.252 and 0.263, respectively.

This data was compared with the results of the FDTD modelling done on these cavities. Figure 13 shows the calculated quality factor ($Q$) spectrum and the measured lasing spectrum from a particular $D_4$ cavity. The fabricated dimensions of this device were used in the numerical model. The calculation contains only a few modes with $Q$ values above 1000. The two modes with the highest calculated $Q$ value, again labelled A and B, correspond to the lasing modes A and B in figure 12. Figure 13 shows a lasing spectrum from one of these lasers operating in mode B overlaid with the results from the FDTD $Q$ spectrum calculation. Excellent agreement was obtained between the measured spectrum and the calculated $Q$ spectrum. The small difference in spectral position between the observed and the calculated lasing mode, which is less than 1%, is attributed to imperfections in the fabrication and the lack of precision in the indices of materials used in the FDTD simulation. Although this data is shown for a single laser, the level of agreement between the observed and the calculated spectral position of the lasing frequency is typical for these devices.

When the gain peak of the quantum well active region was aligned with the spectral position of the cavity mode B, very...
single mode behaviour was observed. Figure 14(a) shows a lasing spectrum of mode A from a $D_4$ cavity pumped above threshold under CW conditions at room temperature. The lasing wavelength is 1589 nm. The side-mode-suppression-ratio (SMSR) is about 30 dB. This is the largest SMSR that we have observed for a photonic crystal laser. The power from this laser was collected from the top of the cavity through an objective lens and an optical fibre into an optical spectrum analyzer (OSA). Most of the power radiated from this cavity is not collected from the top [10]. There is 19 dB of optical loss in the optics so we collected only 40 nW of power from the laser. We expect that the power emitted from this laser is much larger than this value. Figure 14(b) shows the input power versus output power characteristic from such a device.

The discussion above contains a comparison of the spectral positions of the calculated and observed modes in these lasers. Now we proceed to describe our efforts to characterize the optical losses in these lasers and therefore allow a comparison of the calculated and observed quality factors in these devices. To experimentally characterize the optical loss of these lasers, we fabricated an array of these devices. The array had six columns and the eleven devices in each column were identical, in principle. Each column contained devices with a different number of photonic crystal lattice periods cladding the central defect. The number of cladding periods varied from three to eight across the columns of the array. Figure 15 shows an SEM image of the array along with images of a device with three periods and a device with seven cladding periods from the end columns. Devices containing eleven cladding periods were also fabricated on the same sample. The threshold pump powers of the set of devices in each column were measured. No lasing was achieved in cavities with less than five periods of photonic crystal cladding. Cavities with five to seven cladding periods operated under pulsed conditions and cavities with eight periods could be operated in either pulsed or CW mode. The pulsed input power versus output power characteristics from four typical cavities with five to eight periods of cladding are shown in figure 16. All of these laser cavities had the same lattice constant, 400 nm, and were optically pumped at room temperature with a 1% duty cycle and an 8 ns pulse width. All of these lasers were observed to operate in the same optical mode. The typical side mode suppression ratio for these devices under these pulsed conditions was approximately 15 dB. As expected, the threshold pump power increased as the number of photonic crystal lattice periods cladding the central defect decreased. Figure 16 shows data illustrating this phenomenon. Figure 17 shows the extracted threshold pump powers versus the number of cladding periods. The slope of these characteristics also generally decreased as the number of photonic crystal periods decreased as expected.

Using the measured threshold pump power conditions for the elements in each column of the array, we estimated the quality factor of the cavities in each column of the array. To do this, the threshold pump power was converted into an effective current with radiative, Auger and surface recombination components. Then, we used the effective current at threshold to calculate the threshold modal gain. The material gain was calculated based on a model for the gain versus current relationship derived from edge-emitting lasers using the same active region [19]. The optical confinement factor was calculated using a finite-difference model and this was combined with the material gain value to get the threshold
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Figure 15. Scanning electron microscope (SEM) image of the sapphire-bonded photonic crystal laser array. The number of photonic crystal periods is varied from 3(P3) to 8(P8), and the lattice constant of a cavity is varied from 360 to 460 nm in each column. The two insets are images of two elements in the array with 3 and 7 periods of photonic crystal cladding, respectively [10].

Figure 16. Incident pump power versus output power ($L_L$) curves from five photonic crystal laser cavities with 5–11 periods of photonic crystal cladding [10].

Figure 17. The extracted threshold pump powers of the $D_4$ photonic crystal cavities versus the number of cladding periods.

modal gain. Once this value was determined we used the following relationship

$$Q = \frac{2\pi n_{\text{InP}}}{\lambda G_{\text{th}}},$$

(2)

where $n_{\text{InP}} = 3.17$ and $G_{\text{th}}$ is the threshold modal gain, to determine the quality factor, $Q$, of these devices. Figure 18(a) shows the quality factors (hollow circles) determined using this method as a function of the number of photonic crystal periods cladding the cavity. For eight periods of photonic crystal cladding we obtain a $Q$ value of 1 100, and in a device with 11 periods we obtained a $Q$ value of 1 200. This data agrees well with a three-dimensional FDTD calculation that predicts a theoretical quality factor of 1 200 for this mode in a cavity with eight cladding periods. The theoretical calculation was done for a purely passive case with no gain or absorption. The actual cavity can be expected to have additional absorption due to the quantum wells in the regions outside of the pump spot.

By varying the in-plane loss in these cavities across the
array, we were also able to extract the components of the loss due to out-of-plane emission and in-plane emission. Using the threshold pump power data and a simple model for the in-plane and out-of-plane losses we fit the in-plane and out-of-plane quality factors as a function of the number of cladding periods. The total quality factor contains the in-plane and the out-of-plane quality factors:

\[ \frac{1}{Q_{\text{total}}} = \frac{1}{Q_{\text{in-plane}}} + \frac{1}{Q_{\text{out-of-plane}}}. \tag{3} \]

The in-plane quality factor depends on the reflectivity of the photonic crystal cladding the cavity. Based on the results of coupled mode theory of distributed Bragg reflectors [20] we model \( Q_{\text{in-plane}} \) as

\[ \frac{1}{Q_{\text{in-plane}}} = b \ln \left( \frac{1}{R} \right), \tag{4} \]

\[ R = \tanh^2(c \tau_l), \tag{5} \]

where \( R \) is the reflectivity, \( \tau_l \) is the number of cladding periods and \( b \) and \( c \) are the fitting constants. The out-of-plane radiation loss depends simply on the in-plane cavity geometry and the cavity thickness. These parameters did not change across the array of devices so we modelled the \( Q_{\text{out-of-plane}} \) as a constant. The in-plane and out-of-plane quality factors determined using this model and this data as a function of the number of cladding periods are shown in figure 18(b).

This data exhibits strong similarities to numerical models of these components of the quality factors calculated for smaller cavities [21,22]. From this data, we observe that cavities with eight or more lattice periods cladding the defect are vertical emitters. The dominant loss in these devices is a result of the confined mode containing wave vector components that are not confined to the slab but are instead coupling to the radiation modes of the slab. Finally, room temperature CW operation was only obtained in devices with eight or eleven photonic crystal cladding periods surrounding the central defect. This indicates that experimental quality factors of the order of 1 100 or greater are required for the room temperature CW operation.

5. Small-signal modulation response and the laser linewidth

An investigation of the laser dynamics in these devices has begun. To date, our investigation has focused on the small-signal modulation response and the linewidth versus pump power characteristics of these microcavity lasers. We measured the small-signal intensity modulation response of these devices by spatially overlapping the laser emission from a modulated VCSEL operating at 850 nm with the emission of an edge-emitting CW diode pump laser also operating near 850 nm. The out-of-plane emission of the photonic crystal cavities was collected using a microscope objective lens and then coupled into an optical fibre. 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 analysed using a network analyser.

Figure 19(a) shows the differential modulation response or the small-signal response of a typical \( D_4 \) laser cavity operating at several bias levels after the frequency response of the modulating VCSEL, photodetector, microwave amplifier and all other elements of the measurement system other than the photonic crystal laser are calibrated out. A curve fit was applied to the measured modulation response curves in order to determine the relaxation oscillation frequency. The relaxation frequency is shown as a function of optical bias point in figure 19(b). We obtain a \(-3 \) dB bandwidth of about 9.75 GHz for \( D_4 \) laser cavities when operating at a bias level of 2.5 times threshold.

We expect that with better thermal management and therefore an ability to pump these devices farther above threshold we can further increase the \(-3 \) dB bandwidth of these devices.

The emission linewidth was also characterized as a function of optical bias. To do this, we employed an optical self-heterodyne method [24]. The light from the photonic crystal laser was collected into a single mode fibre and then
amplified using an EDFA. Again a bandpass filter was used to suppress ASE–ASE beat noise. The amplified and filtered optical signal was then split 50:50 using a fibre splitter and one arm was delayed using a 2.2 km long single mode fibre. The signals were then recombined in another 50:50 splitter. The light was then detected using a 25 GHz photodiode, and the spectrum of the electrical current was observed on a spectrum analyzer. A plot of the room temperature CW linewidth versus the inverse of the collected output power is shown in figure 20(a). The linewidth is seen to increase linearly versus $1/P_{\text{collected}}$ as expected [25] but saturates at higher output powers. Figure 20(b) shows the measured laser lineshape at 3 times threshold. The mechanism causing this linewidth saturation is still under investigation.

6. Comparison of suspended membrane and sapphire-bonded photonic crystal cavities

In general, suspended membrane photonic crystal resonant cavities have larger quality factors than similar sized photonic crystal resonant cavities on sapphire due to increased radiation loss into the sapphire substrate in the latter case. As a result, we have fabricated lasers on sapphire that are slightly larger, one more lattice constant in ‘radius’, than the suspended membrane lasers discussed in the first part of this work. It is therefore difficult to make a direct comparison between these two types of devices because the mode spectra in these two cavities are different. However, both laser types allow tuning of the high $Q$ mode to achieve operation at a desired wavelength. The threshold carrier density of the $D_4$ suspended membrane lasers is approximately $2.51 \times 10^{18}$ cm$^{-3}$ and the threshold carrier density of the $D_4$ sapphire-bonded lasers is approximately $2.72 \times 10^{18}$ cm$^{-3}$. More importantly, only lasers bonded to a transparent sapphire substrate have allowed CW operation. This also facilitates demonstrating higher SMSRs, characterization of the radiation fields and characterization of the small-signal modulation response and laser linewidth.

7. Summary

A great deal of progress has been made in the development of photonic crystal lasers since the first demonstration in 1999. There is still much work to be done in order for this technology to reach its potential. This paper has discussed the basic characteristics of suspended membrane and sapphire-bonded photonic crystal defect lasers from the early work, which focused on understanding and controlling the optical modes of these microcavity lasers to the more recent work, which aims to improve these lasers to the point where they become viable chip-scale sources. The modal characteristics of both types of lasers were included in this discussion, and data characterizing the optical loss in the sapphire-bonded lasers were presented along with data characterizing the basic small-signal response of these lasers.

References

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