Sub-threshold measurements of a photonic crystal (PC) microcavity laser operating at 1.3 μm show a linewidth of 0.10 nm, corresponding to a quality factor \( Q \sim 1.3 \times 10^4 \). The PC microcavity mode is a donor-type mode in a graded square lattice of air holes, with a theoretical \( Q \sim 10^5 \) and mode volume \( V_{\text{eff}} \sim 0.25 \) cubic half-wavelengths in air. Devices are fabricated in an InAsP/InGaAsP multi-quantum well membrane and are optically pumped at 830 nm. External peak pump power laser thresholds as low as 100 μW are also observed.

In order to measure the properties of the donor-type \( A_2 \) mode, graded square lattice PC cavities were fabricated in an active material consisting of five InAsP compressively-strained quantum wells, with peak spontaneous emission at 1285 nm. The details of the epitaxial growth and some of the important properties of the materials system are reported in Ref. 10. The creation of the 2D PC membrane is accomplished through a number of steps, including electron-beam lithography, pattern transfer to a SiO₂ mask using an inductively coupled plasma reactive ion etch (ICP/RIE), and a high-temperature (205 °C) Ar-Cl₂ ICP/RIE etch through the active material into a sacrificial InP layer. The sample is undercut by removing the InP layer with a HCl:H₂O (4:1) solution leaving a 252 nm thick free-standing membrane; scanning electron micrographs (SEMs) of the graded lattice cavity are shown in Figure 2. Each cavity consisted of a total of 32 rows and 25 columns of air holes, with a
We initially pump the cavities with a broad pump beam objective lens, also used to collect emitted photoluminescence. A typical L-L (light-in vs. light-out) curve using the broad pump beam condition is shown in Figure 2(a), where the power in the laser line is taken over a 10 nm bandwidth about the laser wavelength of \( \lambda = 1298.5 \text{ nm} \). In addition, the off-resonance background emission at \( \lambda = 1310 \text{ nm} \) was measured over a similar 10 nm bandwidth. For low pump powers (< 300 \( \mu \text{W} \)), the off-resonance emission and resonant wavelength emission linearly increase with pump power and are essentially identical in level, i.e., no resonance feature is observed. Above 300 \( \mu \text{W} \), we just begin to see a resonance peak in the spectrum and a characteristic super-linear transition from below threshold to above threshold follows. In order to estimate the position of threshold we extrapolate back the L-L curve from above threshold (Fig. 2(b)), giving an approximate threshold pump level of 360 \( \mu \text{W} \). A plot of the off-resonance emission (Fig. 2(c)) shows a (weak) slope change around 365 \( \mu \text{W} \) giving a similar value for the estimated threshold value. The slope change in the laser line versus pump power is initially a result of the material becoming transparent (more photons being radiated as opposed to being absorbed), and is then due to an increase in the stimulated rate of emission into the cavity mode as the lasing threshold is crossed, increasing the radiative efficiency into the cavity mode due to the presence of non-radiative carrier recombination and spontaneous emission into other modes. The kink in the off-resonance background emission L-L curve can be attributed to the clamping of the carrier density (gain) in the region of the cavity mode and consequent saturation of the off-resonance (non-lasing modes') emission. The background emission continues to increase after crossing threshold (rather than completely saturating) as a result of the pumping of areas which are outside of the cavity mode volume and thus not affected by the gain clamping (non-equilibrium carrier distributions\(^17\) may also play a role).

In order to estimate the cold cavity \( Q \) value of the PC microcavity mode we measured the linewidth of the resonance in the PL around threshold. The full-width half-maximum (FWHM) linewidth narrows from 0.138 nm (at the lowest pump level we could accurately measure the linewidth, 320 \( \mu \text{W} \)) down to 0.097 nm at threshold. A simple steady state rate equation model\(^18\) of the cavity photon and excited state populations estimates the threshold pump level (with this beam size) to be \( \sim 350 \mu \text{W} \) for \( Q \sim 10^4 \) in this quantum well active material, close to the experimentally measured value. In this model the transparency carrier density occurs within 10\% of the threshold carrier density for cavity modes with \( Q > 10^4 \).

The broad pump beam covers a significant portion of the cavity area, so that after diffusion of carriers, the majority of the cavity should be pumped and therefore non-absorbing, and (ii) use of a broad pump beam limits the effects of thermal broadening, which, as discussed below, are significant for focused pump beams. Devices are optically pumped (typically with a 10 ns pulse width and 300 ns period) at room temperature with a semiconductor laser at 830 nm through a 20X objective lens, also used to collect emitted photoluminescence (PL) into an optical spectrum analyzer (OSA). We initially pump the cavities with a broad pump beam (see Figure 2(b)), area \( \sim 21 \mu \text{m}^2 \) for two reasons: (i)
A PL spectrum (Fig. 3(a), inset) for this device with the broad pump conditions, measured soon after detection of a resonance feature in the spectrum and below the estimated threshold level by about 10%, shows a resonance feature when the pump power exceeds 95 $\mu$W. Estimates for the threshold pump power from the laser line curve and off-resonance background emission are 120 $\mu$W and 125 $\mu$W, respectively. The reduction in lasing threshold from the broad pump beam to the focused pump beam follows a nearly linear scale with the area of the pump beam. Through further optimization of the pump beam, lasers with thresholds as low as $\sim 100$ $\mu$W have been observed. From the sub-threshold spectrum shown in the inset of Figure 3(d) it is readily apparent that the lineshape has thermally broadened (the measured linewidth is now 0.220 nm), as evidenced by its asymmetric shape on the short-wavelength side. To reduce the effects of this thermal broadening, the duty cycle can be decreased to 1% (1 $\mu$s period and 10 ns pulse width), resulting in a less asymmetric resonance and sub-threshold linewidth of approximately 0.13 nm. Conversely, we have also increased the duty cycle to 25% (1 $\mu$s period and 250 ns pulse width) and still observe lasing; heating in the membrane precludes lasing at even higher duty cycles.

To determine whether the laser mode described above is indeed the localized $A_2$ mode of Figure 1, we have measured polarized intensity in the far-field as well as the sensitivity of the emitted laser power to pump position. The measurements show the mode to be predominantly polarized along the $\hat{x}$-axis (Fig. 4(b)) of the cavity, consistent with FDTD results, and eliminating the possibility that the mode is of the other potential symmetry supported by the cavity. Furthermore, the lasing mode discussed above is the longest wavelength mode observed in the devices tested (higher frequency resonances are observed in some detuned devices), suggesting that it is the fundamental mode shown in Figure 4(b), and not a higher order version of it. In Figure 4(a) we show measurements of the emitted laser power as a function of the pump beam position (taken to be the center of the beam) relative to the center of the cavity (uncertainty in the pump position is $\sim 0.25$ $\mu$m). The measurements indicate the mode is highly localized within the center of the cavity, consistent with simulations.

In summary, we have observed linewidths of $\Delta \lambda = 0.10$ nm, corresponding to a cavity $Q$ of $1.3 \times 10^4$, in sub-threshold measurements of graded square lattice photonic crystal microcavities lasers fabricated in an InAsP/InGaAsP multi-quantum well membrane. In addition, lasing is seen at threshold peak external pump powers as low as $100$ $\mu$W. Measurements of the emitted power as a function of pump position show the mode to be strongly localized and give an estimate of the modal localization that is consistent with FDTD results. This realization of a high $Q$, small mode volume microcavity is an important step in demonstrating the potential of PC microcavities for use in optoelectronics and quantum optics.

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**FIG. 4:** (a) Emitted laser power as a function of pump position along the $\hat{x}$ and $\hat{y}$ axes of the cavity. FDTD-generated Gaussian fits to the envelope of the electric field energy density of the cavity mode are shown for comparison (note that the effective mode volume is calculated from the peak electric field energy density). $L_x$ and $L_y$ correspond to the physical extent of the PC in the $\hat{x}$- and $\hat{y}$-direction, respectively. (b) Emitted laser power as a function of polarizer angle with respect to the $\hat{x}$ axis of the cavity.

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