laser to longer wavelengths resulted in CW rather than mode-locked operation.

In conclusion, we have demonstrated the first passively mode-locked diodepumped bulk Er^{3+}:Y^{3+}:glass laser. We obtained shorter pulses and significantly higher pulse energies than previously obtained with actively modelocked bulk Er^{3+}:Y^{3+}:glass lasers [4].

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Photonic bandgap disk laser

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A two-dimensional photonic crystal defined hexagonal disk laser which relies on Bragg reflection rather than the total internal reflection as in traditional microdisk lasers is described. The devices are fabricated using a selective etch to form free standing membranes suspended in air. Room temperature lasing at 1650nm for a 150nm thick, ~15μm wide cavity fabricated in InP/InGaAsP is demonstrated with pulsed optical pumping.

Since their introduction in 1992, [1] microdisk lasers have attracted significant attention as high-Q light sources with very strong optical confinement. Their lasing modes approximate whispering-gallery modes which depend on total internal reflection at the curved boundary of the semiconductor disk. In this Letter, we describe a demonstration of lasing action in a hexagonally shaped disk with a similar whispering-gallery-like mode based on Bragg reflection from a photonic bandgap crystal instead of the large dielectric discontinuity between the semiconductor layer and a surrounding low index medium. [2] The confinement of whispering-gallery modes depends strongly on the curvature of the disk boundary. The use of a photonic bandgap allows the lateral confinement and the device size to be decoupled.

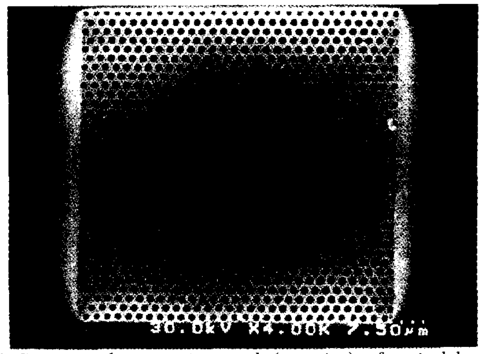

Fig. 1 *Scanning electron micrograph (top view) of typical hexagonal membrane cavity bounded by 2D photonic bandgap crystal*

We have designed and fabricated two-dimensional photonic crystals in a thin semiconductor membrane bounded above and below by air. An electron micrograph of a typical device is shown in Fig. 1. The optical cavity consists of a $\lambda/2$ thick dielectric slab waveguide suspended in air. The strong confinement provided by the index contrast between the semiconductor membrane and air helps to reduce the scattering out of the plane of the waveguide by the photonic crystal. The membrane is patterned with a hexagonal two-dimensional array of air holes which is used to define the boundaries of a hexagonal cavity. The ratio of the hole size to the lattice space (r/a) was ~0.35. The calculated band structure for this photonic crystal, taking into account the finite extent of the photonic crystal in the third dimension, exhibits a TE bandgap from a normalised frequency of a/λ = 0.3476 to a/λ = 0.4654 for modes guided within the semiconductor slab. Details of this calculation have been previously described [3 – 5]. The cavities were designed with the photonic bandgap centred around the peak emission wavelength at a normalised frequency of a/λ = 0.406. In this Letter, cavities ~10–15μm across were examined. At the emission wavelength of 1.55μm, this structure forms a multimode cavity.

The membrane consisted of six lattice matched InGaAs quantum wells with InGaAsP barriers grown by metal organic vapour phase epitaxy (OMVPE) on an InP substrate. The total waveguide thickness was 150nm. The InGaAsP system was chosen for its relatively low surface recombination velocity since the photonic crystal has a relatively large surface-to-volume ratio. The photonic crystal structure was patterned using electron beam lithography. This pattern was transferred from the electron beam resist into a multilayer mask and then etched into the semiconductor membrane using Ar/Cl_2 chemically assisted ion beam etching (CAIBE). A dilute HCl solution was then used to selectively etch away the InP material beneath the membrane while leaving the InGaAsP waveguide layer. This results in a free standing, air suspended membrane.

The laser cavities were optically pumped normal to the membrane using an InGaAs laser emitting at 980nm focused to a spot size of ~ 15μm. The pump laser was pulsed with 10ns pulses at a duty cycle of 0.3–0.5%. The low duty cycle was used in order to minimise heating of the membrane which lacks a good thermal conduction path for heat dissipation. Luminescence from the quantum wells at λ = 1.55μm was collected normal to the membrane, in the same direction as the pump. Hexagonal photonic crystal disks similar to the device in Fig. 1 showed a lasing spectrum at room temperature as shown in Fig. 3. The lasing spectrum was centred at $\lambda \simeq 1645$nm with a linewidth measured to be less than ~ 2Å (limited by the spectrometer resolution). The lasing wavelength was significantly red-shifted from the designed quantum well emission peak of $\lambda = 1550$nm because of heating of the active layer by the pump laser which shifted the gain peak towards longer wavelengths. These lasers were fabricated with a lattice spacing of $a = 640$nm. For a lasing wavelength of 1645nm, this corresponds to a normalised frequency of 0.389, within the photonic bandgap, near the bandgap centre frequency of 0.406. Fig. 3 also shows a number of side modes, spaced by ~30nm with full-width at half-maximum (FWHM) linewidths of 20nm, corresponding to a cavity quality factor $Q \simeq 80$.

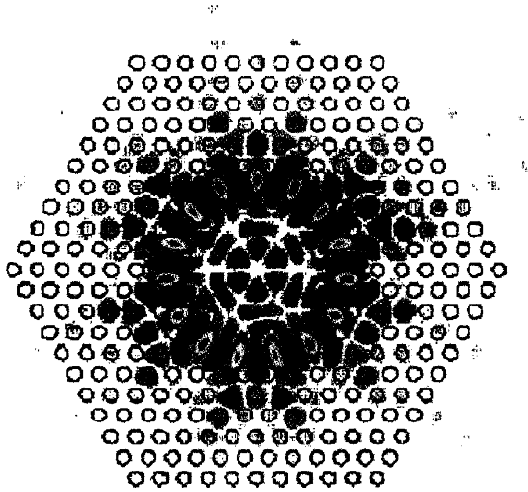

Fig. 2 *Calculated field distribution for whispering gallery-like mode in this cavity*

In this image, field intensity is represented by shading; triangular array of circles represent air holes etched into semiconductor waveguide

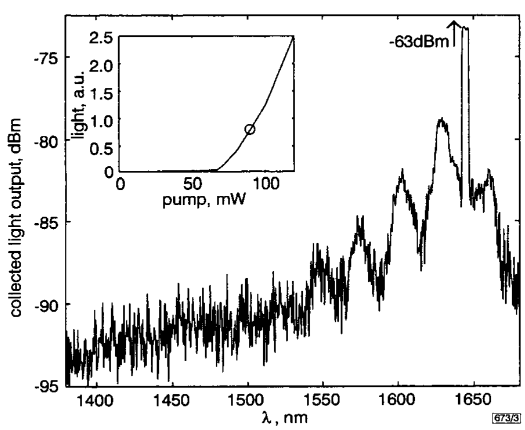

Fig. 3 *Spectrum from lasing hexagonal PBG disk slightly above threshold with spectral resolution of 5nm*

Lasing line is clearly visible at 1650nm; width of line as well as its rectangular profile are due to wide spectral resolution
Inset: light intensity against pump power demonstrating a clear threshold
O point where spectrum was measured

The light output against pump power response for the laser is shown in the inset of Fig. 3. The lasing threshold occurred at a peak pumping power of 66mW. The relatively high threshold required is due largely to the mismatch between the pumping profile and the lasing mode as well as the relatively low Q of this non-optimised structure. For a whispering gallery-like mode as shown in Fig. 2, the majority of the field intensity lies around the perimeter of the cavity. However, optically pumping the device with a Gaussian beam concentrates the peak pumping power at the centre of the cavity. This poor pump to mode overlap was experimentally verified. Lasing occurred with a pump spot size of 15μm however, when the pump spot was focused to smaller sizes (2–10μm), it was not possible to reach lasing threshold even with peak pump powers up to ~ 150mW. The lasing mode in Fig. 3 does not correspond to one of the prominent equispaced ($\Delta\lambda$ = 30nm) modal peaks but occurs between two such resonances. Below threshold, only these regularly spaced side modes are visible with very little emission occurring at the lasing wavelength. This indicates that these side modes have a strong overlap with the pump profile, giving strong spontaneous emission, but low Q so that the lasing threshold is not reached. The lasing mode is a much higher Q mode, which lowers the lasing threshold but has a relatively poor overlap with the pump. These regularly spaced modes have been previously observed [6].

Finite difference time domain calculations have shown that the relatively large hexagonal cavities exhibit an extremely complex modal structure including whispering gallery-like modes (Fig. 2), as well as more plane-wave like modes reflecting between opposing faces of the hexagon. However, because the photonic crystal has a very wide bandgap (and is thus highly reflective over a wide range), these are all relatively high Q modes. This suggests the possibility of using pumping geometry to select the lasing mode (and therefore also the lasing wavelength) due to the differences in spatial field distribution between the modes. By adjusting the pump beam alignment with the laser cavity, we have been able to observe an abrupt shift of the lasing wavelength to $\lambda = 1660$nm corresponding to one of the previously mentioned regularly spaced modes.

In summary, we have demonstrated planar hexagonal disk lasers based on a two-dimensional photonic band gap structure in the InP material system. Lasing occurred at room temperature under pulsed pumping conditions in spite of the poor thermal conduction path for heat removal. Different lasing modes in the disk were selected by adjusting the pump alignment. A relatively high lasing threshold was observed due to the poor overlap between the pump and the lasing mode and the relatively high membrane temperature. Heat dissipation could be improved by including a supporting post similar to that found in microdisk lasers.

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