Photonic crystal heterostructure cavity lasers using kagome lattices

A.V. Giannopoulos, C.M. Long and K.D. Choquette

The lasing characteristics of a photonic crystal membrane heterostructure cavity that utilises a kagome type lattice is demonstrated. A heterostucture cavity is formed by interfacing two photonic crystals such that the dispersion maximum of the inner lattice falls within the photonic bandgap of the surrounding lattice. Feedback to slow Bloch modes allows for localisation of band edge modes and a reduction of in-plane losses. Singlemode lasing is observed in relatively large area lasers at 1550 nm.

Introduction: Two-dimensional photonic crystal defect cavity lasers have enabled ultra-small modal volumes and high quality factors [1–4] by using the extremely high reflectivity that a photonic bandgap provides. Another phenomenon in photonic crystal membranes, slow group velocity at the dispersion symmetry points, has enabled band edge lasing [5, 6]. Recent work has indicated that the two phenomena, bandgap localisation and slow group velocity, can be combined [7–9]. Incorporation of hexagonal lattices which differ in hole diameter only, has allowed for the localisation of band edge modes within a heterogeneous defect cavity with low lasing thresholds [10]. In this Letter, we report the lasing characteristics of a photonic crystal heterostructure laser using a kagome lattice. In this device, two different photonic crystal geometries with the same nearest neighbour distance are used to form a relatively large area cavity. The inner kagome lattice that forms the cavity uses fewer air holes than a simple hexagonal or square photonic crystal lattice and thus provides more gain material for the resonant mode.

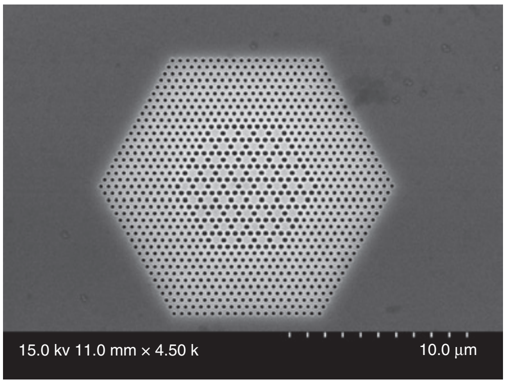

Fig. 1 *Image of photonic crystal heterostructure laser cavity*

a Hexagonal
b Kagome

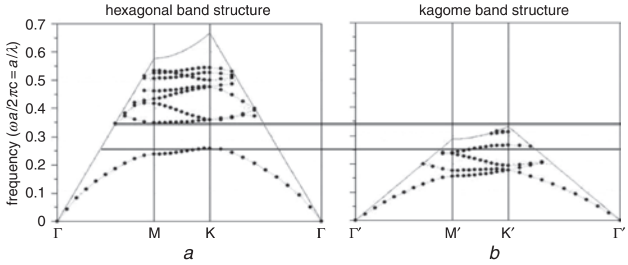

Fig. 2 *Hexagonal and kagome photonic band structures*

There is an overlap of band maximum at approximately $a/\lambda = 0.27$ at K-point of kagome lattice with bandgap of hexagonal lattice (horizontal lines)

Device design: The kagome lattice is a hexagonal lattice of air holes with an intermeshed hexagonal lattice of defects with a period of twice the hexagonal lattice. Fig. 1 shows a scanning electron microscope image of a photonic crystal heterostructure membrane laser using a kagome lattice. The central kagome lattice is surrounded by a hexagonal crystal with no defects. The calculated band diagrams for both lattices are shown in Fig. 2. The bandgap of the hexagonal region is tuned to overlap a local maximum at the K-point of the kagome lattice allowing for feedback of the slow Bloch modes of the central region. In both photonic crystal lattices, the nearest neighbour hole spacing, a, is the same, while the hole radius to a ratios are used to tune the lattice dispersion. When operating at the K-point of the kagome lattice, out-of-plane losses are minimised owing to operation below the light cone, and in-plane losses are minimised by the bandgap effect of the surrounding hexagonal lattice.

Device fabrication: The devices are fabricated in the InGaAsP/InP material system. There are six quantum wells with a photoluminescence peak around 1550 nm embedded in an InGaAsP membrane with a total thickness of 280 nm grown on an InP substrate. The photonic crystal structure is patterned using electron beam lithography. A Freon 23 etch is used to transfer the pattern into an SiO_2 etch mask. Inductively coupled plasma reactive ion etching is used to transfer the pattern through the InGaAsP film and into the substrate. A 1:1 mixture of $HCl{:}H_3PO_4$ at room temperature allows the photonic crystal to be undercut in order to create a suspended membrane.

Device characteristics: The cavities are pumped with a 980 nm laser diode using 100 ns pulse widths and 1% duty cycle at room temperature. Light output from the device is collected though a 20× objective and focused onto a fibre, which is the input to an optical spectrum analyser. Fig. 3 shows the lasing spectrum of a photonic crystal heterostructure cavity with nearest neighbour hole spacing, a, of 418 nm. Holes in the kagome central region have radii of approximately $0.37a$ and holes in the outer hexagonal region have radii of approximately $0.32a$. The kagome cavity studied in this work has an area of 36.7 μm^2 (approximately $15.3\lambda^2$), of which approximately 63% is the semiconductor. The collected power at the lasing wavelength against pump power is shown in Fig. 4. The input power has not been calibrated to the pump spot size and a pump spot larger than the cavity is used. The device has a soft turn on with a linearly extrapolated threshold of approximately 8.0 mW. The inset in Fig. 3 shows the emission spectrum at a pump power of 7.0 mW. A Lorentzian fit to the emission spectrum at 7 mW pump power gives a linewidth of approximately 0.64 nm (spectrometer limited), corresponding to a quality factor of about 2400.

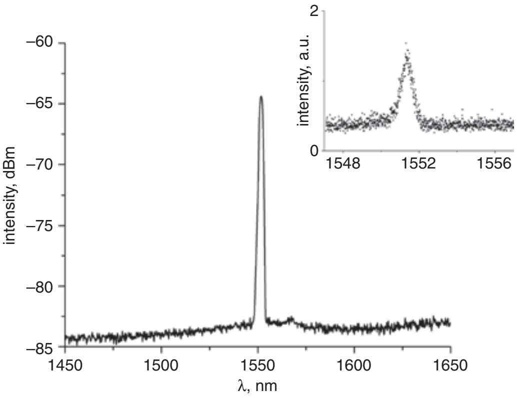

Fig. 3 *Lasing spectrum at pump power of 13 mW*

Inset: Emission on linear scale just below threshold

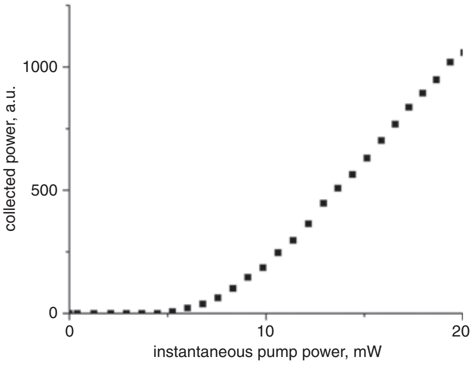

Fig. 4 *Collected power against instantaneous pump power at 980 nm*

Conclusions: The kagome type lattice operating at the band edge in the central region of the device should lower the material gain needed to achieve threshold by using the gain enhancement that a slow group velocity provides [7]. The hexagonal outer lattice also enables feedback owing to the presence of a photonic bandgap. The larger semiconductor volume in the kagome lattice as compared to a simple hexagonal lattice results in the availability of more carriers for the production of optical gain. In spite of the relatively large area cavity design, singlemode lasing is observed. These attributes make the photonic crystal heterostructure promising for use as an electrically injected laser.

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