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Photonic Crystal Band-edge Laser on a Flexible Substrate

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1. Introduction

Photonic crystal lasers have been developed and integrated with functionality optical or optoelectronic components as wavelength–scale coherent light sources. The photonic crystal lasers are interesting because of its geometrical tuning optical properties [1]. In this work, we demonstrated flexible triangular-lattice photonic crystal band-edge lasers on a polydimethylsiloxane (PDMS) substrate.

2. Fabrication

The fabricated triangular-lattice photonic crystal structure was formed in a 240 nm thick InGaAsP active layer on a PDMS substrate. Fig. 1(a) shows the illustration of the structure. In fabrication, the photonic crystals were implemented in a 240 nm thick InGaAsP layer on the InP substrate. The InGaAsP layer consisted of four strained InGaAsP quantum wells (QWs) with an emission peak at 1.55 μm. A silicon-nitride (SiN_x) layer and a polymethylmethacrylate (PMMA) resist were deposited on the epitaxial wafer for the dry etching processes and electron-beam lithography. The triangular-lattice air holes were defined on PMMA by electron-beam lithography. Followed by RIE and ICP dry etching processes, the patterns were transferred to the SiN_x layer with CHF_3/O_2 mixture gases at 20℃and further to the QWs layer with $CH_4/Cl_2/H_2$ mixture gases at 150℃. After that, we bonded the QWs layer to a 500 μm thickness PDMS substrate. The structure was formed by removing the InP substrate with HCl solution. The scanning electron microscope (SEM) picture of fabricated PCs is shown in Fig. 1(b)

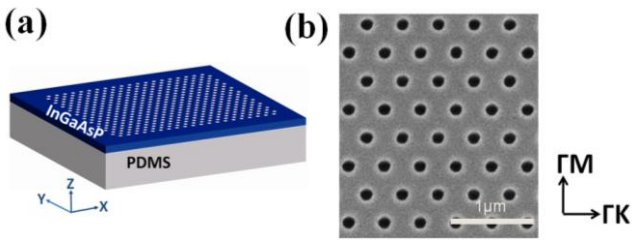

Fig. 1(a) The illustration of a triangular-lattice photonic crystal band edge laser on a PDMS substrate. (b) The SEM image of the fabricated structure.

3. Measurement and Discussion

The devices were then optically-pumped at room temperature by using an 850 nm wavelength diode laser at normal incidence with a 1.5% duty cycle and a 30 ns pulse width. The pump beam was focused on the devices by a 100x objective lens. The pumped beam spot size is approximately 2 μm in diameter. The output power from the lasers was collected from the top of the structures by a multi-mode fiber connected to an optical spectrum analyzer. The structure achieves lasing with a low threshold power. Fig. 2(a) shows a lasing spectrum from the photonic crystal band-edge laser with 430 nm lattice constant. The lasing wavelength is around 1627 nm. The light-in light-out (L-L) curve of this laser is show in Fig. 2(b). The threshold power is about 2.7 mW. To confirm the optical modes of the band-edge laser, the structures with different lattice constants were optically-pumped and the lasing wavelengths were recorded. The normalized frequency of the lasing modes is about 0.264.

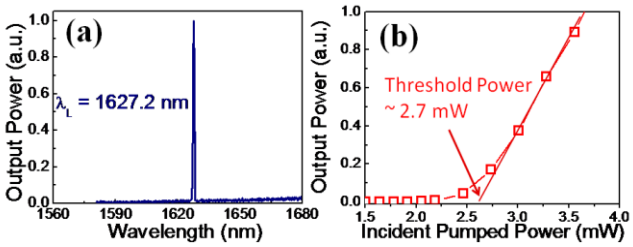

Fig. 2(a) The lasing spectrum from a triangular lattice photonic crystal band edge laser on a PDMS substrate. (b) The L-L curve from the laser.

To understand the lasing modes, the corresponding band structure for TE-like modes are calculated with 3D plane-wave expansion (PWE) method. The band structure is shown in Fig. 3(a). The band-edge lasing modes are likely to occur around the high-symmetry points of the band structure. The flat dispersion curve near the band-edge implies a low group velocity of light and strong localization. Compared the measurement with the simulation, the lasing mode of 0.264 normalized frequency corresponds to the first K (K_1) band-edge point. Fig. 3(b) shows the calculated H_z mode profile of the K_1 band-edge mode.

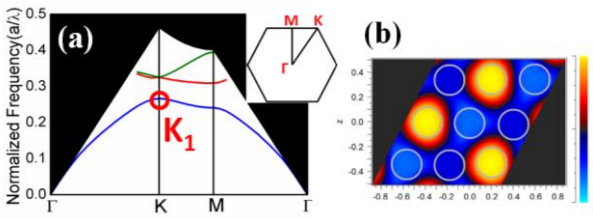

Fig. 3(a) The band structure of the triangular-lattice photonic crystal with 0.25 r/a ratio calculated with the 3D PWE method. The lasing mode is shown with a red circle. (b) The H_z field mode profile of the K_1 band-edge mode.

After characterizing the band-edge laser on a flat surface, we bent the device along the Γ-M direction on a bent mental surface. The maximum bending radius is only approximately 15 mm, which is large enough for most of applications. Fig. 4(a) illustrates the bent triangular-lattice photonic crystal structure with the curvature 1/R. We bent the structure along the Γ-M direction. Fig. 4(b) shows a curved structure on a bent mental surface. Under the same pumping condition and pumping position, the fabricated structure achieved lasing at various bending curvatures. Fig. 4(c) shows the L-L curves of the laser with the 430 nm lattice constant at different bending curvatures 1/R. Fig. 4(d) shows the lasing wavelength red-shifted as the bending curvature was increased.

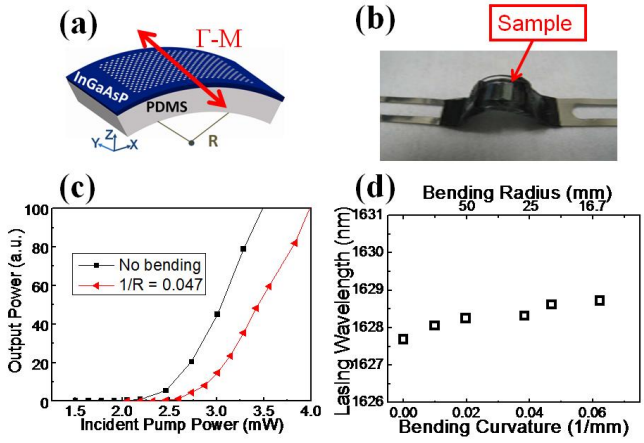

Fig. 4(a) The illustration of the bent photonic crystal laser. (b) The curved sample on a bent mental surface. (c) The light in light out curve of the 430nm lattice constant photonic crystal laser with different bending curvature. (d) The lasing wavelength red-shift as the curvature is increased.

The lasing wavelength of the photonic crystal lasers strongly depends on the laser geometry. The red-shift implies that the geometry of the laser would be changed when the structure is bent. Also, the refractive index of the PDMS substrate would become lower when the structure is bent [2]. Here, we attribute the red-shift to the lattice distortion and the PDMS index variation.

In order to characterize these wavelength red-shift behaviors, we perform simulations with 3D plane-wave expansion method. In the simulation, we assume that the lattice constant in the Γ-K direction is extended and the lattice constant in Γ-M remains the same. Fig. 5(a) shows the illustration of the lattice distortion. When the bending curvature is increased to 0.06 mm^{-1}, the lattice would be extended approximately 0.02% in the Γ-K direction. The red-line of Fig. 5(b) shows the simulated frequency due to the lattice distortion. The frequency of the K_1 mode decreases as the curvature is increased. The blue-line of Fig. 5(b) shows the simulated frequency of the K_1 mode which increases as the PDMS index is decreased. The green line of Fig. 5(b) is the linear fitting results of the measured data. The observed red-shift in frequency (green) is resulted from the combination of the lattice distortion and the PDMS refractive index change.

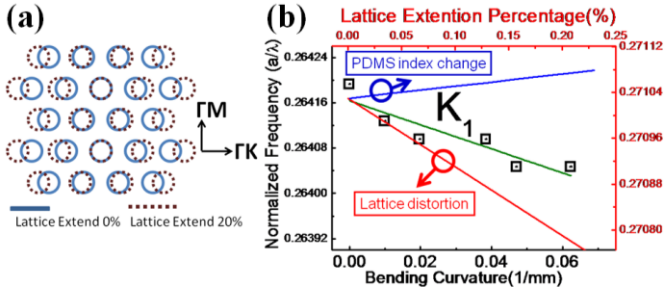

Fig. 5(a) The illustration of the photonic crystal lattice distortion. (b) The comparison of the measured lasing frequency (green), the frequency due to PDMS index change (blue) and frequency due to lattice distortion (red).

4. Conclusions

In conclusion, the triangular-lattice photonic crystal band-edge laser on a flexible PDMS substrate was demonstrated. The lasing action was achieved around 1550 nm wavelength with a threshold power. The observed lasing mode was identified to be around the symmetry point K of the first photonic crystal band by comparing experimental results with 3D PWE simulation. The lasing action of the bent photonic crystal lattices was also observed at various bending curvatures. The lasing wavelength red-shifted as the curvature was increased, and the red-shift in wavelength is dominated by the lattice extension along the Γ-K direction.

References

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