Surface emitting lasers with two-dimensional nanoimprinted photonic crystals

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Abstract: We report on the fabrication and characterization of two-dimensional polymer photonic crystal lasers operating in the visible range. The components have been fabricated in a dye chromophore-loaded polymer matrix by nanoimprint lithography. The experimental lasing frequencies are in good agreement with those calculated using a two-dimensional plane wave algorithm. These results demonstrate the potential of nanoimprint lithography for the fabrication of two-dimensional planar photonic crystal structures in an active medium in a one-step process.

Polymer photonic devices generate a great interest to serve as new platforms for planar photonic integrated circuits. However the fabrication of PhCs often requires elaborate and expensive techniques, such as electron-beam lithography and reactive ion etching. For the last ten years, nanoimprint lithography (NIL) has become an alternative cost-efficient technology to replicate features with a sub-10 nm resolution. We show here the fabrication and optical characterization of polymer PhC band edge lasers and polymer PhC with photonic band-gaps fabricated by NIL in a polymer layer doped with rhodamine 6G on glass substrates. Silicon PhCs stamps with different lattice constants were fabricated and successfully imprinted by standard NIL process. Figure 1 shows a scanning electron microscope (SEM) image of a stamp structure and the corresponding two-dimensional PhC imprinted in the active polymer. The pattern is well reproduced, with a surface roughness comparable to the one of the stamp. These polymer lasers were pumped optically using a frequency-doubled Q-switched Nd:YAG laser (532 nm, 0.7 ns, 10Hz). The beam was focused to a ~20 μm radius spot. The emission from the PhCs was analyzed with a CCD spectrometer. Figure 2 shows the measured spectra of 460 nm lattice constant honeycomb PhCs made in polymer, excited above the lasing threshold. By scaling the lattice constant of the PhC, the emission wavelength can be tuned. Insets in Figure 2 shows the light input-output relation of these lasers, exhibiting a sharp turn-on at the laser threshold. At much higher excitation levels, multimode laser oscillations were observed. The lasing mode has been matched with a very good agreement to the expected band edge lasing modes calculated with a plane-wave-basis frequency-domain method (Table 1). Furthermore, microcavities have the potential to exhibit an ideal cavity for the control of the spontaneous emission. A simulated example by 2D FDTD of the transmission of a plane wave along the ΓM direction of the microcavity is presented Figure 3. It shows a sharp resonance inside the bandgap. The light is expected to be strongly localized in the defect induced by the PhCs exhibiting a photonic band gap (inset). Experimental validation is under progress.

In conclusion, we fabricated polymer photonic crystal band-edge lasers using nanoimprint lithography. The laser emission wavelength can be tuned by controlling the lattice constant of the PhCs, covering a wavelength range of 30 nm around 550 nm. A minimum lasing threshold of 3 μJ/mm2 was obtained for the defect-free PhC (value at the state of the art at the best knowledge of the authors). Nanoimprinted microcavities with two-dimensionnal photonic crystals have been successfully fabricated opening the way on the realization of ultrasmall laser cavity. Unlike the electron-beam lithography commonly used for patterning nanophotonic structures, NIL offers a cost-efficient, rapid and large area processing capability. The direct transfer of the PhC pattern in an active layer reduces the number of process steps for the fabrication of this type of lasers. An overview of nanoimprinted polymeric optical resonators will be given showing the relevance of nanoimprinted photonic crystals for accurate light control.

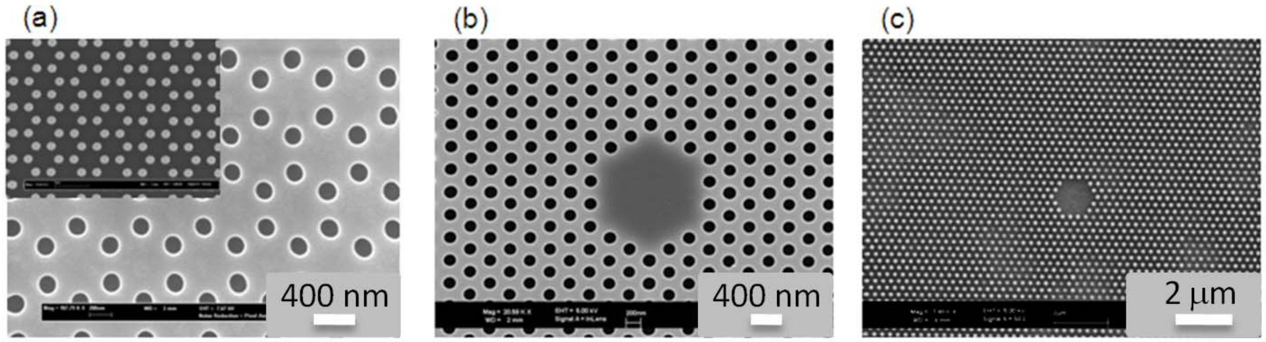
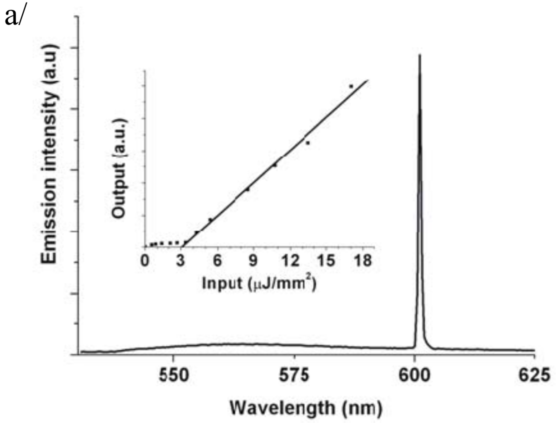


Fig. 1: a/ SEM micrographs of nanoimprinted photonic crystals in mr-NIL 6000, in which rhodamine 6G have been incorporated (concentration: 5.10^{-3} mol.L^{-1}), Inset: SEM micrographs of a silicon stamp containing two-dimensional honeycomb array of pillars, b/ SEM micrographs of a silicon microlaser stamp containing two-dimensional triangular array of pillars, c/ SEM micrographs of nanoimprinted photonic crystals in the dye doped polymer.



Lattice constant (nm)	460	580	
Calculated reduced frequency (a/λ)	0.766	0.954	1.022
Measured reduced frequency (a/λ)	0.765	0.962	1.017

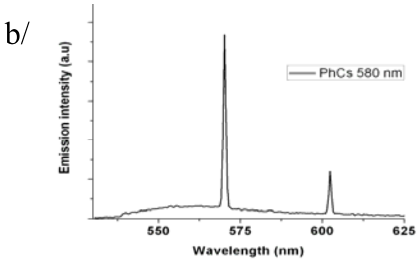


Figure 2: Emission spectra of a band edge laser (a/ lattice constant: 460 nm, b/ lattice constant: 460 nm). Inset: Radiated power as a function of the excitation energy. Table: Comparison of the calculated and measured reduced frequencies for the PhC band-edge lasers with the lattice constants *a*=460 nm (one lasing mode), and *a*=580 nm (two lasing modes)

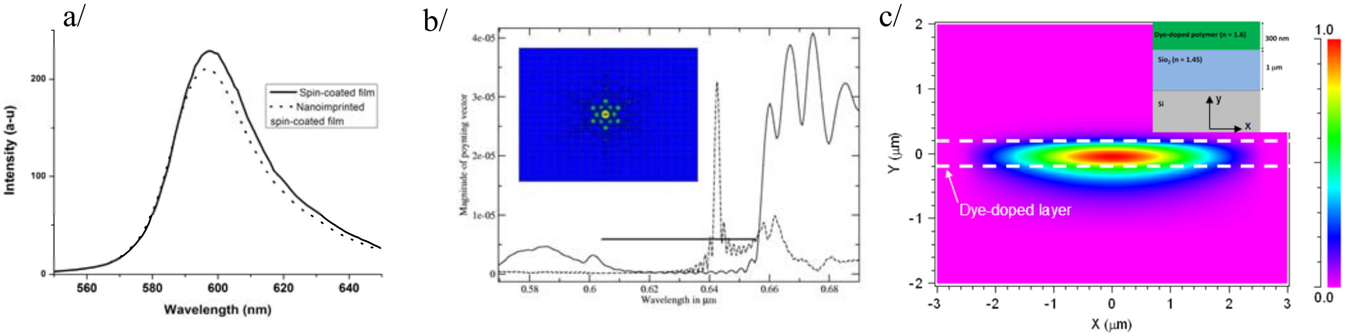


Figure 3: a/ Emission spectra for mr-NIL 6000 doped with Rhodamine B taken before (solid line) and after the nanoimprint process (dot line), b/ Results of the FDTD simulation of transmission of a plane wave through a PhC with a defect (in dotted lines) and without defect (solid line). Inset: Electric field in the out-of-plane direction for the PhC at the resonant wavelength, c/ Mode distribution propagating in the multilayer Si/SiO_2/active layer/air system showing a mode confinement of 0.58 in the active layer, calculations performed by 3D FDTD.

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