

Mechanochromic photonic crystals as strain sensors

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1 Introduction

Photonic crystals (PCs) provide a new idea for the design and fabrication of novel sensors because of their special light manipulation properties. Direct optical detection via the structural colours of PCs could be an attractive way to detect a signal without complex data collection or display units. So far, various sensors based on PCs that directly respond to environmental stimuli with an optical signal have been fabricated. For instance, Asher and co-workers [1] have pioneered the fabrication of PC hydrogel-based sensors for temperature, pH, ionic species, creatinine, etc. Takeoka and co-workers [2] have extensively studied gels that exhibit switchable colours over the visible region when exposed to external stimuli. Xia et al. [3] have studied solvent-swelling colloidal crystals with tunable colours that served as a photonic paper for coloured writing. Gu et al. [4] have studied the stopband shift of PCs based on the refractive index change. Stein et al. [5] have reported solvent-filling effects in the optical properties of ceramic inverse opals, which could be used in detecting organic solvents through the change in refractive index.

In this paper, we propose a novel structural coloured material, composed of closely packed colloidal particles embedded in a poly-dimethylsiloxane (PDMS) elastomer that is sensitive to the applied strain. The protocol employed for the fabrication of the PC structures, and their optical characterization as a function of the horizontal applied strain, are discussed.

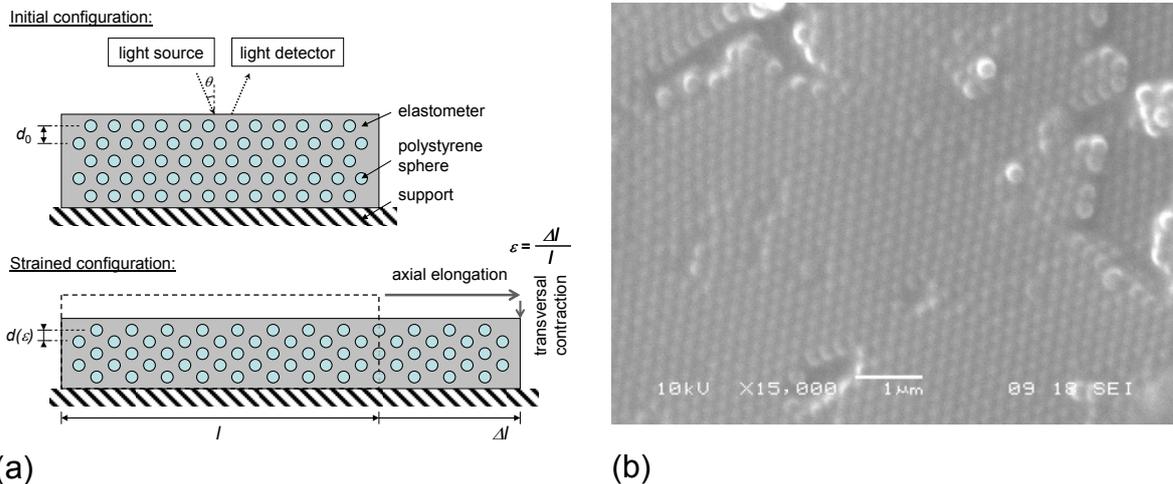
2 Experimental

The crystals have been prepared by polystyrene spheres (PS) embedded in a PDMS elastomeric matrix. The procedure involves three steps: (i) the PS that will form the opal structure are produced by the protocol previously described [6]; (ii) the PS are arranged in a lattice structure on the support (viton substrate); (iii) finally they are infiltrated with the elastomer (PDMS). The details are reported elsewhere [7]. It is

worth to note that the elastomer has the fundamental function of providing a flexible PC structure that can be easily handled. Furthermore, this process affects the range of deformability of the PC; in fact, infiltration prevents direct contact between the PS under transversal contraction, avoiding non-linear effects in the strain response.

3 Results and Discussion

Figure 1(a) illustrates the concept of tuning the structural colour of the PC. Figure 1(b) shows its scanning electron microscopy (SEM) image.



(a) dependence of the inter-planar spacing on the applied strain. Comparison between the initial (upper figure) and strained (lower figure) configurations; (b) SEM image of the surface section of the PS spheres arrayed with cubic close packing in a PDMS elastomer.

Generally, the overall reflecting behaviour of the PC can be expressed by the modified form of Bragg's law [8]:

$$\lambda = 2 \cdot d \cdot \sqrt{(n_{\text{eff}})^2 - (\sin \theta)^2} \quad (1)$$

where λ is the free-space wavelength of the light, d is the inter-planar spacing, n_{eff} is the effective refractive index and θ is the angle measured from the normal to the planes. When an axial strain is applied to the PC, the inter-planar spacing is modified due to the transversal contraction, as illustrated in Fig. 1(a). Hence the initial value d_0 is reduced to value $d(\epsilon)$ depending on the applied strain value ϵ . As a consequence, the refractive index n_{eff} is also linearly affected by the stress variation [9]. The combination of these two effects makes the reflectance properties of the PC, and particularly the wavelength of the reflection peak, sensitive to the applied strain. Once the relation is known, a measure of the colour reflected by the PC allows to estimate the strain inherited from the structure on which it is attached.

A prototype sample of PC, produced by the technique described above, has been tested to identify the relationship between the applied strain and the wavelength of the reflected peak.

Figure 2 shows the changes in the structural colour of the unperturbed colloidal crystal film from yellow to green by the elongation ΔL of the structure due to mechanical strain.

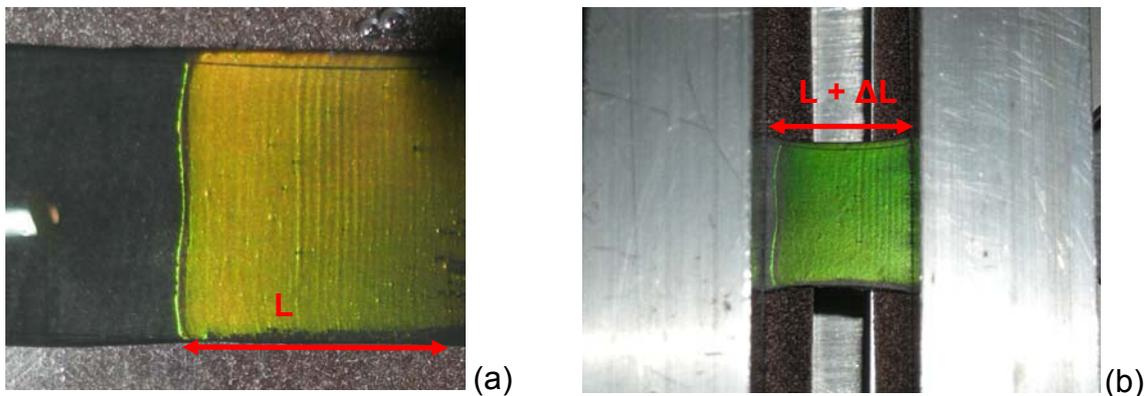


Figure 2: changes in the structural colour of the colloidal crystal film deposited onto a viton substrate ($1.6 \times 1.6 \text{ cm}^2$); (a) photographic image of the initial sheet (L), (b) photographic image of the stretched sheet ($L + \Delta L$).

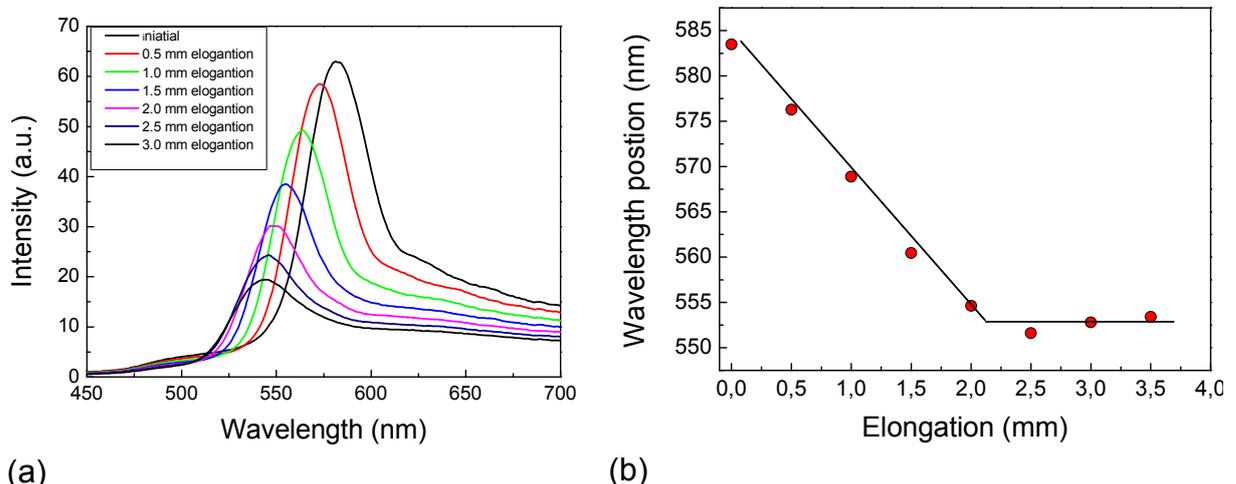


Figure 3: Relationship between the peak positions and elongation of the silicone rubber sheet owing to stretching. (a) Reflectance of the photonic crystal. (b) Peak reflectance wavelength as a function of the elongation.

In Figure 3(a) the reflectance spectrum due to the Bragg diffraction from the cubic close-packed (ccp) (111) planes of the PC crystal is reported as a function of elongation ΔL . We can notice that the peak position blue shifts from 583 (initial point) to 550 nm, while the reflectance intensity gradually decreases [7].

Figure 3(b) shows the shift of the reflectance peak as a function of elongation; one can notice, in particular, that a linear relationship exists for elongations as large as 2 mm. In this region, the lattice distance of the ccp (111) planes, d , also decreases at the same rate. For higher elongation values, the position of the peak does not change significantly, due to the fact that interplanar distance remains constant for the applied mechanical strain since the PS spheres are in contact with each other.

4 Conclusions

In this paper we have proposed a novel structural coloured material, composed of closely packed colloidal particles embedded in a PDMS elastomer, that is sensitive to the applied strain. We have shown that for suitable strain values the variation of the colour of the structure can be easily observed by the naked eye (in the example, from yellow to green). Moreover, quantitative optical measurements have evidenced a blue shift of the diffraction peak as a function of the applied strain; the realized structures present a dynamic range of about 35 nm, suggesting that these systems can have potential applications as smart mechanical strain sensors. These sensors may be advantageously combined with fiber Bragg grating or fiber long-period grating sensors, which are able to measure much smaller elongations with higher resolution and sensitivity.

5 Acknowledgements

This work was funded by the Autonomous Province of Trento by the CRS2007 project “Tecnologie innovative per il monitoraggio di torri e turbine eoliche installate in siti complessi” and performed in the framework of PAT FaStFal 2007-2010 and COST MP0702 research projects.

6 References

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