Optically controllable photonic crystals and passively tunable terahertz metamaterials using dye-doped liquid crystal cells

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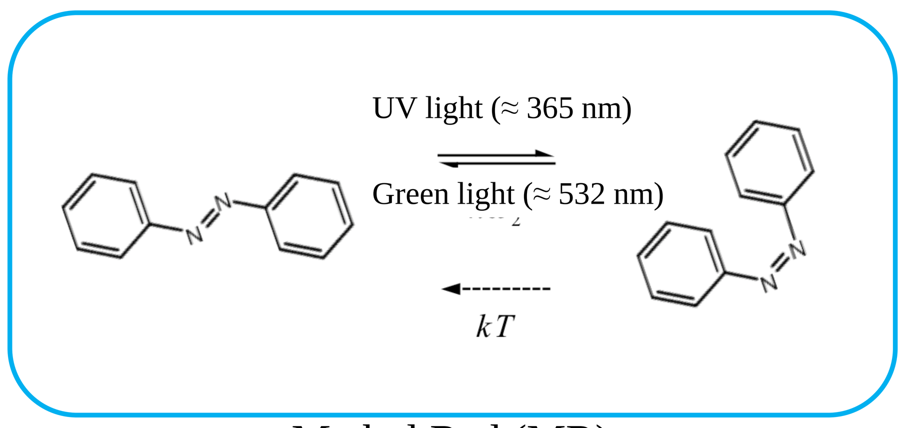
Abstract

This work fabricates a fishnet grating by exerting two one-dimensional (1D) holographic interference fields with mutually orthogonal grating vectors separately on the substrates of a dye-doped liquid crystal (DDLC) cell. The DDLC mixture in the cell includes a nematic LC, methyl red (MR) dye, and 4-methoxyazobenzene (4MAB) dye. The fishnet grating is formed because the periodical adsorption of the MR dye on the irradiated surfaces of the cell causes the anisotropic photoalignment of the LC. The fishnet grating can be erased (recovered) by the illumination of a UV (green) beam since the *trans*→*cis* (*cis*→*trans*) isomerization of the 4MAB dye causes the isothermal nematic→isotropic (isotropic→nematic) phase transition of the LC. Such a grating can be used to develop optically controllable photonic crystals. Simulated results depict that a photoresist-coated plastic substrate that is exposed to the fishnet pattern of a 2D grating can be used to develop terahertz fishnet metamaterials, and their resonance spectra can be passively tuned by moving the substrate and lens that forms the fishnet pattern during fabrication. Therefore, the mask-free photolithography can be used to fabricate passively tunable terahertz filters.

Experimental

The grating is fabricated from a DDLC cell that is exposed to a 2D interference field. The DDLC mixture in the cell is prepared using a nematic E7 LC (Merck), methyl red (MR) dye (Sigma-Aldrich), and 4-Methoxyazobenzene (4MAB) dye (Fluka). The mixing ratio of E7: MR: 4MAB in this mixture is 69:1:30 by weight. Figure 1 schematically depicts the fabrication process of a 2D LC grating.



Methyl Red (MR)

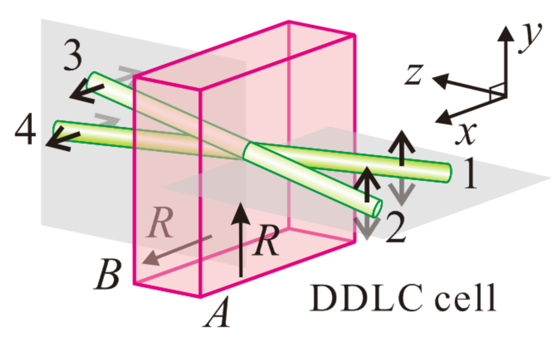


Figure 1. Fabrication of 2D LC grating

The DDLC cell, which is separated by 18μm-thick spacers, comprises glass substrate A/ DDLC mixture/ glass substrate B. The two uncoated substrates A and B are rubbed along the y and x axes of Fig. 1, respectively. The rubbed substrates exert a twisted nematic (TN) alignment of weak anchoring on the LC in the cell. Four coherent pump beams from an Ar+ laser (λ = 514.5 nm) are used to fabricate a 2D LC grating, as shown in Fig. 1. Two pump beams 1 and 2 (3 and 4) which intersect at an angle of ~1.46º in the xz (yz) plane are incident to the DDLC cell from substrate A (B), and their polarizations are along the y (x) axis. Each of the pump beams has a light intensity I_0 of 1.5 mW/cm^2. The interference formed by beams 1 and 2 (3 and 4) generates a spatial variation of light intensity on surface A (B), establishing a corresponding distribution of the adsorption of the MR dye, and causing the position-dependent surface director reorientation. The adsorbed MR dye molecules on each surface reorient the surface director toward a direction perpendicular to the interference field which acts on that surface.5,6 The director reorientations on surfaces A and B form two 1D gratings, which compose a 2D grating in the DDLC cell.

Results and discussion

A 2D grating with a spatial period of 20 μm is formed after the irradiation of 30 min. As the irradiated time is increased to 40 min, the 2D grating exhibits a fishnet pattern. Figure 2. POM images of DDLC cell that is irradiated for (a) 30 min and (b) 40 min. Upper and bottom intensity images are obtained under parallel polarizers (P//A) and crossed polarizers (P⊥A), respectively.

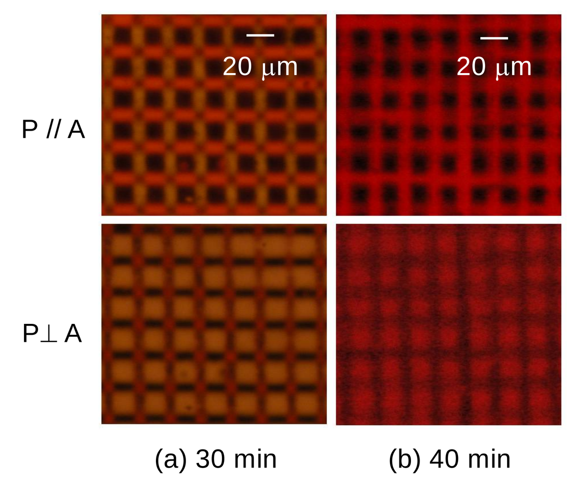


Figure 2. POM images of DDLC cell

Figure 3. Models of DDLC cell in simulation. (a) Orientations of surface directors before photoalignment. Ideal orientations of surface directors that rotate in (b) opposite directions and (c) unidirectional direction after photoalignment. $I_{1,2}$ and $I_{3,4}$ are the intensity distributions of the interferences on surfaces *A* and *B*, respectively. Λ is the spatial period of the intensity distributions.

Figure 4. Orientations of surface directors that rotate in (a) opposite directions and (b) unidirectional direction after photoalignment. The green units which neighbor the yellow unit have a lower surface free energy density under the opposite rotation than under the unidirectional rotation because the surface directors in the green units exhibit a smaller twist angle under the former than under the latter. As a result, the photoaligned cell has the relatively stable fishnet grating as the surface directors are rotated in the opposite directions.

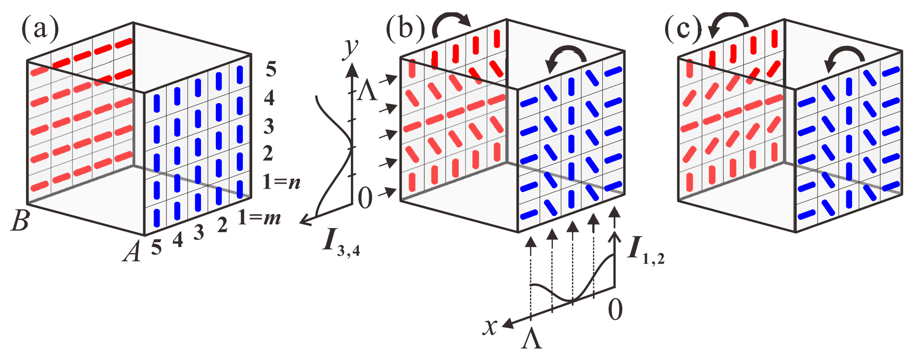


Figure 3. Models of DDLC cell in simulation

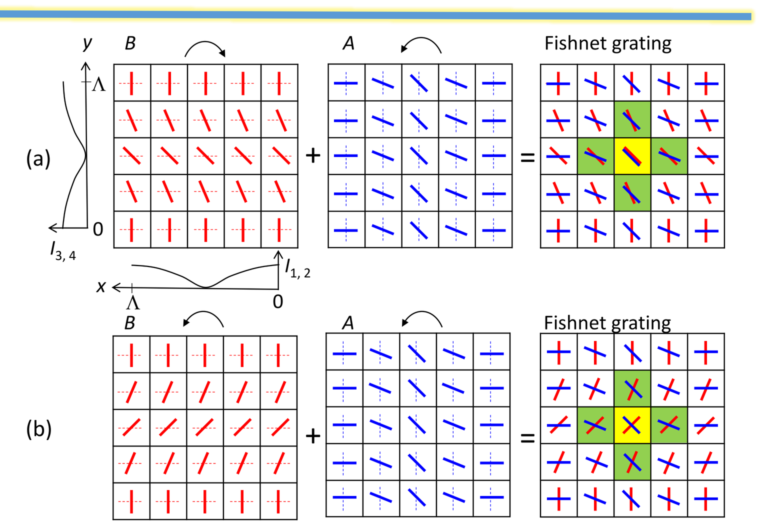


Figure 4. Orientations of surface directors that rotate

Application

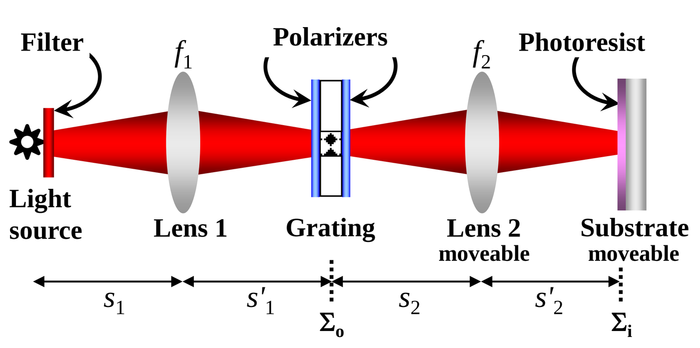


Figure 5. Optical system for fabricating passively tunable terahertz fishnet metamaterials

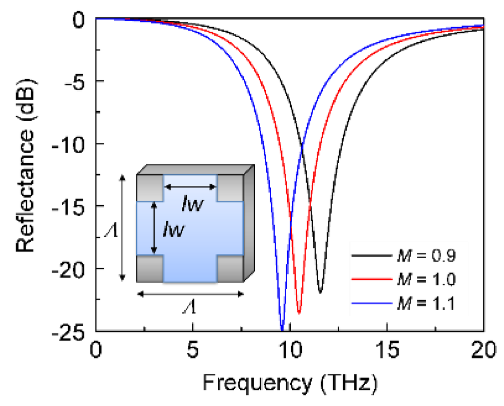


Figure 6. Simulated terahertz spectra

- **Passively tunable terahertz fishnet metamaterial:**

Fig6. Presents the simulated terahertz spectra of the reduced, normal and enlarged fishnet metamaterials at *M* = 0.9, 1.0 and 1.1, respectively. The resonance peaks of the reduced, normal, and enlarged fishnet metamaterials are at 11.6, 10.4 and 9.6 THz, respectively. The resonance peak of the reduced (enlarged) fishnet metamaterial is blueshifted (redshifted) from that of the normal fishnet metamaterial by 1.2 (0.8) THz.

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