Functional Photonic Elements Based on Liquid Crystal Metasurfaces

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Abstract. We study versatile soft-matter metasurfaces based on self-assembling of nematic liquid crystal on polymer alignment layers processed with a focused ion beam. Digital control of the beam path allows imprinting patterns that induce different complex distributions of the refractive index within several micrometer thick liquid crystal layers. We optimize them to implement various optical functionalities, such as broadband anomalous refraction, wide-aperture focusing, and beam splitting in tens of channels.

1. Introduction
Alignment of liquid crystals (LCs) by surfaces belongs to the core of the design of all LC-based devices, as it is commonly employed to establish a homogeneous near-surface LC director orientation preferential for a particular functionality [1]. Recently, specially prepared surfaces supporting inhomogeneous LC alignment have attracted significant attention as the applied potential of the self-assembled modulated LC configurations has been revealed [2, 3, 4, 5]. In particular, such layers can be produced by patterning with a focused ion beam (FIB) of thin films of rubbed polyimide. While the latter are routinely employed to sustain planar orientation of the adjacent LC director, mild irradiation with the FIB locally flips the favorable director orientation to vertical. Combining micrometer-scale pristine and FIB-treated areas allows establishing precise intermediate surface LC orientations [6]. Periodic patterns of micrometer-wide stripes produce deep LC modulations sufficient for strong visible light diffraction [4]. More complex superperiodic patterns optimized for anomalous refraction establish strongly asymmetric LC configurations allowing deflecting the light in the direction of a single dominating diffraction order [5]. Importantly, all such systems as susceptible to low-voltage signals applied across the LC layer and switch between different regimes in several milliseconds [7].

Digital control of the FIB in modern scanning electron microscopy (SEM) devices allows imprinting practically arbitrary 2D patterns than can induce very different LC textures. Therefore, relying on essentially the same materials and components, it is possible to design and fabricate optical elements with very different functionalities. Here we demonstrate the broad potential of the approach and report on three optical elements optimized for specific advanced functionalities: refracting double-sided metasurfaces with the efficiency and spectral...
range enhanced due to synchronous superperiodic patterning of the both substrates (Section 2.1); arrays of cylindrical high-power short-focused LC microlenses (Section 2.2); as well as the LC Dammann-type gratings designed to evenly split the transmitted light energy between several tens of diffraction orders (Section 2.3).

2. Results

2.1. Double-Sided Metasurfaces for Anomalous Refraction

Superperiodic aligning patterns consisting of many parallel stripes of various widths have proven to induce complex LC textures giving rise to strongly asymmetric light diffraction effectively resulting in efficient anomalous refraction. Implementing such patterns on a single LC-cell substrate has allowed deflecting about 60% of the normally incident light energy into a particular oblique direction [5]. Natural factors limiting the anomalous refraction of LC layers modulated near one substrate are: the LC orientational elasticity that smooths the outgoing phase profile and prevents it from approaching the discontinuous saw-tooth shape optimum for the perfect refraction; and the moderate optical anisotropy of the LC that does not allow achieving efficient refraction at all visible light wavelengths.

Combining modulated aligning action of the both substrates allows enhancing the main functional characteristics. The main idea of the double-sided LC-metasurface design is illustrated in Fig. 1(a), where it is shown how different stripe patterns on the both substrates produce a gradual variation of the LC orientation throughout the whole layer. Note that the LC alignment is first (from left to right) varied at the top substrate and then at the bottom one. Particular optimal patterns depend on the specific LC material properties, the LC layer thickness and the overall periodicity. In order to avoid high computational costs of the design optimization based on the first-principles, we employ an approximate semi-analytical model neglecting the difference of LC elastic modules and considering the LC layer as an inhomogeneous phase grating. Such
Figure 2. Cylindrical LC-lens: (a) numerical model of LC alignment and focusing of light of a 450 nm wavelength by a lens with an aperture of 15 µm; (b) SEM-image of a fragment of substrate patterned for a 25 µm periodic array of cylindrical LC-lenses; (c) optical images of a 35 µm periodic microlens array in vertically polarized light in the plane of aligning substrate and in the focal plane 35 µm above it; (d) intensity distribution (arbitrary units) in the focal plane of a 35 µm periodic microlens array, red (1), green (2) and blue (3) curves correspond to the linear RGB data of the camera sensor in red, green and blue channels, respectively.

Precise synchronous alignment of the both patterned substrates is very important for the double-sided device functionality. As is shown in Fig. 1(c), the transmitted light spectrum substantially varies upon fine relative substrate displacement. We judge on the achievement of the optimal alignment by the transmission spectra approaching those predicted by the numerical simulations. Observing the metasurfaces using back focal plane optical microscopy (see Fig. 1(d)) confirms all theoretical predictions: the +1 diffraction order dominates in the whole visible range, while the −1 order remains notably suppressed. Note also the asymmetry of the ±2 orders, as the violet light is predominantly refracted into the +2 order. For comparison, the optimal single-sided design of similar periodicity and thickness is only capable of a moderate asymmetry of the ±1 diffraction orders in the blue and violet ranges [5].

2.2. Microlens Arrays

Controlling the LC by a single substrate supporting a binary (planar-vertical) director alignment profile allows creating arrays of LC microlenses. By varying the location and width of the treated and untreated micrometer- and submicrometer-wide stripes we achieve the director tilt angle distribution near the surface seen at the bottom in Fig. 2(a). As the LC elasticity transfers the alignment perturbation into the LC layer, specific spatial distribution of the LC refractive index is achieved which creates lens-like refraction of light and its focusing also shown as modeled in Fig. 2(a). The numerical simulations performed using finite-difference time-domain module of our in-house LCDTDK software predict the focal length of about 23 µm for a cylindrical lens of a 15 µm aperture, which corresponds to a remarkably low f-number of 1.5.

To implement such lenses, we fabricate them as periodic arrays by subjecting rubbed polyimide alignment layers to FIB patterning as illustrated in Fig. 2(b) and assembling 30 µm thick LC-cells filled with E7 nematic. Optical microscopy verifies that the arrays focus the light
Figure 3. Optimization of LC Damann gratings: (a) spectra of diffraction efficiencies of the first 11 orders (indicated on the lines) of a 4 μm thick LC layer assembled into a 10 μm periodic grating upon the stripe pattern (shown in the inset) optimized for even distribution of light of a 450 nm wavelength (vertical dashed line) into 9 transmission diffraction orders; (b) schematic of a 20 × 20 μm² unit cell of a 2D pattern optimized to induce a Damman grating in a 8 μm thick LC layer splitting the light of a 450 nm wavelength; and (c) diagram of the corresponding diffraction efficiencies.

polarized along the lens axis at about 35 μm above the aligning substrate. This determines the actual f-number equal to 2.3, i.e., higher than the predicted one, but, nevertheless, allowing classifying the microlenses as fast (wide-aperture).

By extracting the linear intensity distributions recorded by the pixels of the optical camera sensor (from a RAW file of Olympus OMD EM-5 camera) we obtain the light intensity distributions shown in Fig. 2(d) for the three color channels. In addition to a high degree of optical contrast in the focal plane, we also observe a high optical resolution just slightly below the diffraction limit. The location of the focused peaks of intensities of all colors within the same focal plane indicates a remarkably low level of potential color aberrations.

2.3. Beam-Splitting Damann Gratings
While the efficient beam deflection described in Section 2.1 relies on the enhancement of a single outgoing diffraction channel, important optical applications spanning from parallel computing to 3D object recognition require even splitting of light beams in arrays of many bright spots. Specific diffractive elements, known also as Dammann-type gratings, are being developed for such purposes, see, e.g., the recent work [8] and references therein. Relative complexity of grating unit cells required to generate many equal output beams poses fabrication challenges. In particular, the only known so far type of electrically switchable LC-based Damann gratings is formed upon substrates subsequently photoaligned by illumination through different masks, which allows patterning with the periodicity not smaller than 200 μm thus limiting the angle between the split channels by just 0.19° [9]. Our technique of the FIB patterning naturally avoids all such limitations and allows producing Dammann-type gratings with the diffraction angles larger by at least an order of magnitude.

To illustrate the potential possibilities, we start with optimizing 1D stripe patterns for producing a line of many equally strong diffraction spots. An example of such pattern obtained by semi-analytical optimization is shown in Fig. 3(a), along with the spectra of expected diffraction efficiencies. The symmetry of the pattern unit cell ensures the diffraction symmetry as well as simplifies the optimization by reducing the number of independent optimization variables (the coordinates $s_i$). One can see that the obtained pattern of a period of just 10 μm can split
the light of a particular wavelength evenly in 9 directions.

Generalizing the optimization for 2D Dammann-type square patterns (see an example in Fig. 3(b)) we are able to generate structures having 20 \( \mu \text{m} \) periodicity and splitting the light in several tens of diffraction orders as is illustrated in Fig. 3(c). Note that restricting ourselves to the Dammann-type patterns reduces the potentially very large number of optimization variables describing a square unit cell to a small set of the coordinates \( s_i \).

3. Conclusion

We have shown that polymer alignment layers patterned with the FIB according to various optimized designs support self-assembling of LC layers into optical elements performing qualitatively different functions: beam deflection, focusing and splitting. Naturally, the presented opportunities do not exhaust the possible LC-metasurface applications. The design flexibility, fabrication simplicity along with the options of fast electro-optical switching ensure that LC-metasurfaces are generally a very promising platform for applied flat optics.

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