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Polarization manipulation in single refractive prism based holography lithography

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Abstract

We propose theoretically and demonstrate experimentally a simple but effective strategy for polarization manipulation in single refractive prism based holographic lithography. By tuning the polarization of a single laser beam, we can obtain the pill shape interference pattern with a high-contrast where a complex optical setup and multiple polarizers are needed in the conventional holography lithography. Fabrication of pill shape two-dimensional polymer photonic crystals using one beam and one shoot holography lithography is shown as an example to support our theoretical results. This integrated polarization manipulation technique can release the crucial stability restrictions imposed on the multiple beams holography lithography.

Keywords: Polarization manipulation; Holographic lithography; Photonic crystal

1. Introduction

Holographic lithography has been demonstrated as an effective and inexpensive way to fabricate photonic crystals (PhCs) [1–3]. Combining with the interference between several noncoplanar beams, all five 2-D and all fourteen 3-D Bravais lattices can be obtained [4]. In the conventional method, a laser is split into several beams with different optical paths and then all the beams are superimposed at the exposure medium [1]. This kind of realization needs crucial alignment accuracy which is difficult to guarantee during the whole process. Adjusting the polarization state and the phase of each individual beam offers extra degrees of freedom to tailor the atom shape of the unit cell [5]. However, several wave plates or phase delay elements should be inserted to the corresponding optical paths which brings extra stability requirement of these complex experiment setup [6–8]. All these optical elements make the coherent system very sensitive to small vibrational instability of environment indicating that the conventional holographic lithography is not the best way for large volume PhCs fabrication or other processes using interference [9].

Diffraction element mask can be used to obtain 3D PhCs in photosensitive polymer, by which the alignment

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and stability of the fabrication setup can be improved [10,11]. Alternatively, by using an expanded laser and a single refractive prism, the feasibility of fabricating large area two- and three-dimensional defect free polymer PhCs was demonstrated [12]. Such simple while stable set-up can be generalized to fabricate more sophisticated periodic structure [13–19]. Adding optical elements into such simple process facilitates the tunable production [14,19]. Manipulating polarization in a single prism based holographic lithography is very important in obtaining high-contrast interference pattern [20]. In general, several polarizers should be inserted into the optical path of the expanded and collimated beam which brings extra instability [21]. Some of the researcher working in this field believe that it is difficult to manipulate the polarization only if several polarizers are added into the optical path [22]. In other word, manipulating the polarizations of the interfering beams by the prism itself have not been addressed before. In this paper, based on the basic law of refraction at dielectric interface, we show both theoretically and experimentally that such prism based holography naturally integrates the function of polarization manipulation. This kind of lithography would further release the requirement of stability in the holography lithography. As a particular example, we demonstrate this integrated set-up can be used to fabricate template for PhCs with polarization-independent self-collimation characteristic [23].

2. Theoretical design

The interference pattern formed by N noncoplanar beams (indicated by Fig. 1(a)) can be expressed as:

$$I = Re\left(\sum_{l,m=1}^{N} e_l{}^{*} \cdot e_m \exp(i(k_l - k_m)\cdot \mathbf{r} + i(\delta_l - \delta_m))\right) \quad (1)$$

where $e_{l,m}$ stand for the electric vectors, k represents the k-vector of each beam and δ is phase delay. Please note here that we use the plane wave approximation in Eq. (1) and it can reasonably represent the interference pattern produced by several expanded and collimated beams. In practice, using Gaussian beam as a light source would introduce background modulation which is with macroscopic scale after beam expansion and collimation. The k-vectors of the beams determine the translation and rotation symmetry while the intensities and the polarization states of the beams affect the atom shape in the unit cell of the PhCs. A linear polarized light would reflect and refract when it imprints on a dielectric interface.

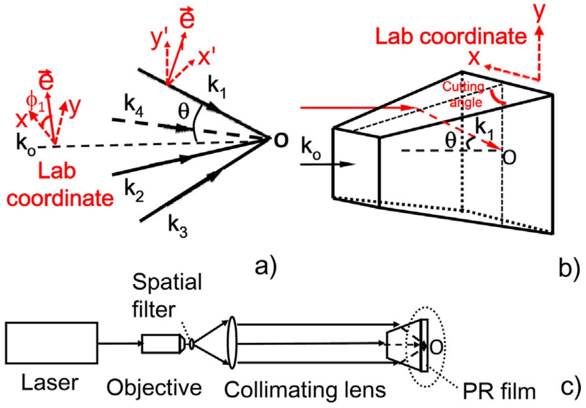

Fig. 1. (a) A typical four beams geometry. The coordinates are outlined by dashed red arrows (X and Y are the lab coordinate while X' and Y' are the rotated beam coordinates). (b) The specially designed refractive prism (F2) with cutting angle 55°. The k vectors 1–4 in (a) can be produced by the prism shown in (b). For better visualization, we only label k_1 in (b). (c) Sketch map of the optical setup used for the fabrication of PhCs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The polarization component laying at the direction of the incident plane normal (S wave) would not change its direction while the component laying at the incident plane (P wave) would change its direction because of the electromagnetic boundary condition. Therefore, different cutting faces of the prism thus obtain different refraction and polarization rotation angles referring to the lab coordinate, as is indicated in Fig. 1(a). It means that the prism integrates not only the function of beam splitter and combiner but also the function of polarization management. Without loss of generality, we choose the prism with four-folds rotation symmetry (the cutting angle of the prism is 55°) as an example [shown in Fig. 1(b)]. We plot the output polarizations (the electric field component of refractive beam 1 at the Lab coordinate) in Fig. 2(a) when the input polarization (ϕ_1) varies from 0° to 360°. It can be seen from the figure that the polarization direction of the refracted beam can be controlled by simply adjusting the input polarization. All directions inside the plane normal to the k-vector of the refractive beam can be obtained. At the same time, the electric vectors of the beams refracted from different cutting faces could be tuned via the input beam [see Fig. 2(b)]. Please note that there are double degeneracy in the output polarization because of the four-folds rotation symmetry of the prism.

Pill shape PhCs have the advantage to minimize the spatial dispersion discrepancy between the transverse electric wave and transverse magnetic wave in