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Designing of the tapered helical photonic metamaterial structure using multi-exposure phase-controlled interference lithography

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This paper is dedicated to Padma Shri Prof R S Sirohi

Three-dimensional Photonic crystal structures have complex geometry with periodic variation of optical constant in all three dimensions. Studies on the optical properties of such systems gain immense attention as the cost-effective laser interference lithography technique can effectively replace the existing complex fabrication techniques. Here, we have introduced a laser interference lithography technique based on phase-controlled multi-beam interference. The 4+1 beam interference pattern with multi-exposures provides the designed tapered complex helical structure. The beam engineering and phase pattern are explained, and the simulation techniques are discussed. The controlled exposure dosage and rotation of the k vector in the azimuthal plane offer the desired structure's design.

Keywords: Nanophotonics, Photonic crystals, Metamaterial, Light-emitting diodes, Integrated circuits.

1 Introduction

The field of nanophotonics deals with the interesting optical processes in the nano-scale dimension. Generally, such systems are characterized as photonic crystals (PhC) with periodic variation of refractive index in either one, two, or three-dimensions. Simple one-dimensional (1-D) and two-dimensional (2-D) structures are mostly explored for the designing of sensors [1], reflectors [2], and light trappers [3]. More complex three-dimensional (3-D) structures are demonstrated for designing light trapping [4] in energy harvesting applications, as light-emitting diodes [5], integrated circuits, and biomedical applications, including drug delivery [6]. Metal incorporated PhC architectures are explored for designing various metamaterial structures and circular polarizers [7,8].

For the experimental realization of such 3D structures, electron beam lithography, ion milling, glancing angle deposition, and direct laser writing methods have been widely used [9]. The cost-effective laser interference lithography has been introduced recently to fabricate such a complex structure with much simplicity [10]. Indeed, this fabrication technique offers the tuning of structure parameters rather quickly without defects on a large area scale. Among the established laser interference lithographic methods, the multi-beam interference technique is demonstrated to fabricate complex structures, including woodpile [11], chiral woodpile [12], and double helix [8], structures with controlled laser doses and proper selection of polarization states. In the phase-controlled interference lithography, we control the phase of the individual beam through a spatial light modulator (SLM), by manipulating the direction of k vectors and its initial phase offset. The process of designing and recording through phase-controlled interference lithography has been extensively discussed in reference [9]. On the SLM, the incident collimated beam can be diffracted into the grating orders either in reflected or transmitted mode and can carry the desired different phase factors.

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In the present paper, we will discuss the multi-beam interference scheme for designing a tapered complex helical structure. We have adopted the 4+1 beam configuration, where the four-sided beam and central beam will interfere in a double exposure manner to form the designed pattern. The designed structure is expected to possess a chirality and find possible applications in light trapping and a circular polarizer.

2 Designing methodology

Here, we are introducing the multi-exposure into the phase-controlled interference lithography (PCLIL) method. Typically, multi-exposure lithography is explored using two-beam laser interference lithography and multiple-beam interference to fabricate 2D photonic structures over suitable photoresists. [13-17]. Such multiexposure method comprises the rotation of sample through the various angles normal to the sample, resulting in rotation of 1D grating vector. The superimposed pattern of one-dimensional grating structure in the same plane leads to the formation of two-dimensional structure.

However, Such a multiexposure technique includes mechanical disturbance in an optical setup, which could be a source of error to attain exact overlapping of the interference pattern in each rotation to realize the desired structure with perfectness. Here, we present a multiexposure technique that will deal only with the k vectors rotation azimuthally by addressing the proper phase through a spatial light modulator (SLM) without the mechanical rotation of the sample. The desired phase is addressed in each exposure with SLM. Instead of rotating the sample, we rotate the beams azimuthally for the subsequent exposure, resembling the sample rotation technique in multi-exposure with classical Lloyd's two-beam interference lithography. This approach can generate a periodic tapered coupled helix structure in the square symmetry over the large area. The designed helix structure shows variation in radius of helix unit along z-direction that brings tapered profile in helix. Our proposed technique shows the fabrication of helix structure in square symmetry over a large area. In the designed geometry, each unit cell consists of four helical elements of opposite handedness (right and left-handedness) with respect to its adjacent one, as shown in Figs 1(b) and 2 (b).

In the mutual interference of linearly polarised 4+1 beams in double exposure, the electric field of the individual beam can be defined as,

$$\vec{E}_m = E_{0m}\,\hat{e}_m \exp\,[i(\vec{k}_m\cdot\vec{r} - \omega t + \phi_m)] \tag{1}$$

k_m, ω, ϕ_m and $\hat{e}_m$ are the wavevector, frequency, initial phase offset, and unit polarization vector of the m^{th} beam, respectively. The resultant intensity profile is expressed as,

$$I = I_0\left[1 + \sum_{n>1}^{N} V_{ij}\cos\{(\vec{k}_n - \vec{k}_m)\cdot\vec{r} + \phi_m - \phi_n\}\right] \tag{2}$$

where, $I_0 = \frac{1}{2}\sum_{m=1}^{N} E_{om}^2$ and $V_{ij} = \frac{E_{om}\cdot E_{on}\,(\hat{e}_m\cdot\hat{e}_n)}{I_0}$

V_{ij} is known as an interference coefficient and determines the intensity contrast in the pattern; it will be maximum when $\hat{e}_m\cdot\hat{e}_n = 1$, i.e., interfering waves have a parallel polarization vector. Here, $N = 5$ is the total number of beams. The k vector corresponding to the four-sided beam will follow the umbrella geometry and can be defined as,

$$\vec{k}_{tm} = k_0\,[\cos\psi_m \sin\theta,\ \sin\psi_m \sin\theta,\ \cos\theta] \tag{3}$$

where θ is the interference angle (or tilt angle) and ψ_m is the azimuthal angle of the m^{th} interfering beam and k_{tm} corresponds for k vector of m^{th} beam during t^{th} exposure. We use k_{1m} (t=1) and k_{2m} (t=2) for the k vector representation in 1st and 2nd exposures, respectively.

The tapering in the coupled helix structure can be designed by considering two different approaches. In one configuration, the structure possesses a gradual decrease in helix radius when looking from its base to top, on the other hand, in the second design, these ascending characteristics appear from top to bottom. The first kind of tapered structure is designed by following the beam configuration, as shown in Fig 1(a). The central beam is tilted about the z axis in the 1st exposure, while the central beam is along the z-direction in the 2nd exposure. The beam arrangement will generate the helix structure, as shown in Fig 1(b).

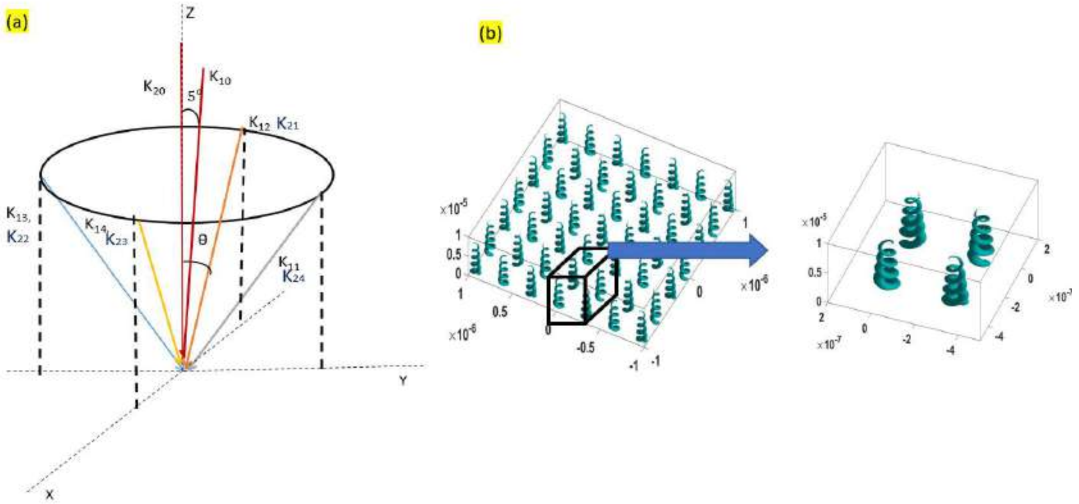

Fig 1. (a) Beam arrangements for designing the periodic tapered coupled helix structure. K_{im} is the wavevector corresponding to each beam, where i (= 1 & 2) is the number of exposures for m^{th} beam. (b) The generated 3D intensity pattern for tapered helical structure from bottom to top.

The 2nd kind of helix structure shown in Fig 2 (b) can be designed by keeping the center beam along the z axis (Fig 2a), whereas providing a tilt of 5° in the central beam with respect to z axis in the 2nd exposure. Thus, the helical structure is obtained by the double exposures with modified central beam configuration as shown in Fig 1(a) and Fig 2 (a).

The different parameters for designing the structure is tabulated in Table 1. The spatial and axial periodicity are given as $\lambda/\sin\theta$ and $l = \lambda/(1 - \cos\theta)$, respectively. MATLAB simulation has been performed for the realization of the structure with defined parameters. The 3D intensity profile with the proper threshold value of normalized intensity, displays the designed system in both beam geometry configurations as shown in Fig1(b) and Fig 2(b), respectively.

The designed structure can be realized experimentally by employing interference of beams as discussed before at the sample plane. The experimental setup can be done with a collimated light source coming from a laser source (405 nm) after spatial filtering falling on the SLM. The SLM will diffract light into 4+1 orders, and a 3D printed square mount can guide that to the sample plane. Finally, all the 4+1 beams will get interfere with the sample plane. The experimental setup and process can be adopted from the previously reported studies [11]. In their study, they have employed a 6+1 beams configuration using a hexa-mount. Whereas, in our proposed method, we have adopted a configuration of 4+1 beams to interfere in the sample plane using a square mount. The four reflecting mirrors will be placed on four arms of a square mount such that the diffracted orders coming from SLM can be guided through reflection from the mirrors towards the sample plane so that they can interfere with the central beam. Here, the sample needs to be coated with a negative photoresist material to realize the proposed structure. The thin photoresist layer with the desired thickness can be coated on the substrate using a spin coating technique. In the proposed structure, we have considered the angle between the interfering beams as 40 degrees. Thus the spatial periodicity of the structure is calculated as 320 nm. A negative resist with high resolution is a preliminary requirement for realizing such a structure. An optimized exposure dosage and developing time can lead to the materialization of the proposed hybrid tapered helix structure.

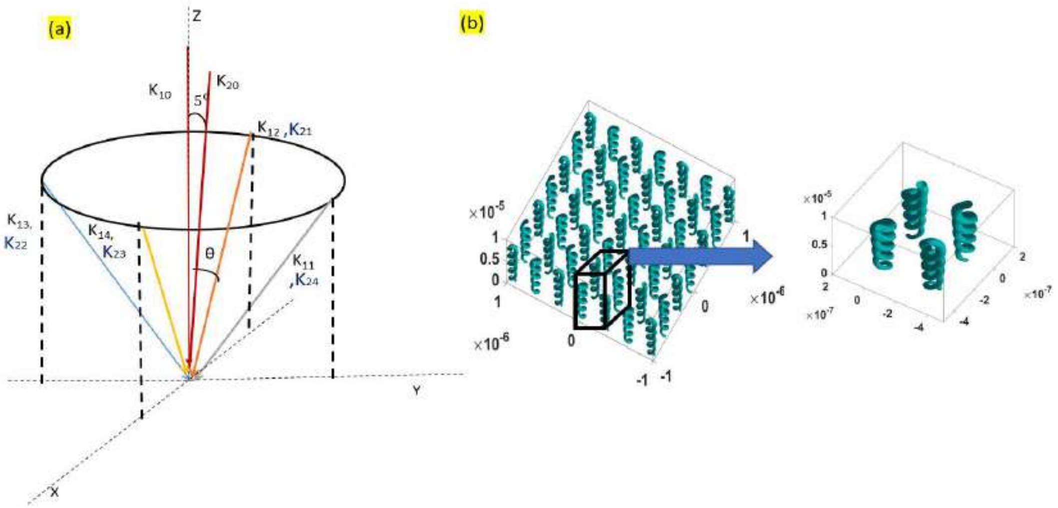

Fig 2. (a) Beam configuration for designing the tapered helix from top to bottom. (b) 3D intensity profile of designed structure.

Table 1. Parameters used for formation of the structure

Wavelength	405nm
Amplitude	1V/m
θ	40°
Contrast factor (V_m)	1
N+1	4+1
ψ_{1m}	$2(m-1)\,\pi/N$
ψ_{2m}	$2(m)\,\pi/N$
$\Phi_{1m} = \Phi_{2m}$	$2(m-1)\,\pi/N$

3 Discussion and conclusion

The introduction of multi-exposure into the phase-controlled interference lithography (PCLIL) is discussed to design a tapered helical structure. Our proposed double exposure method is free from any mechanical movement of the sample plane. The designed structure is a racemic mixture, i.e., containing a chiral object (here, a helix unit) of opposite handedness [17,18]. Therefore, in the proposed tapered chiral structure, chiral properties are not expected to be substantial. However, these properties can be enhanced by optimizing the structural parameters and periodicity. Nevertheless, such systems have been applied to tailoring the chiral field enhancement and studying the mechanism [19]. Tapering of the helix structure can lead to the gradient effective refractive index axially (along the z-axis) and periodic alteration for the same in spatial directions (along X and Y). Such characteristics in the refractive index variation can offer potential applications in various nanophotonic and metamaterial aspects. Moreover, the designed structure can be explored for various light-trapping applications and light coupling devices by investigating the structure's antenna properties.

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