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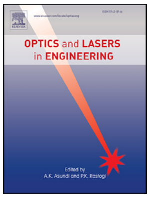

Double-helix array structure using phase controlled interference of 6 + 6 beams

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A R T I C L E I N F O

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A B S T R A C T

We describe a novel single-step approach to form hexagonal array of DNA like intertwined double-helix structure. The lattice structure has been simulated by using interference of 6 + 6 mutually counter-propagating beams arranged in a double-cone geometry. This is a phase controlled interference technique where each of the twelve beams is assigned a suitable phase offset and the helicity of the double-helix structure depends on the phase offsets of the interfering beams. For the application of the structure as a broadband circular polarizer, a simulation study has been performed using standard FDTD (finite difference time domain) method. A comparative study between aluminium(Al) based single-helix and double-helix hexagonal lattice structures is also carried out, showing that the operating wavelength range of the double-helix structure is much larger as compared to the single-helix structure.

1. Introduction

Over the past few years metamaterials have drawn considerable attention of physicists, chemists, material scientists and engineers. These artificially designed structures make a revolutionary change in research and applications due to their exotic features [1–3] which cannot be obtained in the natural materials. Amongst a variety of chiral metamaterials, chiral structures interact strongly with the electromagnetic waves incident on them which can result in rotating the polarization state of the incident light itself. In such cases the handedness and the strength of polarization rotation depend on the constitutional material properties and the structural parameters such as periodicity and the lattice type. The flexibility in choosing the material and its lattice structure facilitates to design suitable nanostructures which can control and manipulate the flow of light within them. Helical metamaterials, a sub-group of chiral structures exhibit macroscopic physical property like circular dichroism [4]; which promise to act as broadband circular polarizers. For the application of helical array structure, Gansel et al. proposed gold single helices as a compact broadband circular polarizer [5,6]. where the single-helices are arranged in a square array. Yang et al. [7] have done a numerical study on single-helix nanowire metamaterial as circular polarizer in the visible region.

A variety of techniques such as glancing angle deposition [8], direct laser writing(DLW) [9], self-assembly of nano-particles [10], nanoimprint lithography [11] are extensively used to fabricate the chiral nanostructures. In contrast to the all other techniques, the laser interference lithography is the most preferred technique when cost effectiveness and the ease of fabrication over a large area are considered. Researchers have already fabricated moth-eye [12], woodpile [13], fishnet [14], diamond and gyroid [15] like structures using different arrangements of multiple beams interference. Campbell et al. [16] fabricated photonic crystals structures in the visible spectrum by holographic lithography. Naturally found 14 Bravais lattices are formed by interference of four non-coplanar beams [17–20]. By tuning the polarization properties of the interfering beams many complex structures have also been designed [21–24]. Single-helix array structures have been formed using interference of 6 + 1 beams in an “umbrella” geometry [25]. “inverted umbrella” geometry has been used for 6 + 1 beams interference to get single-helix structures with very small pitch compared to umbrella geometry [26].

Here we propose a novel approach for fabrication of hexagonal lattice of intertwined double-helix structure over a large area using 6 + 6 counter-propagating phase engineered beams arranged in a “double-cone” geometry. It is shown that the helicity of the chiral structure depends on the offset phases of the interfering beams. The optical properties of the proposed hexagonally packed double-helix structure are studied using FDTD (finite difference time domain) method.

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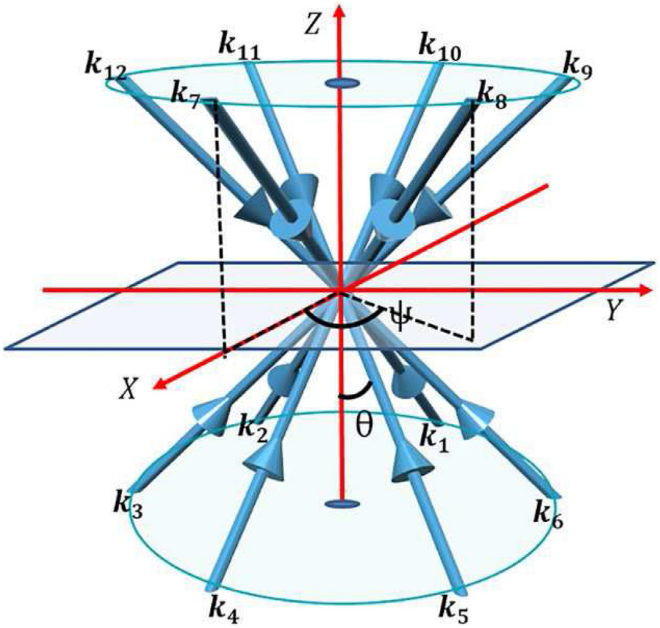

Fig. 1. Beam arrangement for double-helix, 6 + 6 symmetrically arranged beams in a double-cone geometry.

2. Formation of double-helix structure

2.1. Phase controlled interference of 6 + 6 beams

Here we describe a single step formation technique of hexagonal array of intertwined double-helix structure over a large area. The structure is produced by the interference of 6 + 6 counter propagating linearly polarized plane beams with appropriate phase offset among each other. Fig. 1 shows the schematic representation of the beam geometry where 6 + 6 beams are symmetrically arranged in a double-cone geometry and interference occurs in the region around the common vertex of the two cones. The origin of the coordinate axes are chosen at the vertex and z-axis as the axis of the double-cone. Each cone contains six beams oriented symmetrically with azimuthal angle difference ($\delta\psi$) of 60° between any two neighbouring beams. From the geometry, it is clear that for each beam of the upper cone there is a counter-propagating beam in the lower cone i.e. the wave vector($\boldsymbol{k}$)s of each beam pair are in opposite direction to each other. There are total six pairs of mutually counter-propagating plane beams for such an arrangement of 6 + 6 beams as shown in Fig. 1 where the electric field of mth beam is represented by,

$$\boldsymbol{E}_m = E_m \exp[i(\boldsymbol{k}_m.\boldsymbol{r} + \phi_m)]\boldsymbol{e}_m \tag{1}$$

where E_m is the field amplitude, $\boldsymbol{e}_m$ is polarization unit vector, ϕ_m is the initial offset phase of the mth beam. $\boldsymbol{r}$ denotes the position vector. Wave vectors of the lower cone (m = 1 to 6) are defined by,

$$\boldsymbol{k}_m = k\left[\cos\left\{\frac{2(m-1)\pi}{6}\right\}\sin\theta, \sin\left\{\frac{2(m-1)\pi}{6}\right\}\sin\theta, \cos\theta\right] \tag{2}$$

whereaes the wave vectors of the upper cone (m = 7 to 12) are defined by,

$$\boldsymbol{k}_m = -k\left[\cos\left\{\frac{2(m-7)\pi}{6}\right\}\sin\theta, \sin\left\{\frac{2(m-7)\pi}{6}\right\}\sin\theta, \cos\theta\right] \tag{3}$$

Here, m denotes the index of the interfering beams, θ is the tilt angle of the side beams with the z-axis, $k = \frac{2\pi n}{\lambda}$ is the magnitude of wave vector, λ denotes the free space wavelength and n denotes the refractive index of the medium of interference. In the interference pattern, the helicity of the double-helix structure solely depends on the phase offsets of the interfering beams. For left-handed helix structure the offset phases of the beams are chosen as,

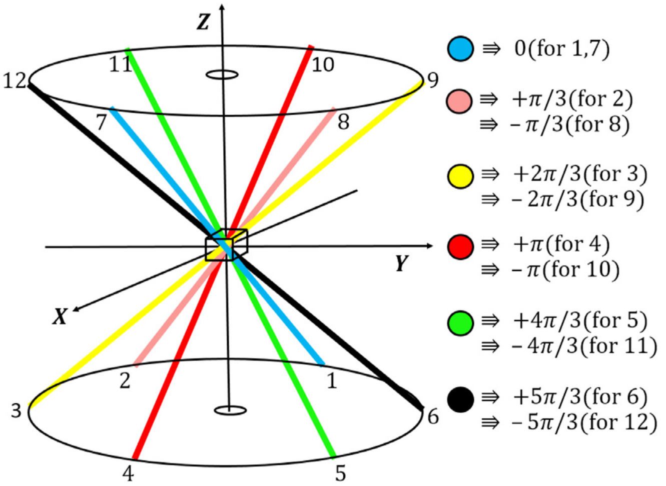

Fig. 2. Phase offset (ϕ_m) assigned to the interfering beams in the double-cone geometry, different colours correspond to different phases; this phase values are for left-handed structure where (0–2π) are distributed among the beams in anticlockwise sense from the top (+ve z axis); to get right-handed structure phase distribution needs to be clockwise.

Table 1
Parameter values chosen for the computation.

Parameter	Notation	Value
Wavelength	λ	400 nm
Wave amplitude	E_m	1 V/m
Polar/Tilt angle	θ	22.22°
Refractive index	n	1.7

$$\phi_m = \begin{cases} +\frac{2(m-1)\pi}{6}, & \text{for } m = 1 \text{ to } 6 \\ -\frac{2(m-7)\pi}{6}, & \text{for } m = 7 \text{ to } 12 \end{cases} \tag{4}$$

Similarly, for right-handed helix structure, the phase offsets of the beams are taken as,

$$\phi_m = \begin{cases} -\frac{2(m-1)\pi}{6}, & \text{for } m = 1 \text{ to } 6 \\ +\frac{2(m-7)\pi}{6}, & \text{for } m = 7 \text{ to } 12 \end{cases} \tag{5}$$

For such a beam arrangement the resultant intensity profile of 6 + 6 linearly polarized plane waves is given by,

$$I(\boldsymbol{r}) = \sum_{p=1}^{12} |\boldsymbol{E}_p|^2 + \sum_{p\neq q}^{12} E_p E_q^*(\boldsymbol{e}_p.\boldsymbol{e}_q^*)\exp[i(\boldsymbol{k}_p - \boldsymbol{k}_q).\boldsymbol{r} + i.\delta\phi_{pq})] \tag{6}$$

where $(\boldsymbol{e}_p.\boldsymbol{e}_q^*)$ denotes the cross term due to polarization and $\delta\phi_{pq} = (\phi_p - \phi_q)$ is the difference of initial offset phase between pth and qth beams. Mutually counter-propagating beam pairs $[(1-7), (2-8), (3-9), (4-10), (5-11), (6-12)]$ are shown in Fig. 2. Left-handed double-helix can be obtained if the phase offsets(0–2π) are distributed among the beams in anticlockwise sense from the top (+ve) z axis. Similarly, the right-handed double-helix can be obtained for phase distribution in clockwise sense. The region of interference of 6 + 6 beams is shown by the rectangular box around the origin in Fig. 2, where the actual double-helix interference pattern has been formed. A detail of the choice of the simulation parameters are listed in Table 1. The spatial and axial periodicity, contrast etc. of the double-helix structure can be modulated by tuning these parameters. Keeping the application in mind, some specific values of the parameters are chosen for the

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