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An interferometric patchwork to generate high-order quasi-nondiffracting vortex lattices

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ABSTRACT

We propose an novel kind of interferometer to generate various quasinondiffracting vortex lattices with high topological charges. The wave vectors of the interfering beams distribute spatial-symmetrically on the surface patchwork of two concentric cones of different opening angles, and their transverse components site at the vertices of two mutual-inscribed common regular polygons. With certain beam number and particular initial phase distribution at the beams, novel vortex lattices such as Kagome type lattice with unusual vortex distribution are obtained. We further extend such interferometric scheme to multipoint interferometers for easier experimental realization, where the generated vortex lattices lose nondiffracting property. Such interferometric method have potential applications in fields such as direct nanostructure writings and multichannel optical manipulations.

1. Introduction

Mentioning the interferometric mechanism, as is well known, phase singularities with zero amplitude may appear naturally due to the superposition of no less than three beams. Such wave fields possessing phase singularities are called optical vortices. The enduring interests on vortices depend mainly on two of their most distinctive properties: the helical phase distribution $2m\pi$ associated with the spiral flow of its electromagnetic energy and the orbital angular momentum of $m\hbar$ carried by each of its photons, where the integer m characterizing its vorticity is called topological charge. Isolated vortices have been obtained by various experimental means [1,2], and they have played a remarkable role not only in the traditional optical tweezers and free-space communications, but also in a diversity of new fields. For instance of optical micro-manipulating, Martin Siler studied the stable trapping and circulating of particles by vortex beams of $m = 1 - 5$ [3]. For nanostructure fabrications, Kohei Toyoda fabricated chiral metal nanoneedles by transferring the helicity of optical vortices to the constituent elements of the irradiated material and revealed that the tip curvature of these chiral nanoneedles was measured to be less than 1/25th of the laser wavelength [4]; Benjamin Wetzel reported the fabrication of micro and nano-disks in single-layer graphene on glass substrate using femtosecond laser ablation with Bessel vortex beams of multiple topological charges [5]. To introduce the applications of optical communications or micro-manipulations into multichannel manners, a better and competent way may be to arrange the vortices into various arrays.

Simultaneously with the generation of the vortex array, the intensity distribution having crystalline or quasicrystalline transverse pattern is another fascinating topic, especially when the pattern is propagation-invariant. Such wave fields are called vortex lattices, and are most famously known as the Kagome lattice and the Honeycomb lattice which both consist of hexagonal arrays of light dots [6–8]. Vortex lattcies have found applications in diverse fields, e.g., tuning ultrocold atoms, manipulating solitons, inducing photonic lattices in photorefractive crystals and creating colloidal particle lattices in biophysics [9–12]. Besides, due to the controllable structures and sizes, vortex lattices are superior to many chemical or physical means in the current topic of fabricating novel periodic nano patterns and forming intended superstructures [5].

Obviously, the key factors that contribute to these applications are the vorticities and the arrangement styles of the vortex lattices, as they determine the phase distribution of wave field and the gradient forces exposed on particles. This fact inspires the quest for increasing the structural and topological variety of vortex lattices [13,14]. In literature, spatial light modulator [15,16] with well-designed phase distributions have been a widely applied

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method to theoretically increase the vorticity and arrangement varieties to be infinite. However, the delicate phase modulations needed in such process are often complex and not generalized, and are difficult to be realized by other phase-modulating means. A complementary method is the interference of multiple waves with easy and simple phase modulation, e.g., the vortex lattices generated by interference of three plane waves [17], the Hexagonal vortex lattices and the Kagome vortex lattices generated by six wave interference [6,18]. Moreover, the resulted vortex lattices are often nondiffracting or quasinondiffracting, and this may be more valuable in practical application. In previous reports, the limited number of interfering beam vectors are often restricted on the surface of a single cone to maintain nondiffracting properties. However, the structural variety of available vortex lattices are confined. Meanwhile, except for the second order vortices in Kagome lattice [19] and the isolated vortices at the symmetric centers of quasicrystalline lattice fields [20], the topological charge of the generated vortices, in both crystalline and quasicrystalline lattices, are confined to be zero or unity. In this paper, we propose a novel interferometric method with simple initial phase modulations to generate various types of high-order vortex lattices.

2. Design of the interferometers

Similar with the superlattice-generating work in [16], our interferometer is also a patchwork of two interferometers and the N beams of each constituent one are spatial-symmetrically arranged. But different from adjusting the relative angle between the two constituent interferometers in azimuthal direction therein, such angle in our work is determined as π/N and is unique for a certain N. Another distinctive difference is that the two constituent interferometers are not identical in our work, i.e., the wave vectors $\boldsymbol{k}$ of the interfering beams distribute on the surfaces of two concentric cones with different opening angles, as can be seen in Fig. 1 (a). Consequently, the sites of the transverse vector components distribute at two concentric circumferences of radii $k_{t1} = 2\pi \sin\psi_1/\lambda$ and $k_{t2} = 2\pi \sin\psi_2/\lambda$, where ψ_1 and ψ_2 are the angles between the two cone surfaces and the axis of the interferometer, respectively. On each circumference (which is essentially the Fourier transform of the interfering beams in Fourier space), the azimuthal angle between two neighboring sites is constant $2\pi/N$, due to the spatial-symmetrically distribution of the beams on each interferometer in real space. As schematically shown in Fig. 1(b), these sites on each circumference may be regarded as the vertices of a N-regular polygon. The two N-regular polygons are mutual-inscribed, i.e., the vertices of the smaller polygon locate right at the midpoints between neighboring vertices of the larger one. This is the base feature of our proposed interferometer, and the radius ratio of the above circumferences is consequently defined as $k_{t1}: k_{t2} = 1: \cos(\pi/N)$. And this is essentially realized by adjusting the propagation directions of the $2N$ interfering beams.

Once an initial phase modulation of $2m\pi$ with constant azimuthal increment of $m\pi/N$ is impressed on these beams, the interference field may be expressed in cartesian coordinates as

$$\begin{aligned} &E(x, y, z) \\ &= E_0 \sum_{n=1}^{2N} exp\{i(k_{x,n}x + k_{y,n}y + k_{z,n}z + nm\pi/N)\} \\ &= E_0 \sum_{n=1}^{N} exp\{i(k_{x1,n}x + k_{y1,n}y + k_{z1,n}z + 2nm\pi/N)\} \\ &+ E_0 \sum_{n=1}^{N} exp\{i(k_{x2,n}x + k_{y2,n}y + k_{z2,n}z + (2n+1)m\pi/N)\}. \end{aligned} \quad (1)$$

This equation is the direct superposition of the two wave fields resulted respectively by the two constituent interferometers with phase modulations. Herein, $(k_{xj,n} + k_{yj,n})^{1/2} = k_{tj}$ determines structural size of the transverse modulation $g = \pi/k_{tj}$ in real space, and $k_{zj,n} = 2\pi \cos\psi_j/\lambda$ are the longitudinal components of the wave vectors. The difference between $k_{z1,n}$ and $k_{z2,n}$ indicates the limited maintenance of the nondiffracting feature of the generated lattices along z axis. However, this difference may be regarded as zero when the opening angles of the two cones are relatively small or when the number N is not small. In fact, the 3-dimensional space where all the $2N$ beams can interfere with each other is confined by both the opening angles and the finite beam diameters, and this space is usually shuttle-shaped. If the studied volume of interest is much smaller than the shuttle, the generated lattices may still be regarded as nondiffracting. Thus in this paper where we concentrate mainly on the structural variety and topological charges

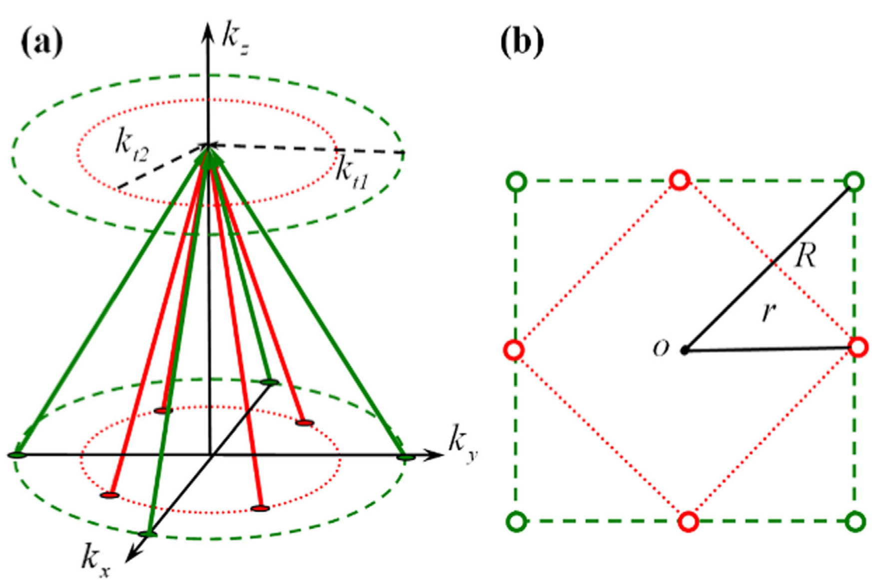

Fig. 1. Schematic illustration of the interferometer of $2N$ beams. (a) Wave vectors distributing spatial-symmetrically on two concentric cone surfaces. Their longitudinal components are regarded as the same when the opening angles of the cones are small, and their transverse components are represented by k_{t1} and k_{t2}, respectively. (b) Schematic illustration of the transverse vector components. They site at the vertices of two mutual-inscribed regular polygons with relative azimuthal angle π/N, and the ratio of R to r is $1: \cos(\pi/N)$.