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Generation of the compound optical vortex array wave field

Yuanmei Gao [a,*], Zengrun Wen [a], Jie Shan [a], Lina Zhao [a], Liren Zheng [b]

[a] Shandong Provincial Key Laboratory of Optics and Photonic Device, School of Physics and Electronics, Shandong Normal University, Jinan 250014, PR China
[b] College of Physics and Electronic Engineering, Taishan University, Tai'an, Shandong 271021, PR China

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ABSTRACT

We give out an universal function of the compound vortex lattice fields through Fourier transform of several δ functions with different phases. Based on this method, we study different classes of vortex lattice and conclude a series of interesting laws. As special cases, we introduce the classes of fivefold and eightfold lattice fields from the intensity modulation to phase modulation in detail, in which the lattice pattern for varying phase difference of adjacent δ functions may be nearly similar. The experimental realization of this compound vortex lattices is by using the numerically calculated phase mask and a spatial light modulator(SLM).

1. Introduction

As is well known, an optical vortex beam possesses a helical wavefront with an azimuthal phase term of exp($il\theta$), where the integer l is the topological charge of the optical vortex. The vortex beam can transfer orbital angular momentum to dielectric particles at a rate proportional to its topological charge. Thus vortex beams are widely used as optical tweezers [1–4] and in the study of the transfer of angular momentum to micro particles or atoms [4–8], especially optical vortices arrays [9] have shown a potential ability to assemble colloidal particles into mesoscopic pumps for microfluidic systems [10]. Two different fork gratings obtained by interfering a plane wave with a focusing and a defocusing vortex beam are overlapped to produce the desired moiré pattern, which generating the bottle beam are useful to trap and manipulate aerosols [11]. So highly efficient and flexible creation of different optical vortices arouse considerable interest. During the last decades, several methods for generating optical vortices including the use of a spiral phase plate or a cylindrical-lens mode converter, and the direct formation of a beam inside a laser resonator et al. have been reported [12–17]. The most practical methods are the use of computer-generated holograms (CGHs) [18–27] and spatial light modulators (SLMs). In reference [23], Boguslawski et al. studied the discrete non-diffracting beams (NDBS) by interfering of several plane waves with different phase. And they gave out threefold, fourfold, fivefold, sixfold and tenfold non-diffracting beams. But they just gave out the NDBS and their phase distributions without attention to the laws of vortex distribution in these lattice structures. Harb et al. fabricated large-area three-dimensional Penrose-type photonic quasicrystals through a holographic lithography method using a lab-made diffractive optical element [28]. While vortex distribution of the lattices was still not mentioned. In reference [29], we used a Fourier transformation method through an amplitude mask(six-hole aperture) superimposed with a phase mask(three tilted glass plates) to fabricate the honeycomb and related photonic lattices. The

* Corresponding author.
E-mail address: gaoyuanmei@sdnu.edu.cn (Y. Gao).

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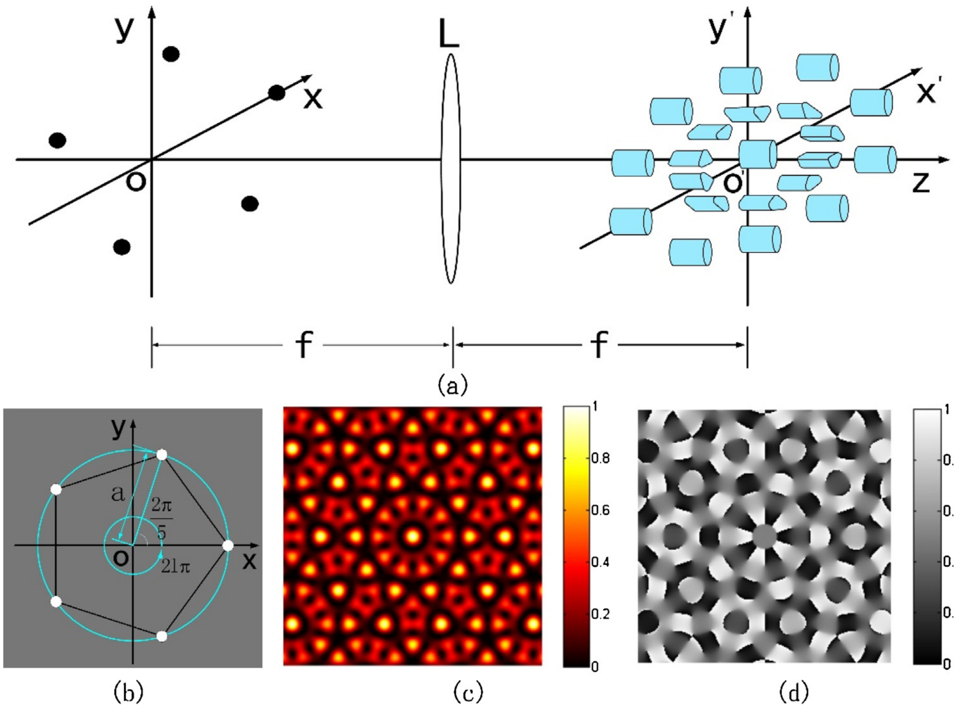

Fig. 1. (a) Schematic diagram of lattice via optical Fourier transformation. (b) The distribution of five point light sources and their phase difference. (c) and (d) Computer simulated intensity pattern and phase distribution of lattice beam for $N = 5$and $l = 0$, respectively.

area of the lattice generated by this method is very small (with diameter about 200μm) and the light distribution is not uniform. Similarly, we didn't give out the law of vortex in the lattices.

In this paper, we derive the universal index function of vortex array wave fields with Fourier transformation of several combined δ function with different phases. We can derive a concise and precise function for each complex vortex field from this universal index function. And we systematize the different classes of vortex lattice which is decided by the number (N) of the δ function. Then we conclude some interesting laws and explain them. In addition, as special cases, we introduce the classes of fivefold and eightfold lattice fields, in which several vortex lattices according to different phase difference have the similar transverse intensity distribution and phase distribution. Finally we experimentally get this lattices by use of a phase-only spatial light modulator (SLM) in a 4f Fourier filter setup where the SLM is displayed with a numerically calculated phase mask. The resulting vortex array laser beam can be applied to optical tweezers and atom traps in the form of two dimensional arrays, or used to study the transfer of angular momentum to micro particles or atoms.

2. Theoretical analysis and simulation

The schematic of optical Fourier transformation method is given in Fig. 1(a). Five point light sources expressed by deltas is placed in the front focal plane of the Fourier transform lens. The five light sources with anticlockwise increasing $2l\pi$phase is shown in Fig. 1(b), where l is topological charge value. Five light sources are on a circle with a radius of 'a'. A $2l\pi/5$-phase difference can be introduced between the adjacent light sources. The light field distribution (U_1) of this five light sources for $l = 1$ in the $x - y$ plane can be described by the following five combined δ functions:

$$U_1(x, y) = \delta(x - a, y) + \delta(x - a\cos\frac{2\pi}{5}, y - a\sin\frac{2\pi}{5})\exp(\frac{i2\pi}{5}) + \delta(x - a\cos\frac{4\pi}{5}, y - a\sin\frac{4\pi}{5})\exp(\frac{i4\pi}{5})$$
$$+\delta(x - a\cos\frac{6\pi}{5}, y - a\sin\frac{6\pi}{5})\exp(\frac{i6\pi}{5}) + \delta(x - a\cos\frac{8\pi}{5}, y - a\sin\frac{8\pi}{5})\exp(\frac{i8\pi}{5}) \quad (1)$$

Now let us change the number of point light sources from five to N (distributed as regular N- polygons). And N point light sources are with different phases, in turn, $0, 2\pi l/N, 4\pi l/N, \cdots 2\pi l$. The complex amplitude distribution (U_2) in $x - y$ plane becomes

$$U_2(x, y) = \sum_{n=0}^{N-1} \exp(\frac{i2\pi nl}{N})\delta(x - a\cos\frac{2n\pi}{N}, y - a\sin\frac{2n\pi}{N}). \quad (2)$$