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Optical fabrication of large area photonic microstructures by spliced lens

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ABSTRACT

We experimentally demonstrate a convenient approach to fabricate large area photorefractive photonic microstructures by a spliced lens device. Large area two-dimensional photonic microstructures are optically induced inside an iron-doped lithium niobate crystal. The experimental setups of our method are relatively compact and stable without complex alignment devices. It can be operated in almost any optical laboratories. We analyze the induced triangular lattice microstructures by plane wave guiding, far-field diffraction pattern imaging and Brillouin-zone spectroscopy. By designing the spliced lens appropriately, the method can be easily extended to fabricate other complex large area photonic microstructures, such as quasicrystal microstructures. Induced photonic microstructures can be fixed or erased and re-recorded in the photorefractive crystal.

1. Introduction

Nonlinear periodic structures have recently become an active area of research due to many exciting possibilities of controlling wave propagation, manipulating and trapping [1–3]. Photonic microstructures can affect the motion of photons in a similar way that periodicity of a semiconductor crystal affects the motion of electrons. It offers new possibilities to route, control, and steer photonics in all-optical information processing and micro-nano photonics devices. Therefore, fabrication of photonic microstructures has always been of great interest [4,5].

Thus far, some sophisticated fabrication techniques have been proposed and developed for making periodic optical microstructures, such as self-assembly, two-photon absorption, colloidal crystallization and electron beam lithography [6–9]. However, it is still a challenge to fabricate large area two-dimensional photonic microstructures in bulk media. The optical induction technique, a convenient method which adapts multiple beam interferences in photorefractive material, has attracted much interest recently in fabricating photonic microstructures such as photonic lattices [10,11]. Although the period of optically induced photorefractive photonic microstructures is bigger (μm), many interesting nonlinear optical phenomena have been found in these materials, e.g. discrete solitons, discrete diffraction and spatial gap solitons [10–12]. Therefore, photorefractive photonic microstructures represent an accessible test-bed for studies of generic bandgap phenomena in photonic periodic structures. But conventional optical induction methods usually rely on complicated and expensive devices, or the induced processes are inefficient, videlicet, the induced areas of photonic microstructures are very small [13–15]. Therefore, low-cost and efficient fabrication of large area photonic microstructures is still a focus of research. In this paper, we report on experimental fabrication and analysis of large area two-dimensional photonic microstructures in iron-doped lithium niobate ($LiNbO_3$:Fe) photorefractive crystal using optical induction method with a spliced lens. The experimental setup of our method is very simple and compact which avoid complicated optical alignment devices and beam alignment system. The setup is also very low-cost, so it can be applied in all optical laboratories. Induced large area photonic microstructures can be fixed or erased even re-recorded in the crystal, which suggests potential applications in micro-nano photonic devices. What is more, this method is not limited to this kind of photorefractive material. It can be easily well adapted to various photosensitizer materials on the basis of the different applications.

2. Experimental methods

It has been shown that, various periodic and quasiperiodic microstructures can be generated in photorefractive media by multiple beams interference [16–18]. Conventional multiple beams interference is employed by a complex optical setup. Using a single element to produce multi-beam interference can effectively reduce the complexity of the optical setups. However, current single element methods have some imperfect, such as high cost, poor flexi-

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bility, and production inefficient [19–21]. In our experiment, we get large area multiple beams interference by a spliced lens. The schematic diagram and the processing method of the spliced lens are given in Fig. 1. A converging lens has a useful property of performing two-dimensional Fourier transform. A point source is located at the front focal plane of the lens and sends a spherical wave. According to the Fourier transform properties of the lens, the spherical wave from the point source is transformed into the plane wave at the output of the lens. As shown in Fig. 1(a), a point source S is located on the front focal plane of the lens, and the vertical distance from the point source S to the optical axis of the lens is a. The focal length of the lens is f. A spherical wave from the point source S is transformed into a plane wave by the lens. The plane wave is deflected toward the centre of the lens, and the angle between the plane wave vector and the optical axis of the lens satisfies the relationship $\beta = \arctan(a/f)$. As shown in Fig. 1(b), the lens is cut from the middle and divided into two equal parts. The section of each part is cut off a portion which thickness is a. And then the two parts are spliced together to form a new optical element named spliced lens. A point source S is placed on the optical axis of the spliced lens, and the distance between the spliced lens and the point source is f. So each part of the splice lens emits a plane wave. The plane waves are deflected toward the centre of the spliced lens, and the angles between each plane wave vectors and the optical axis of the lens are equal $\beta = \arctan(a/f)$. Therefore, these plane waves will inevitably overlap and interfere at the output of the spliced lens. By changing the ratio (a/f), the angle between the interfering beams can be adjusted. The lens has a larger light transmitting area, so that the generated interference region has a larger area. Accordingly, a spliced lens realizes wide plane waves interferences and produces a large area interference light field. Similarly, the lens is divided into three (four, five, six, etc.) parts and processed into a spliced lens, can achieve large area three (four, five, six, etc.) plane waves interference. The processing method of the spliced lens is not difficult and even manual processing in laboratories. Here, we get the large area triangular lattice-forming wave by a spliced lens with three parts. The processing method of spliced lens with three parts is given in Fig. 1 (c). A lens with a diameter of 40 mm, its focal length is 78 mm. The material of the lens is optical glass (K9), and the refractive index is 1.5163. The lens is cut into three equal parts according to the dotted lines, as shown in the left end of the Fig. 1(c). Then, a portion of the thickness a is removed from each section along the cut profile, as shown in the middle part of the Fig. 1(c). Here, the excision thickness a is 3 mm. Finally, the three processed parts are spliced together with adhesive. This constitutes a spliced lens with three parts, as shown in the right end of the Fig. 1(c). According to the above analysis, when the point light source is located in front of the spliced lens 78 mm, the output of the spliced lens can produce large area three beams interference.

The schematic representations of the experimental setups are shown in Fig. 2. In Fig. 2(a), the devices are used to fabricate large area photorefractive photonic microstructures. A linearly polarized beam of a Nd:YAG laser with a radiation wavelength of $\lambda = 532$ nm and power $P = 100$ mW is expanded by a spatial filter, and then incident to the spliced lens, giving rise to the required lattice-forming wave, which is irradiated to the input face of the photorefractive $LiNbO_3$:Fe crystal (dimensions are 10 mm × 10 mm × 2-mm, doped with 0.03 wt%Fe). The lattice-forming wave is linearly polarized perpendicular to the c-axis of the $LiNbO_3$:Fe crystal (o-polarized). The intensity of the lattice-forming wave is about 45.3 mW/cm^2 which is measured in the front face of the crystal. In Fig. 2(b), these devices are used to verify and analyse the induced microstructures. The beam A is used for the plane wave guiding and the far field diffraction pattern imaging to analyze the induced lattice microstructures. The He-Ne laser ($\lambda = 632.8$ nm, $P = 1.5$ mW) is expanded by a spatial filter and a collimation lens as the probe beam. The probe beam is linearly polarized parallel to the c-axis of the $LiNbO_3$:Fe crystal (e-polarized). We can capture images of guided wave intensity and far-field diffraction pattern of the induced photonic microstructures in the crystal by a CCD. In beam path B, a telescope and a rotating diffusor near its focal plane constitute a Brillouin-zone spectroscopy configuration [22,23]. The telescope can radiate the randomized light field which is focused onto the front face of the crystal to motivate a broad spatial spectrum of waves. The Fourier image of the waves transmitted through the crystal gives important structural information about the induced photonic microstructures. The CCD cap-

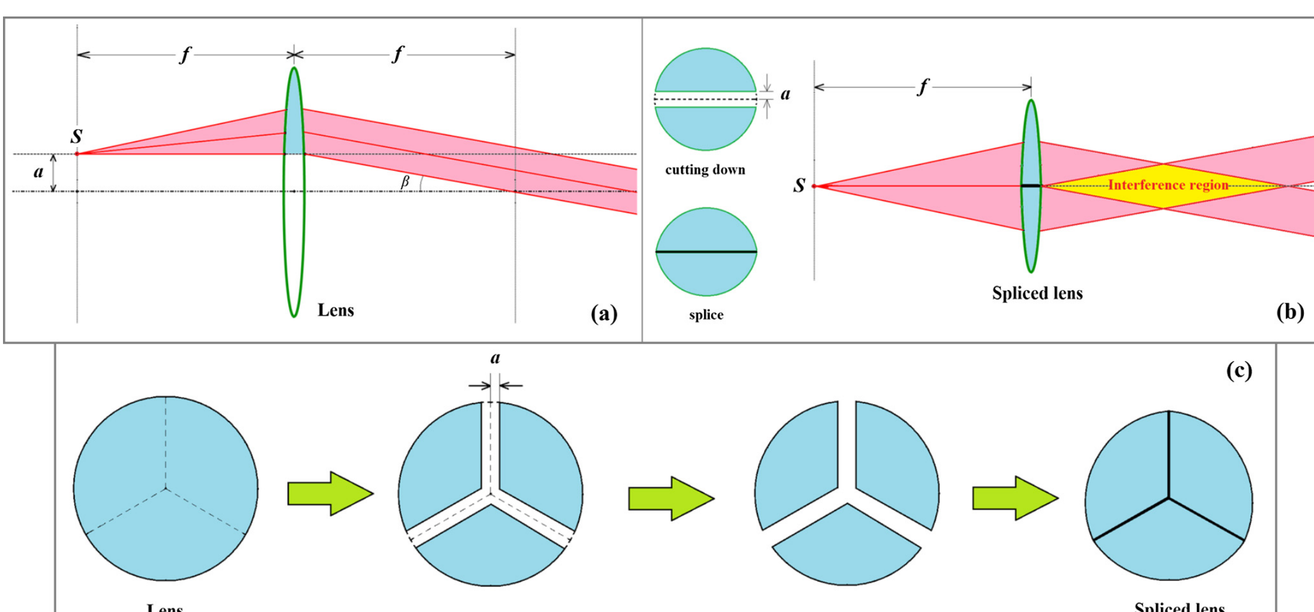

Fig. 1. (a) The schematic diagram of a spherical wave is transformed into a plane wave by a lens. (b) The schematic diagram of large area two beams interference by a spliced lens with two parts. (c) The processing method of the spliced lens with three parts.