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Area scalable optically induced photorefractive photonic microstructures

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ABSTRACT

A convenient approach to fabricate area scalable two-dimensional photonic microstructures was experimentally demonstrated by multi-face optical wedges. The approach is quite compact and stable without complex optical alignment equipment. Large-area square lattice microstructures are optically induced inside an iron-doped lithium niobate photorefractive crystal. The induced large-area microstructures are analyzed and verified by plane wave guiding, Brillouin-zone spectroscopy, angle-dependent transmission spectrum, and lateral Bragg reflection patterns. The method can be easily extended to generate other more complex area scalable photonic microstructures, such as quasicrystal lattices, by designing the multi-face optical wedge appropriately. The induced area scalable photonic microstructures can be fixed or erased even re-recorded in the photorefractive crystal, which suggests potential applications in micro-nano photonic devices.

1. Introduction

Photonic microstructures have become one of attractive research areas in the past several years, holding strong promises for applications in controlling and manipulating the propagation of light [1–4]. Photonic microstructures can have significant prospects only when they are with scalable areas. The optical induction technique, a handy method combining multi-beam interference and photorefractive material, has attracted much interest recently in fabricating photonic microstructures such as photonic lattices [5,6]. Periodic or quasi-periodic microstructures can be induced optically in the photorefractive media at very low power level based on refractive index modulation via photo-induced refractive index change effect [5–10]. The induced photonic microstructures can be fixed or erased and re-recorded in the media by the appropriate process [11]. However, these conventional fabrication techniques have some shortcomings, such as process complexity, high cost, and low efficiency, stuck in the fabrication of scalable-area photonic microstructures [12–15]. So it has been a challenge to fabricate scalable-area photonic microstructures in bulk media.

Conventional multiple-beam interference is often implemented by a complicated optical setup. Improved multi-beam interference using a single element helps to reduce the complexity of the setups [16–18]. However, these single element methods usually rely on a special and expensive device (e.g. diffractive beam splitter, spatial light modulators [16,17]), or the induced areas are small and the induced processes are inefficient (e.g. multi-pinhole plate [18]). Therefore, low-cost and efficient fabrication of photonic microstructures is still a focus of research. In this paper, we present an experimental investigation of the formation of scalable-area two-dimensional photonic microstructures. The key of our method is using a multi-face optical wedge to generate scalable-area multi-beam interference. This is a simple, compact, and efficient way in fabricating various large-area photonic microstructures. In particular, the method is not limited to photorefractive materials alone. It can be easily well adapted to various photosensitive materials on the basis of the variable applications.

2. Experimental methods

Optical wedge is a type of common laboratory element. It can deflect the propagation direction of incident beam without changing the wave front. The deflection angle θ of the incident beam is governed by the representation $\theta = (n_g - 1)\alpha$ with α and n_g the wedge angle and refractive index of the optical wedge (Fig. 1(a)), respectively. The deflection due to the appropriate combination of several identical optical wedges can lead to the

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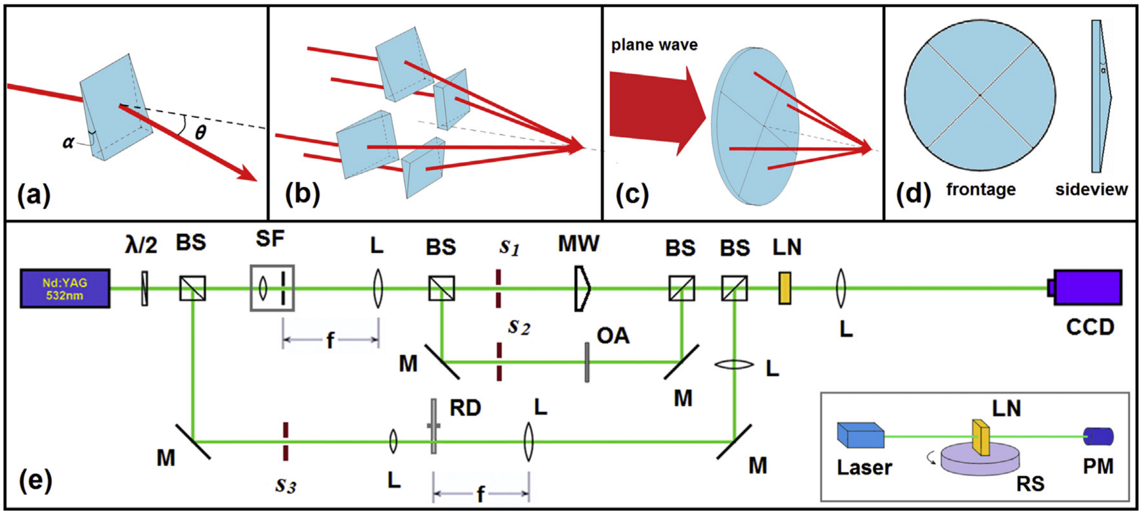

Fig. 1. (a) A schematic drawing of beam deflection by a single optical wedge. (b) Four beams interference is achieved by using four optical wedges. (c) A schematic drawing of four-beam interference by a four-face optical wedge. (d) The four-face optical wedge. (e) Schematic diagram of the experimental scheme for the generation and analysis of scalable-area two-dimensional photonic microstructures. λ/2, half-wave plate; BS, beam splitter; SF, spatial filter; L, lens; s_1 ~ s_3, shutter; MW, multi-face optical wedge; M, mirror; OA, optical attenuator; RD, rotating diffuser; LN, $LiNbO_3$:Fe crystal. Experimental setup for angle-dependent transmission measurement is shown in the inset. RS, rotation stage; PM, optical power meter.

superposition and interference of multiple beams with the equivalent deflection angles, as showed in Fig. 1(b). Since the transmission aperture of the optical wedge is scalable, the interference area of these deflection beams is also scalable. Then a multi-beam interference with scalable area can be achieved. However, the individual and independent multiple optical wedges may require more complicated adjustment to achieve the multi-beam interference. To solve this issue, we assembled the multiple optical wedges into a single integrated optical element named multi-face optical wedge as showed in Fig. 1(c) and (d). The multi-face optical wedge is a special optical wedge which has multiple wedge surfaces. These wedge surfaces have identical wedge angles. When the normal incidence of a wide plane beam occurs to the multi-face optical wedge, the incident beam is divided into several sub-beams by each wedge surface. These sub-beams are deflected and subsequently superimposed over one another forming multi-beam interference. Since the area of wedge surface is scalable, the area of the multi-beam interference region is also scalable. For example, when using a four-face optical wedge with 40 mm diameter, the area of interference region is close to the area of an inscribed circle in the one wedge surface. According to the calculation, the area size is about 215.6 mm^2. The experimental setup with multi-face optical wedge is compact and stable without complex adjustment. Compared to the previous multi-beam interferences by prism, the multi-face optical wedge is easier to be handled [19–24]. This method can be flexibly extended to produce various photonic microstructures by designing various multi-face optical wedges.

In our experiment, scalable-area two-dimensional photonic microstructures are fabricated in an iron-doped lithium niobate ($LiNbO_3$:Fe) photorefractive crystal using a four-face optical wedge. The wedge angle α of the four-face optical wedge is 3.49°, and the refractive index of the optical wedge n_g is 1.516. So the deflection angle θ is about 1.80°. The schematic representation of the experimental setup is shown in Fig. 1(e). A continuous-wave Nd:YAG laser with 532 nm wavelength and the shutters s_1, s_2 and s_3 control three different optical paths, respectively. When only opening shutter s_1, the optical path is used to induce scalable-area photonic microstructures. The lattice-forming beam with the intensity about 52.5 mW/cm^2 illuminates the input face of the $LiNbO_3$:Fe crystal (dimensions are 10 mm × 10 mm × 5 mm, doped with 0.025 wt% of iron) and propagates through it. The diffraction effect of the intensity pattern can be ignored due to the thickness of the crystal is not large. So the size of intensity patterns are the same at front and back planes of the crystal. The lattice-forming beam can induce volumetric refractive index changes inside the crystal via photorefractive effect. In order to realize a non-distorted refractive index modulation, the lattice-forming beam is linearly polarized perpendicular to the *c*-axis of the crystal (*o*-polarized) [25,26]. The suitable exposure time is about 25 min. When only opening shutter s_2, the optical path is used for the plane wave guiding to prove the induced photonic microstructures. When only opening shutter s_3, the optical path is a standard configuration for Brillouin-zone spectroscopy [27,28]. Brillouin-zone spectroscopy pattern, captured by CCD, contains important structural information about the induced lattices. In order to obtain quantitative information, the induced microstructures are analyzed by an angle transmission measuring setup, as shown in the inset of Fig. 1(e). After the generation of the microstructures, the crystal is placed on a precision rotation stage. By rotating the crystal, the incident angles of the probe beam can be changed. So the angle-dependent transmission of the probe beam is measured by an optical power meter. The power of the probe beam is about 0.005 mW. In this level, the probe beam enables the analysis of the induced microstructures, at the same time avoids erasing induced structures or leads to additional refractive index changes.

3. Experimental results and analysis

Typical experimental result of induced large-area photonic microstructure is shown in Fig. 2. Fig. 2 gives the image of guided wave intensity pattern of the induced microstructure which is probed by *e*-polarized probe beam. Large-area square photonic lattice in the crystal can be observed clearly. As the interference area is greater than the size of the crystal, induced microstructures bestrew inside the crystal. The area of the generated photonic microstructure is about 100 mm^2 which is limited by the size of the crystal. If the size of the photosensitive material is increased, the area of fabricated photonic microstructure can be further expanded. The periodic scale of the induced lattice microstructure is measured to be about 12 μm. The corresponding Brillouin-zone