Fabrication of Two-Dimensional Photonic Crystals With Embedded Defects Using Blue-Laser-Writer and Optical Holography

Tao Liu, Mahmoud Fallahi, Jerome V. Moloney, and Masud Mansuripur

***Abstract*—We have demonstrated an approach of relatively rapid fabrication of two-dimensional (2-D) photonic crystals (PCs) with embedded defects by combining a custom-built blue-laser-writer and the technique of optical holography. The blue-laser-writer is used to define various defect patterns first, and then the optical holography is used to create 2-D PCs on the samples with the predefined defects. A beam splitter was fabricated based on this new method and characterized.**

***Index Terms*—Beam splitters, optical waveguides, photonic crystals (PCs).**

I. INTRODUCTION

PHOTONIC crystals (PCs) [1], [2], which attracted significant attention in recent years for their unique characteristics, hold the promise for the construction and integration of optical components in a very compact manner. In order to realize functional PC devices like optical waveguides [3] and microcavities [4], various defect structures have to be incorporated into the otherwise periodic structures. However, due to the extreme difficulty to make the necessary defects in three-dimensional (3-D) PCs, most researchers have been focusing on two-dimensional (2-D) PCs on slab platforms [3]–[5].

Currently, electron beam lithography is a commonly used technique for fabricating 2-D PCs with a high degree of accuracy and design flexibility [3]–[6]. However, direct-write E-beam lithography is a slow and expensive process, which makes it inappropriate for the mass production of large integrated optical circuits. By comparison, optical holography is an ideal candidate for making PCs with high throughput on a large area. But optical holography itself can only produce PCs without any defect structures that are necessary for realizing functional optical components. Taking advantage of the negative photoresist nature of SU-8, Pang *et al.* used a strongly focused UV laser beam to introduce linear defects into PCs produced by optical holography [7]. Since in this method the selective exposure by the focused UV laser beam happens after the holography and before the resist development, it is difficult to differentiate the unexposed area from those exposed and, thus, difficult to find the right location for the defects. The other problem is that the selective exposure not only defines the defects, but also changes the size of the holes adjacent to the defect region, which is not desired.

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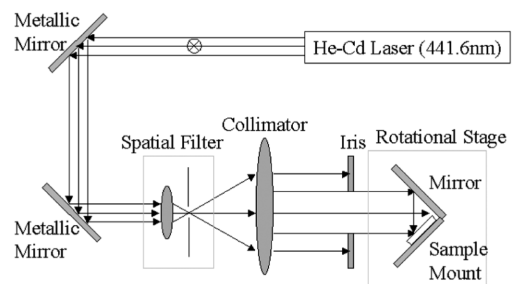

Fig. 1. Schematic of the two-beam interferometic optical holography. Objective lens in the spatial filter: $X60/0.85$. Pinhole in the spatial filter: 5 μm. Collimator: $F5/250$ mm.

In this letter, we describe a new method to produce PCs with controlled defects by combining a custom-built blue-laser-writer and the technique of optical holography. In our method, the defect patterns are defined onto the substrates through direct laser writing and liftoff process before the optical holography. Therefore, the defects are actually visible during the following holography process, which is potentially useful for the alignment between the defects and the PCs. It is also shown that this process has very little effect on the size of the holes adjacent to the defect regions. Based on this method, a simple beam splitter was fabricated and characterized. In the end, we also propose an interferometric method for the strict alignment between the predefined defects and the PCs.

II. FABRICATING 2-D PCs WITH EMBEDDED DEFECTS

In the blue-laser-writer system, the light wavelength is 405 nm. The sample is placed on a stage that is moved with high-resolution picomotors and monitored by two interferometers. The laser beam is focused on the sample through an objective lens. By controlling the laser output power, the exposure time at each point, and the numerical aperture of the lens, different linewidths can be obtained.

The optical holography (two-beam interference) setup is schematically shown in Fig. 1. The He–Cd laser has two emitted wavelengths: 325 and 441.6 nm. In the experiments, 441.6 nm is used because the optics in our setup is transparent at 441.6 nm. The laser beam is routed by two metallic mirrors, expanded by a spatial filter, and then collimated. The top half of the beam is reflected by a mirror and then reaches the sample, while the bottom half of the beam illuminates the sample

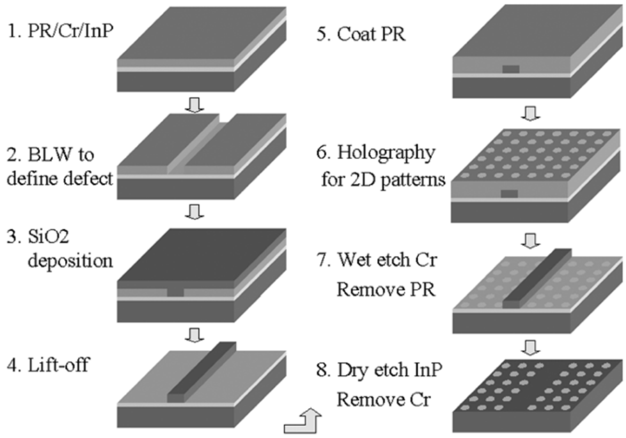

Fig. 2. Schematic of the fabrication procedures. PR: photoresist. BLW: blue-laser-writer.

directly. The two beams combine on the sample and create the interference pattern. The mirror and the sample holder are mounted at 90° on the same rotational stage. By adjusting the orientation of the stage, we can easily change the incident angle of the laser beam onto the sample and, thus, the period of the interference patterns. The period is determined by this formula: $\lambda/[2\sin(\theta/2)]$, where λ and θ are the laser wavelength and the angle between the two beams incident on the sample. A square lattice PC pattern can be created by exposing the sample twice with a rotation of 90° before the second one.

The primary steps of our method are schematically shown in Fig. 2. First, the InP substrate is coated with a thin Chromium (Cr) layer deposited by E-beam evaporator and a layer of positive photoresist (Shipley1805) by a spin coater. The thicknesses of the Cr layer and the photoresist are 40 and 500 nm, respectively. Then the defect patterns are defined into photoresist through direct blue laser writing. After the resist development, a SiO_2 layer 60 nm thick is deposited on the photoresist by E-beam evaporator and patterned by liftoff process. The above process is illustrated in Fig. 2(1)–(4). In the figure, only a linear defect is shown for the purpose of demonstration. Various defects can be defined through the above process. Now the defect regions on the substrate are protected by the SiO_2 layer and the sample is ready for the subsequent optical holography.

Another layer of photoresist is spin coated onto the sample with the predefined defects. Two-dimensional PCs are then created on the above sample through optical holography with dual exposures. After resist development, the PC pattern is then transferred into the Cr layer by wet etching while the Cr layer under the predefined SiO_2 defect regions is protected. After the wet etching, the residual photoresist is removed by O_2 plasma. The subsequent CH_4-H_2-based electron cyclotron resonance (ECR/RIE) dry etching process transfers the PC patterns from Cr to the underlying InP substrate. The protective SiO_2 layer also etches during the dry etching process. Finally, the residual Cr is chemically removed. The above process is illustrated in Fig. 2(5)–(8).

In our experiment, two defect structures, a linear defect and a Y-junction, are used for the purpose of demonstration. Because the linewidth of the defects that can be obtained with the blue-laser-writer around 1 μm, the period of the PC is chosen to be 1 μm in order to demonstrate a linear defect with only one row of holes missing. The scanning electron micrographs (SEMs) of the PC patterns with defects in Cr and InP are shown in Fig. 3. In Fig. 3(a) and (b), the SiO_2 at the defect region is clearly visible. It can be seen from Fig. 3 that the size of the holes adjacent to the defect region is almost the same as those away from the defects. This fact shows that our process has little effect on the size of the holes close to the defect regions.

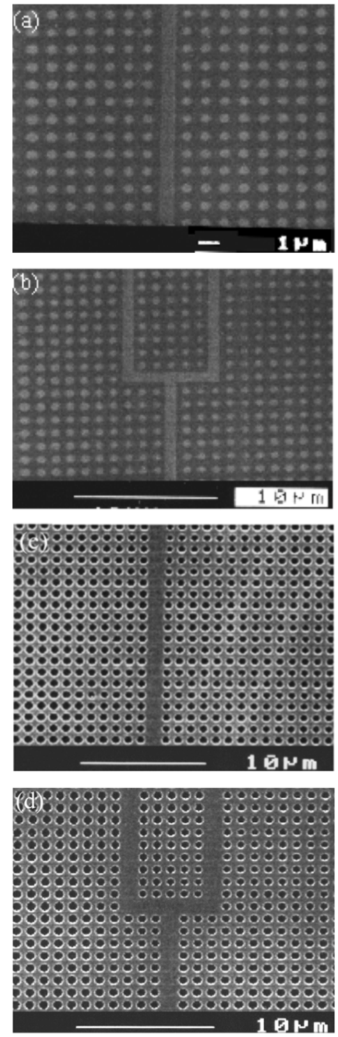

Fig. 3. (a) and (b) SEM micrographs of the PCs with defects in Cr. These figures correspond to Fig. 2(7). The SiO_2 layer in the defect regions is clearly visible. (c) and (d) SEM micrographs of the PCs with defects in InP after removal of residual Cr. These figures correspond to Fig. 2(8).

III. Fabrication and Measurement of a Beam Splitter

Based on the proposed method, a beam splitter in a square lattice PC with the period of 500 nm and the radius of 210 nm was fabricated and characterized. But due to the resolution limit of the blue-laser-writer, a waveguide with a single linear defect could not be made. Instead, seven rows of air holes were missing intentionally for the ease of measurement, which is corresponding a defect width ~3.5 μm. An InP-based heterostructure was used for this fabrication: light confinement in the vertical dimension is ensured by a 420-nm-thick GaInAsP layer capped by an InP protective layer with the thickness of 200 nm. The effective index is ~3.21. For the selected structural parameters, a small bandgap around $\lambda = 1550$ nm for TE polarization is open. Even though this bandgap lies above the light lines of the

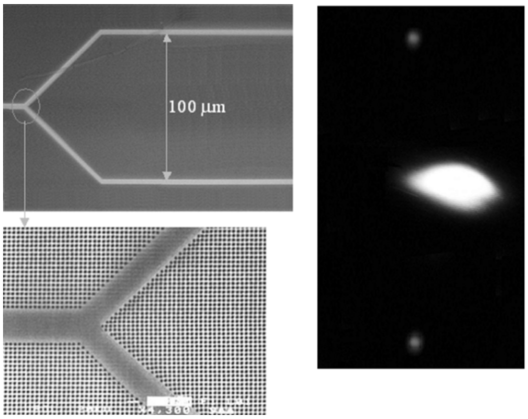

Fig. 4. Beam splitting at $\lambda = 1540$ nm for TE polarization. Top: picture of the fabricated beam splitter (taken with an optical microscope). Bottom: SEM micrograph of the splitter region. Right: signals detected by an IR camera placed at the output end of the splitter for in-plane view. The total length of the structure is ~200 μm.

claddings due to the small index contrast between the guiding layer and the cladding, low-loss transmission is possible and has been predicted [8], [9] and experimentally demonstrated [10]. Therefore, these parameters were used for the ease of fabrication to show the validity of the new fabrication method.

In order to couple the light in and out of the device, the sample was cleaved from both sides. Prior to cleaving, the sample was thinned from 350 to 180 μm. This thinning process enables us to obtain smooth cleaved edges at both sides of the device, which helps improve the coupling in and out of the device. The total length of the device after the cleaving is ~200 μm. The separation between the two output waveguides is 100 μm such that the output signals from the output waveguides can be easily distinguished from the light that is not coupled into the waveguide. In the measurement, a tunable laser with a maximum output power 4 mW was used as the light source; a fiber polarization controller is used to control the polarization of the light incident on the sample; a lensed fiber is used to couple the light into the PC structure; an objective lens is used to collect the light from the output of the device and to image the output facet onto an infrared (IR) camera. The preliminary measurement result together with the fabricated structure is shown in Fig. 4.

In the right picture of Fig. 4, the signals coming out of the two output waveguides for TE polarized light can be clearly seen and are separated from the light that is not coupled into the waveguide (the big bright spot in the center). The output power from a single output waveguide is measured to be ~2 μW. However, similar beam splitting is not observed for TM polarized light whose H-field is normal to the plane of periodicity. Therefore, we believe that the small bandgap for TE polarization, even though above the light lines of the claddings, plays an important role for the beam splitting. Even though this beam splitter has low efficiency, it shows the validity of the fabrication method. To obtain devices with high efficiency, a high index contrast waveguide structure like silicon suspended in air [3] or triangular lattice instead of square lattice may be pursued.

IV. Discussion and Future Direction

The current difficulty with the described method is the alignment between the defects and the PCs. As described above in the process, the defects are visible during the holography process, which makes the strict alignment possible. We propose a way for this purpose. In this way, two lasers can be used during the holography process: 325-nm light from He–Cd laser and 650 nm from a HeNe laser. The period of the interference pattern created by the 650-nm light is twice that of the 325 nm. The two laser beams can be aligned so that the two sets of interference patterns overlap. As a result, if the defect is already aligned with interference patterns of 650-nm light, it is aligned with those of 325-nm light as well. Since the positive photoresist (e.g., Shipley1805) is insensitive to light at 650 nm, this light can be used for the alignment with the help of monitoring equipments. After the alignment is finished, light at 325 nm can be turned on to expose the photoresist. The fact that the light at 650 nm gives the interference pattern with a larger period makes the alignment easier than that with the light at 325 nm.

Even though only linear defects were presented in this letter, other defect types are also needed in order to realize more functional devices, such as point defects with size change of holes. It is rather straightforward to reduce the size of a hole by applying the method in this letter. However, increasing the size of a hole involves much more complexity. The relevant issues will be discussed in further publications.

V. Conclusion

In this letter, we developed a new method to fabricate PCs with embedded defects by combining a custom-built blue-laser-writer and holography. For demonstration, two defect structures, a linear defect and a Y-junction, surrounded by square lattice PCs are defined into InP substrate. It is shown that this method has little effect on the size of the holes adjacent to the defect regions, which is a desirable feature. A simple beam splitter was fabricated and characterized in order to show the validity of this method. We believe that, with this method, various defects can be fabricated to produce different functional PCs at low cost and large volume.

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