JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 12, No. 3, March 2010, p. 770 - 772

Fabrication of 2-D quasiperiodic photonic crystals using single grating phase mask lithography

S. AVINO*, R. WINFIELD
Tyndall Institute, University College Cork, Lee Maltings, Prospect Row, Cork, Ireland

We present a method for the fabrication of large area 2-D quasiperiodic photonic crystals based on phase-mask lithography. An Excimer laser is used to expose a photoresist material through a 1-dimensional grating. The grating is placed in contact with a thin film of photoresist. The near-field interference pattern generated in proximity of the grating transfers its structure into the resist. Performing multiple exposures at different orientations between the grating and the sample it is possible to obtain 2-D quasiperiodic structures. Results on 2-D structures obtained are shown and the potential application of this technique to fabricate low cost and large area 2-D phase masks for generation of 3-D quasiperiodic photonic crystals is discussed.

(Received June 19, 2009; accepted November 3, 2009)

Keywords: Photonic crystals, Photolithography, Phase masks

1. Introduction

Photonic crystals (PCs) have been widely studied and used to manipulate the properties of electromagnetic radiation. PCs are microstructured materials with periodically variable dielectric constant. The dielectric constant modulation affects the propagation of electromagnetic waves at wavelengths comparable to the period of the PCs [1, 2]. One of the most important property of PCs is that they present photonic bandgaps (PBGs) in which electromagnetic propagation is forbidden [1, 2, 3].

Several PCs geometries have proposed and realized to achieve complete PBGs. Among them quasiperiodic photonic crystals (QPCs) have particular advantages. In fact, QPCs can have complete PBG with refraction index contrast significantly smaller than ordinary PCs [4, 5]. Moreover, due to their aperiodicity they show higher rotation symmetries and more isotropic bandgaps with respect to the standard periodic PCs.

In the last years, several techniques to generate PC were demonstrated as, for example, electron beam lithography [6], nanoimprint lithography [7], direct laser writing [8], multiple-beam interference lithography [9, 10] and phase-mask lithography [11].

In this work we combined the multi-beam interference lithography (MBIL) technique with the phase-mask lithography (PML) technique. The advantage in using these techniques is the possibility to fabricate large area structures with reduced costs and fabrication times.

In the MBIL technique, the interference pattern formed by the superposition of different coherent laser beams is projected into a photoresist sample [9]. After processing, the interference pattern remains recorded into the photoresist. A variant of this technique is to perform multiple exposures at different orientations between the sample and the irradiation source [10].

In the PML technique, an interference pattern is obtained by the superposition of scattered beams in proximity of a diffractive optical element, the phase-mask [11]. With respect to the MBIL, the PML allows to avoid problems due to interferometer misalignments and instabilities. Moreover, since the interference pattern is generated in close proximity of the phase-mask, it is possible to relax the constraints on the spatial coherence of the irradiant source which are much more stringent in the case of MBIL.

However, the PML is less versatile than the MBIL. In fact, in the case of MBIL by changing the number of beams and the number and the orientation of the exposures it is possible to easily change the geometry of the interference pattern and then of the structures imprinted into the photoresist. On the contrary, in the case of PML, a proper phase mask is needed for each different structure geometry.

In this paper, we present a fabrication technique which combines the advantages of PML to the ductility of MBIL. A 1-dimensional phase mask grating is used to expose a photoresist sample. Performing multiple exposures at different orientation allows to fabricate various 2-D geometries.

2. Experimental apparatus and technique

In our experiment we used a +1/-1 phase-mask from Ibsen Photonics. The phase-mask is designed to scatter the major part of the light into the +1/-1 orders suppressing the light scattered into the zero-order below 5% of the total incident radiation intensity. As shown in Fig.1 an interference pattern is generated in proximity of the phase-mask surface.

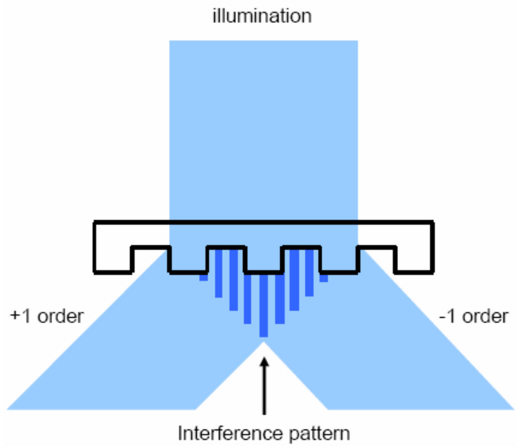

Fig. 1. Working principle of the +1/-1 phase-mask. The major part of the light is scattered into the +1/-1 orders generating an interference pattern in proximity of the phase-mask surface.

The experimental apparatus is shown in Fig. 2. An Excimer laser at 248 nm is first expanded by a telescope and then it passes through a small aperture before being shone through the phase-mask. After the aperture the beam intensity is almost flat allowing a uniform exposure over a large area (1cm x 1cm). A photoresist sample is placed in contact with the phase-mask. The phase-mask and the photoresist sample are mounted on rotation stages in order to modify the relative orientation in the plane perpendicular to the light propagation axis.

Multiple exposures are performed at different angles between the phase-mask and the photoresist sample. After each exposure a "latent" pattern corresponding to the single grating is transferred to the photoresist. By superposing multiple single grating patterns, 2-dimensional patterns are generated. The total intensity distribution can be written as:

$$I_{TOT} = \sum_n I(\theta_n),$$

where $I(\theta_n)$ is the total intensity distribution at the angle θ_n .

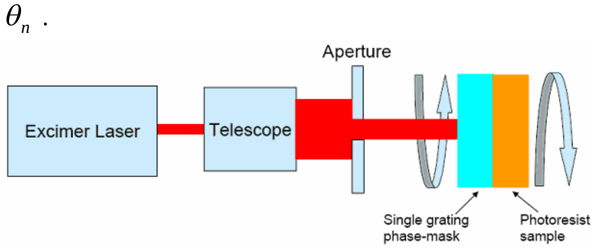

Fig. 2. An Excimer laser at 248 nm shaped by a telescope and a small aperture shines the phase-mask placed in contact with a photoresist sample. The phase-mask and the photoresist sample are mounted on rotation stages in order to modify the relative orientation in the plane perpendicular to the light propagation axis.

3. Experimental results

To fabricate periodic and quasiperiodic structures we used the Shipley S1805 positive photoresist. A 500 nm film of resist was spin-coated on a glass substrate. The resist sample was placed in contact with the phase-mask and multiple exposures were performed at different orientations between the sample and the phase-mask.

The resist sample was exposed to a total intensity pattern which can be represented as the sum of single grating interference patterns at various angles. In this condition, the highest light dosage absorbed by the resist corresponds to the points of intersection of the single grating patterns.

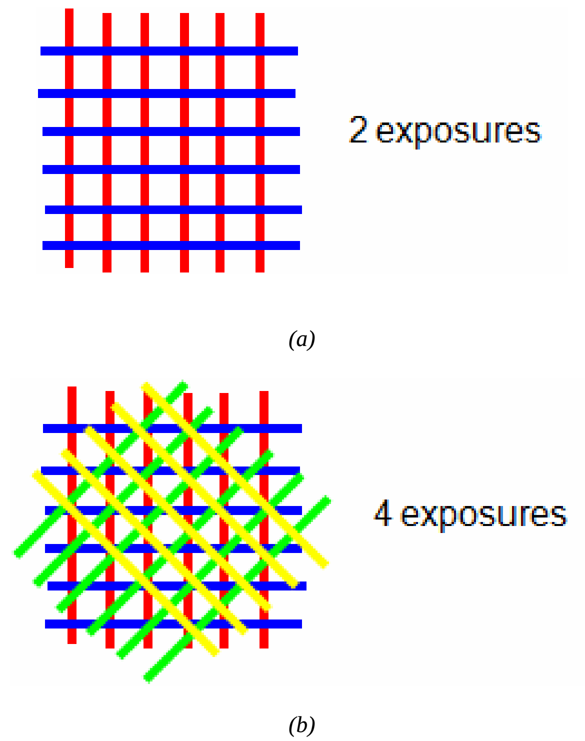

Fig. 3. a) grating intersection pattern corresponding to an orthogonal geometry, obtained by two exposures at ($0^\circ, 90^\circ$); b) grating intersection pattern corresponding to an octagonal geometry obtained by four exposures at (0°, 45°, 90°, 135°).

In Fig. 3 (a) and (b) are shown the grating intersection patterns corresponding to orthogonal and octagonal geometries, obtained respectively by two exposures at ($0^\circ, 90^\circ$) and four exposures at (0°, 45°, 90°, 135°).

In Fig. 4 is shown a SEM image of a periodic orthogonal structure obtained by two exposures. In Fig. 5 is shown a SEM image of a quasiperiodic octagonal structure obtained by four exposures. Both these structures have been obtained over a large area of the photoresist sample (1cm x 1cm).

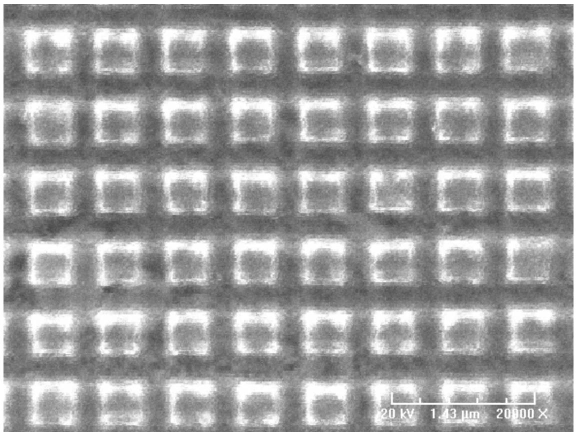

Fig. 4. Orthogonal structure obtained by two exposures at ($0^{\circ}, 90^{\circ}$) through a single grating phase mask.

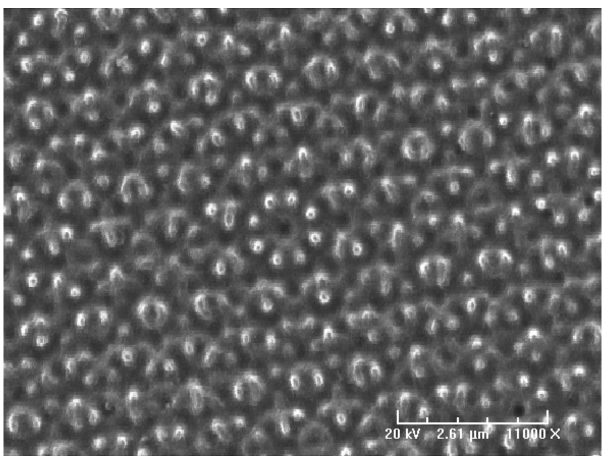

Fig. 5. Octagonal structure obtained by four exposures at (0°, 45°, 90°, 135°) through a single grating phase mask.

4. Discussion and conclusions

In this work we have demonstrated a technique to fabricate 2-dimensional periodic and quasiperiodic structures based on single grating phase-mask lithography. The technique combines the advantages of multi-exposure interference lithography to generate complex periodic structures to the robustness and simplicity of phase-mask lithography.

The main benefit in using this method is the possibility to fabricate large area structures with reduced costs and fabrication times. For example, by using a single grating phase-mask we were able to fabricate large area structures (1cm x 1cm) with orthogonal and octagonal geometry. The technique can be extended to fabricate more complex 2-dimensional structures.

The next step is to transfer the structures generated into the photoresist to a fused silica substrate (by reactive ion etching, for example) to fabricate 2-dimensional phase-masks. The 2-D phase-mask obtained will then be used to generate 3-dimensional structures. In fact, by exposing a 2-D mask it is possible to generate 3-dimensional interference pattern in the region near the mask surface. The pattern can be then recorded into a thick photoresist film placed in contact with the phase-mask. After the processing a 3-dimensional structure, with geometry related to the 2-D mask, is obtained.

Acknowledgments

The authors acknowledge the European Commission for supporting this project under the Seventh Framework Program. Project: HOT, PN-029570.

References

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] J. D. Joannopoulos, Pierre R. Villeneuve, Shanhui Fan, Nature **386**, 143 (1997).
[3] K. M. Ho, C. T. Chan, C. M. Soukoulis, Phys. Rev. Lett. **65**, 3152 (1990).
[4] Y. S. Chan, C. T. Chan, Z. Y. Liu, Phys. Rev. Lett. **80**, 956 (1998).
[5] M. E. Zoorob, M. D. B. Charlton, G. J. Parker, J. J. Baumberg, M. C. Netti, Nature **404**, 740 (2000).
[6] M. Notomi, H. Suzuki, T. Tamamura, Appl. Phys. Lett. **78**, 1325 (2001).
[7] Stephen Y. Chou, Peter R. Krauss, Preston J. Renstrom, Appl. Phys. Lett. **67**, 3114 (1995).
[8] H. B. Sun, S. Matsuo, H. Misawa, Appl. Phys. Lett. **74**, 786 (1999).
[9] X. Wang, C. Y. Ng, W. Y. Tam, C. T. Chan, P. Sheng, Adv. Mater. **15**, 1526 (2003).
[10] R. C. Gauthier, A. Ivanov, Opt. Express **12**, 990 (2004).
[11] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, J. Albert, Appl. Phys. Lett. **62**, 1035 (1993).

*Corresponding author: saverio.avino@gmail.com, saverio.avino@tyndall.ie