Fabrication of 2-D photonic crystals using azo polymers

A. Gharavi, H. Karimi-Alavijeh, E. Sarailou, M.–A. Baghban, and G.–M. Parsanasab
Photonics Lab., Dept. of Electrical Engineering, University of Shiraz, Shiraz, Iran.

Abstract— **In this paper, we have reported the fabrication of two-dimensional photonic crystals, using a direct writing method in azo polymers. Periodic structures have been fabricated using the interference patterns of two coherent laser beams. The frequency response of the initial one-dimensional structure shows an attenuation of 19.3dB at 1554nm. The two-dimensional structure shows 8.3dB and 11.3dB of attenuation at 1554nm in two perpendicular main axes of the structure. The diffraction pattern shows the characteristic rectangular pattern.**

KEYWORDS: Photonic crystal, Cis-trans isomerization, interference pattern, optical polymer.

I. INTRODUCTION

Photonic Crystals (PCs) are optical structures with periodic changes in dielectric constant with a periodicity of the scale of the optical wavelengths. This property leads to the formation of photonic band gaps which prevents light waves propagating through them. These structures have attracted great interest in recent years owing to their capabilities in controlling emission and propagation of light waves. Photonic crystals have been used to fabricate devices such as waveguides [1-3], micro-cavities [3-5], add/drop filters [2, 3], etc. Techniques such as e-Beam lithography [6, 7], holographic lithography [8, 9], nano-patterning lithography [10, 11], etc. are mostly used to fabricate photonic crystal structures. Fabrication of photonic crystals in conventional semiconductor materials is still far from being trivial and requires sophisticated and expensive equipment to fabricate. For the time being, photonic structures are mostly fabricated by adapting lithographic techniques borrowed from the microelectronic industry. A completely different approach is the realization of PCs in organic materials by optical techniques, such as holographic lithography or in our case inducing change in refractive index by optical means. The advantage of this technology is the possibility of recording large-area, homogeneous periodic structures with a fast, simple, inexpensive, and highly reproducible process. Polymeric materials, having advantages such as ease of fabrication, low cost and refractive index compatibility with optical fibers, are becoming attractive alternative for inorganic materials. Several devices such as waveguides [12-14], Mach-Zehnder modulators [15, 16], couplers [17], gratings [18-20], photonic crystals [21-23], and all-optical switches [15] have been fabricated using polymeric materials. All of these devices are currently being investigated in our laboratory.

Polyimides functionalized with azo chromophores exhibit photoinduced birefringence due to the reorientation of the azo chromophores by the *cis-trans* isomerization process. When exposed to light within their absorption band, the azo chromophores align in a direction perpendicular to the polarization of that light. This reorientation results in a change of the refractive index of the polymer, which can be used to fabricate several optical devices. Here, we have fabricated a two dimensional (2-D) polymeric Photonic crystal using the interference pattern of two coherent laser beams.

II. EXPERIMENTS

A. preparing polymeric films

In the polymeric materials, the chromophore was chemically attached to the host polyimide for better thermal and temporal stability. The chemical structure and absorption spectrum of this polymer is shown in Fig. 1. This material was synthesized by an approach similar to that of Saadeh *et al* [24]. To prepare a thin film of these polymers, 300 mg of the polymeric material was dissolved in 2 ml of Dimethyl Formamide (DMF). The solution was filtered by a 0.2 μm filter and was then spin-coated on a 2.5×3.8 cm^2 glass substrate. Depending on the spinning speed, the film thickness ranged between 1 to 3 μm. This film was then cured at 200 °C for 20 minutes to form a hard film. A computer controlled prism coupler was used to measure the refractive index and thickness of the polymeric film. The refractive index of the film for TE polarization at the wavelength of 1550 nm was calculated to be 1.557. Using an 830 nm laser, the film thickness was measured to be 1.71 μm.

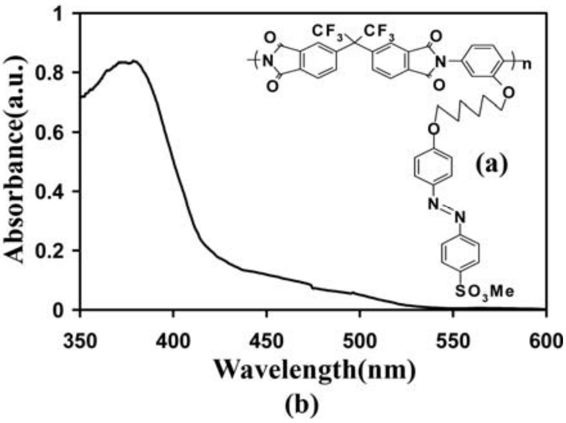

Fig. 1 (a) Chemical structure, and (b) absorption spectrum of the polymeric material used in this experiment.

B. Fabrication of 2-D photonic crystals

The experimental setup used to form photoinduced periodic structures is shown schematically in Fig. 2. A beam splitter cube was used to divide the laser beam into two coherent, equal intensity beams. The beams were reflected by the mirrors towards the polymeric film at a desired angle of θ which was adjusted precisely by the position of the mirrors, b, and the height of the prism from the sample, h. The formula given below expresses the relationship between θ, b and h:

$$b = \frac{h \tan\theta}{\sin 45° + \cos 45° \tan\theta} \quad (1)$$

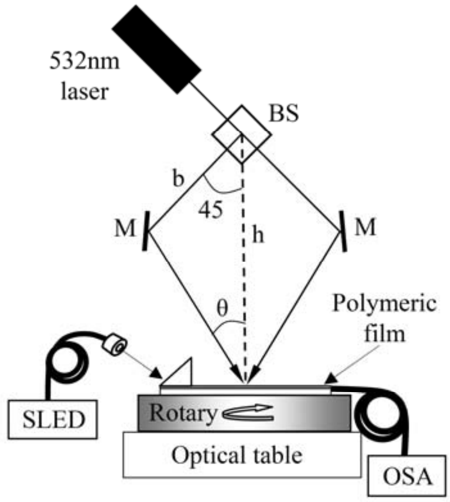

Fig. 2 Experimental setup used to form tilted Bragg gratings. M is mirror, BS is beam splitter, SLED is the Super-luminescent Light Emitting Diode, and OSA is Optical Spectrum Analyzer.

The structures were formed using the interference pattern of two coherent, equal intensity laser beams at the surface of the polymeric film. The formula given below expresses the intensity distribution pattern of two interfering, coherent, equal intensity laser beams:

$$I = |E_1|^2 + |E_2|^2 + E_1 E_2^* + E_1^* E_2 \quad (2)$$

where I is the intensity of light, and E_1 and E_2 are electric fields of each incident beam, propagating at angles of θ and $-\theta$ with respect to the z axis, the normal to the polymeric film plane. Defining E_1 and E_2 at point x of polymeric film as Eq. (3) and (4), substituting them into Eq. (2) and putting z equal to zero, Eq. (5) will be obtained:

$$E_1 = E_0 e^{-jk(x\sin\theta + z\cos\theta)} \quad (3)$$

$$E_2 = E_0 e^{-jk(-x\sin\theta + z\cos\theta)} \quad (4)$$

$$I = 2|E_0|^2 \left(1 + \cos\left(2kx \sin\theta\right)\right) \quad (5)$$

where E_0 is the magnitude of electric field in each light beam and k is the wave number.

The period of the written structures, Λ, is given by the Bragg formula which can be obtained simply from equation. (5):

$$\Lambda = \frac{\lambda_w}{2\sin\theta} \quad (6)$$

where λ_w is the wavelength of the writing laser beam.

To write the periodic structure in the depth of the polymeric film we used the beam of doubled Nd:YAG with 532 nm wavelength which is at the edge of the absorption band of the polymeric material (see Fig. 1**).** To fabricate a 2-D Photonic crystal with a certain periodicity, the length of the arms b was set for a desired θ. We then exposed the sample by the writing laser beams with 15 mw power in each arm. An initial 1-D structure was formed after 20 seconds, reflecting the wavelength of 1554 nm by 19.3 dB of attenuation, which is equivalent to a reflectivity of about 99%. The frequency response of this structure is shown in Fig. 3. To make a two dimensional photonic crystal, the sample and coupling apparatus mounted on rotary stage. The rotary stage was rotated by 90° and another 1-D *grating* structure was written on the first one by the same method. This way, a two dimensional rectangular optical structure is obtained, which is the linear addition of Eq. (5) in two different directions of "x" and "y".

Considering the fact that the change of the refractive index is proportional to the intensity of incident light, the change of refractive index in each writing step can be written as Eq. (7) and (8), where Eq. (5) has been used:

$$\Delta n_x \propto \left(1+\cos\left(2kx\sin\theta\right)\right) \quad (7)$$

$$\Delta n_y \propto \left(1+\cos\left(2ky\sin\theta\right)\right) \quad (8)$$

where Δn_x and Δn_y are the changes of refractive index in "x" and "y" directions. The total change of refractive index at point *(x,y)* of the polymeric film is given as Eq. (9):

$$\begin{aligned}\Delta n(x,y) &\propto \Delta n_x + \Delta n_y \\ &\propto 2+\cos\left(2kx\sin\theta\right)+\cos\left(2ky\sin\theta\right)\end{aligned} \quad (9)$$

where $\Delta n(x,y)$ is the change of refractive index at point *(x,y)*. Therefore the total refractive index *n(x,y)* is the sum of the film refractive index, n_0, plus the optically induced change in the refractive index, $\Delta n(x,y)$. Another word we can write:

$$n(x,y) = n_0 + \Delta n\left(x,y\right) \quad (10)$$

By calculating *sinθ* from Eq. (6) and substituting it in Eq. (9) we get the total index modulation of the polymer film as given below:

$$n(x,y) = n_0 + \Delta n\left(\frac{2+\cos\left(2\pi x/\Lambda\right)+\cos\left(2\pi y/\Lambda\right)}{4}\right) \quad (11)$$

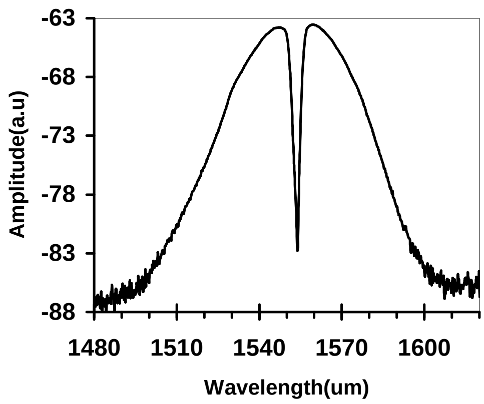

Fig. 3 Frequency response of a 1-D grating structure.

III. RESULTS

To examine the frequency response of the written structures, we used the broadband spectrum of a fiber-coupled, super-luminescent light emitting diode (SLED) with the center frequency of 1560 nm and full-width at half-maximum (FWHM) of about 60 nm. The output light of the SLED was coupled into the film using a prism coupler at the TE mode angle of the film. The output signal from the film was delivered to an Optical Spectrum Analyzer (OSA) using a single mode fiber.

We coupled the output light of the SLED in to the film in two perpendicular directions whose intersection was at the center of the photonic crystal structure. The output light of each direction was delivered to the OSA by the single mode fiber. The frequency response of these paths is shown in Fig. 4. As expected, the resonant wavelengths of 2-D structure in both directions were exactly the same and equal to that of initial 1-D structure (i.e. 1554 nm). The reflectivity of the structure in each direction of coupling was 85% (8.2dB) and 92% (11dB) respectively.

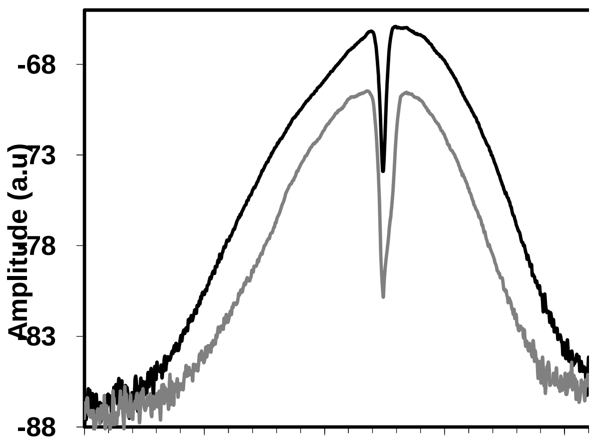

Fig. 4 Frequency response of a 2-D rectangular photonic crystal. The photonic crystal reflects wavelength of 1554 nm in both directions at attenuations of 8.2 dB and 11 dB.

We were able to photograph our structure using two cross polarizers. Since the period of the actual structure of our PC is less than the resolution of our optical microscope we fabricated a structure with a larger period of about 1.5 μm. We were able to photograph this structure of our PC as shown in Fig. 5. The intensity of this figure, shows the refractive index modulation of the polymeric film. The inset shows the diffraction pattern of the structure. This pattern was formed by exposing the structure with a He-Ne laser with a wavelength of 632 nm. The first order modes of diffraction are shown in the picture, indicating a square periodic structure.

Using the photograph shown in Fig. 5 and the fact that a cross-polarized microscope converts the index modulation to intensity modulation, we obtained the intensity modulation pattern of Fig. 5 in two perpendicular directions shown in this figure by "x" and "y". These intensity modulation patterns and sinusoidal curves fitting to them are shown in Fig. 6. As expected, the curves were fitting well to the intensity pattern, which proves that the index modulation pattern has a sinusoidal form in both directions.

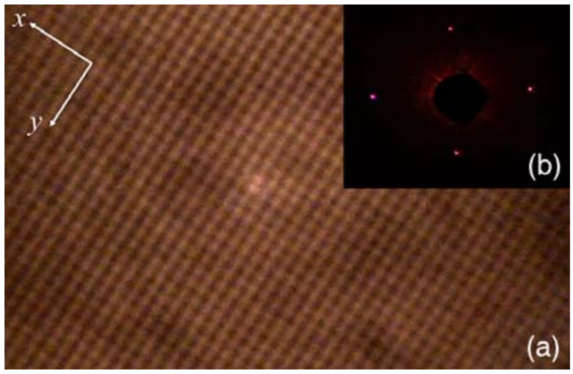

Fig. 5 photograph of an actual fabricated 2-D rectangular structure, as observed under polarizing microscope. The inset shows the diffraction pattern of this photonic crystal obtained exposing the PC to a HeNe laser.

We can define our refractive index modulation pattern in the form of Eq. (11). This pattern of refractive index is plotted in Fig. 7.

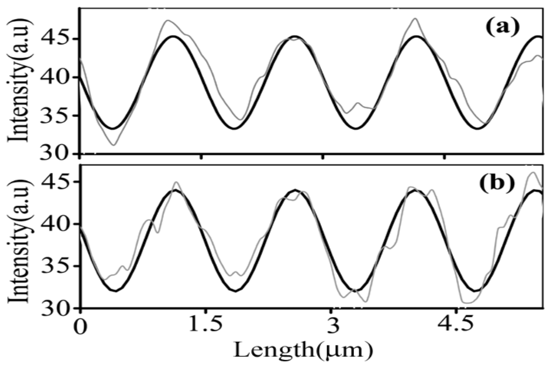

Fig. 6 Intensity modulation of the captured photograph of written photonic crystal (gray lines) and sinusoidal curves fitted to them (dark lines); (a) in "x" direction, and (b) in "y" direction.

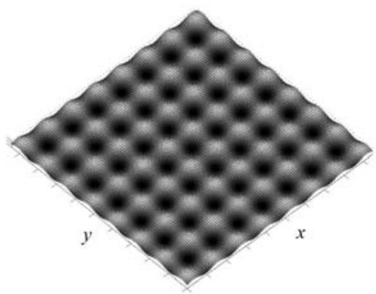

Fig. 7 Refractive index modulation pattern of written structures, simulated by a computer program.

IV. CONCLUSION

In this experiment we have fabricated a 2-D rectangular polymeric photonic crystal using the interference pattern of the coherent laser beams and the photoinduced birefringence in Polyimides functionalized with azo chromophores due to the reorientation of the azo chromophores by the *cis-trans* isomerization process. The frequency response of the written structure shows the 8.3 dB and 11 dB attenuation in the main axes of the periodic structure. The photograph of the structure was shown which obtain using two cross polarizer and also diffraction pattern of the structure for wavelength of 632 nm (HE-Ne laser) was shown in this figure. Using this pattern, the rectangular nation of fabricated structure was verified.

REFERENCES

[1] D. W. Prather, S. Shi, J. Murakowski, G. J. Schneider, A. Sharkawy, C. Chen, and B. Miao, "Photonic Crystal Structures and Applications: Perspective, Overview, and Development," *IEEE J. of Selec. Topics in Quantum Electron.*, Vol. 12, pp. 1416-1437, 2006.

[2] S. Noda, "Recent Progresses and Future Prospects of Two- and Three-Dimensional Photonic Crystals," *IEEE J. Lightwave Technol.*, Vol. 24, pp. 4554-4567, 2006.

[3] S. Noda, M. Imada, M. Okano, S. Ogawa, M. Mochizuki, and A. Chutinan, "Semiconductor Three-Dimensional and Two-Dimensional Photonic Crystals and Devices," *IEEE J. of Quantum Electron.*, Vol. 38, pp. 726-735, 2002.

[4] Y. K. Kim, A. J. Danner, J. J. Raftery, and K. D. Choquette, "Focused Ion Beam Nanopatterning for Optoelectronic Device Fabrication," *IEEE J. of Selec. Topics in Quantum Electron.*, Vol. 11, pp. 1292-1298, 2005.

[5] O. Painter, A. Husain, A. Scherer, P. T. Lee, I. Kim, J. D. O'Brien, and P. D. Dapkus, "Lithographic Tuning of a Two-Dimensional Photonic Crystal Laser Array," *IEEE Photon. Technol. Lett.*, Vol. 12, pp. 1126-1128, 2000.

[6] J. Stodolka, D. Nau, M. Frommberger, C. Zanke, H. Giessen, and E. Quandt, "Fabrication of two-dimensional hybrid photonic crystals utilizing electron beam lithography," *Microelectron. Eng.*, Vol. 78-79, pp. 442-447, 2005.

[7] R. Steingruber, S. Golka, and H. Heidrich, "Useful and cost efficient fabrication of dot arrays for photonic crystals by direct write electron-beam lithography," *Microelectron. Eng.*, Vol. 67-68, pp. 157-161, 2003.

[8] T. Liu, M. Fallahi, J. V. Moloney, and M. Mansuripur, "Fabrication of two-dimensional photonic crystals with embedded defects using blue-laser-writer and holography," *Microelectron. Eng.*, Vol. 83, pp. 1778-1781, 2006.

[9] X. Zhang, S. Liu, and Y. Liu, "Fabrication of large-area 3D photonic crystals using a holographic optical element," *Optics and Lasers in Eng.*, Vol. 44, pp. 903–911, 2006.

[10] M. Belotti, M. Galli, D. Bajoni, L.C. Andreani, G. Guizzetti, D. Decanini, and Y. Chen, "Investigation of SOI photonic crystals fabricated by both electron-beam lithography and nanoimprint lithography," *Microelectron. Eng.*, Vol. 73-74, pp. 405–411, 2004.

[11] C.–G. Choi, C.–S. Kee, and H. Schift, "Fabrication of polymer photonic crystal slabs using nanoimprint lithography," *Current Appl. Phys.*, Vol. 6, pp. e8–e11, 2006.

[12] H. Karimi–Alavijeh, G.–M. Parsanasab, M.–A. Baghban, E. Sarailou, A. Gharavi, S. Javadpour, and V. Shkunov, "Fabrication of graded index waveguides in azo polymers using a direct writing technique," *Appl. Phys. Lett.*, Vol. 92, pp. 041105(1-3), 2008.

[13] Y.-Y. Lin, C. Cheng, H.-H. Liao, S.-F. Horng, H.–F. Meng, and C.–S. Hsu, "Integration of polymer light-emitting diode and polymer waveguide on Si substrate," *Appl. Phys. Lett.*, Vol. 89, pp. 063501(1-3), 2006.

[14] S.-K. Kim, Y.-C. Hung, W. Yuan, D.–H. Cha, K. Geary, H. R. Fetterman, S. M. Ha, Q. Pei, J. Luo, X.-H. Zhou, A. K.-Y. Jen, M.-S. Kwon, and W. H. Steier, "Metal-slotted polymer optical waveguide device," *Appl. Phys. Lett.*, Vol. 90, pp. 243507-243509, 2007.

[15] J.-W. Kang, J.-J. Kim, and E. Kim, "All-optical Mach–Zehnder modulator using a photochromic dye-doped polymer," *Appl. Phys. Lett.*, Vol. 80, pp. 1710-1712, 2002.

[16] R. Song and W. H. Steier, "Overlap integral factor enhancement using buried electrode structure in polymer Mach-Zehnder modulator," *Appl. Phys. Lett.*, Vol. 92, pp. 031103(1-3), 2008.

[17] D. Suh, H. Ryu, Y. Park, and M. C. Paek, "Ultraviolet-replicated focusing grating coupler in polymers at a wavelength of 405 nm," *Appl. Phys. Lett.*, Vol. 87, pp. 161111(1-3), 2005.

[18] E. Sarailou, A. Gharavi, S. Javadpour, V. Shkunov, "Grating based electro-optic switch with azo nonlinear optical polymers," *Appl. Phys. Lett.*, Vol. 89, pp. 171114(1-3), 2006.

[19] D.-H. Kim, W.-J. Chin, S.-S. Lee, S.-W. Ahn, and K.-D. Lee, "Tunable polymeric Bragg grating filter using nanoimprint technique," *Appl. Phys. Lett.*, Vol. 88, pp. 071120(1-3), 2006.

[20] T. Kobayashi, Y. Kanamori, and K. Hane, "Surface laser emission from solid polymer dye in a guided mode resonant grating filter structure," *Appl. Phys. Lett.*, Vol. 87, pp. 151106(1-2), 2005.

[21] A. Gharavi, H. Karimi-Alavijeh, E. Sarailou, M.–A. Baghban, and G.–M. Parsanasab, "Fabrication of 2-D photonic crystals on aso polymers," *Proceedings of the 14th Iranian conference on Optics and Photonics*, pp. 170-173, 2008.

[22] J. H. Wülbern, M. Schmidt, M. Eich, U. Hübner, R. Boucher, F. Marlow, and W. Volksen, "Omnidirectional photonic band gap in polymer photonic crystal slabs," *Appl. Phys. Lett.*, Vol. 91, pp. 221104(1-3), 2007.

[23] V. Reboud, P. Lovera, N. Kehagias, M. Zelsmann, G. Redmond, and C. M. Sotomayor Torres, "Two-dimensional polymer photonic crystal band-edge lasers fabricated by nanoimprint lithography," *Appl. Phys. Lett.*, Vol. 91, pp. 151101(1-3), 2007.

[24] H. Saadeh, A. Gharavi, D. Yu, and L. Yu, "Polyimides with a Diazo Chromophore Exhibiting High Thermal Stability and Large Electrooptic Coefficients," *Macromolecules*, Vol. 30, pp. 5403-5407, 1997.

substrate," *Appl. Phys. Lett.*, Vol. 89, pp. 063501(1-3), 2006.

[14] S.-K. Kim, Y.-C. Hung, W. Yuan, D.–H. Cha, K. Geary, H. R. Fetterman, S. M. Ha, Q. Pei, J. Luo, X.-H. Zhou, A. K.-Y. Jen, M.-S. Kwon, and W. H. Steier, "Metal-slotted polymer optical waveguide device," *Appl. Phys. Lett.*, Vol. 90, pp. 243507-243509, 2007.

[15] J.-W. Kang, J.-J. Kim, and E. Kim, "All-optical Mach–Zehnder modulator using a photochromic dye-doped polymer," *Appl. Phys. Lett.*, Vol. 80, pp. 1710-1712, 2002.

[16] R. Song and W. H. Steier, "Overlap integral factor enhancement using buried electrode structure in polymer Mach-Zehnder modulator," *Appl. Phys. Lett.*, Vol. 92, pp. 031103(1-3), 2008.

[17] D. Suh, H. Ryu, Y. Park, and M. C. Paek, "Ultraviolet-replicated focusing grating coupler in polymers at a wavelength of 405 nm," *Appl. Phys. Lett.*, Vol. 87, pp. 161111(1-3), 2005.

[18] E. Sarailou, A. Gharavi, S. Javadpour, V. Shkunov, "Grating based electro-optic switch with azo nonlinear optical polymers," *Appl. Phys. Lett.*, Vol. 89, pp. 171114(1-3), 2006.

[19] D.-H. Kim, W.-J. Chin, S.-S. Lee, S.-W. Ahn, and K.-D. Lee, "Tunable polymeric Bragg grating filter using nanoimprint technique," *Appl. Phys. Lett.*, Vol. 88, pp. 071120(1-3), 2006.

[20] T. Kobayashi, Y. Kanamori, and K. Hane, "Surface laser emission from solid polymer dye in a guided mode resonant grating filter structure," *Appl. Phys. Lett.*, Vol. 87, pp. 151106(1-2), 2005.

[21] A. Gharavi, H. Karimi-Alavijeh, E. Sarailou, M.–A. Baghban, and G.–M. Parsanasab, "Fabrication of 2-D photonic crystals on aso polymers," *Proceedings of the 14th Iranian conference on Optics and Photonics*, pp. 170-173, 2008.

[22] J. H. Wülbern, M. Schmidt, M. Eich, U. Hübner, R. Boucher, F. Marlow, and W. Volksen, "Omnidirectional photonic band gap in polymer photonic crystal slabs," *Appl. Phys. Lett.*, Vol. 91, pp. 221104(1-3), 2007.

[23] V. Reboud, P. Lovera, N. Kehagias, M. Zelsmann, G. Redmond, and C. M. Sotomayor Torres, "Two-dimensional polymer photonic crystal band-edge lasers fabricated by nanoimprint lithography," *Appl. Phys. Lett.*, Vol. 91, pp. 151101(1-3), 2007.

[24] H. Saadeh, A. Gharavi, D. Yu, and L. Yu, "Polyimides with a Diazo Chromophore Exhibiting High Thermal Stability and Large Electrooptic Coefficients," *Macromolecules*, Vol. 30, pp. 5403-5407, 1997.