International Journal of Optics and Photonics (IJOP)

A pubication of Optics and Photonics Society of Iran (OPSI)

SUMMER-FALL 2016 VOLUME 10 NUMBER 2

In the name of God, the Compassionate, the Merciful

International Journal of Optics and Photonics (IJOP)

ISSN: 1735-8590

International Journal of Optics and Photonics (IJOP) is an open access journal published by the Optics and Photonics Society of Iran (OPSI). It is published online semiannually and its language is English. All publication expenses are paid by OPSI, hence the publication of paper in IJOP is **free of charge.**

For information on joining the OPSI and submitting papers, please visit **http://www.ijop.ir, http://www.opsi.ir**, or contact the society secretarial office via **info@opsi.ir**.

All correspondence and communication for Journal should be directed to:

IJOP Editorial Office
Optics and Photonics Society of Iran (OPSI)
Tehran, 1464675945, Iran
Phone: (+98) 21-44292731
Fax: (+98) 21-44255936
Email: info@ijop.ir

Photonic Crystal-Based Polarization Converter for Optical Communication Applications

Mahmoud Nikoufard and Mohsen Hatami

Department of Electronics, Faculty of Electrical and Computer Engineering,
University of Kashan, Kashan, Iran

Corresponding Author Email: mnik@kashanu.ac.ir

Received: Dec. 31, 2015, **Revised:** May 12, 2016, **Accepted:** Jun. 26, 2016, **Available Online:** Nov. 12, 2016
DOI: 10.18869/acadpub.IJOP.10.2.111

ABSTRACT— A photonic crystal-based TE to TM polarization converter for integrated optical communication is proposed in this paper. The photonic crystal consists of air circular-holes in slab waveguide. The radius of holes are determined to be 291nm having lattice constant of 640nm using the gap map and band diagram. The polarization converter is composed of an InGaAsP triangular-shaped waveguide on SiO_2 substrate. At first, the bandgap wavelengths of two-dimensional structure are determined using finite difference method and then polarization conversion length, polarization conversion efficiency and rotation are determined as a function of the ratio of height to width of the triangle waveguide. The simulation results show a minimum conversion length of 750nm with a conversion efficiency of about 90% could be obtained.

KEYWORDS: hybrid technology, InP material, photonic crystal, polarization converter, triangular waveguide.

I. INTRODUCTION

Photonic crystal has attracted a lot of attention during last decades because of miniaturizing the photonic integrated circuits toward the nanoscale dimensions. Meanwhile, the strong polarization dependence of the wave propagation inside the photonic crystal is available due to the structural anisotropy [1] and the vectorial nature of the electromagnetic waves. So, controlling the polarization of the propagating light in the photonic crystal circuits is mandatory [2, 3]. One of interesting devices utilized for manipulating the polarization dependent properties of photonic crystal is a polarization rotator.

Several types of photonic crystal-based polarization converters have been reported. Laroche *et al.* [4] show that a photonic crystal slab have capability of efficient polarization conversion. This capability results from two mechanisms of the anisotropy of the bulk material and the resonant excitation of leaky surface waves at the interface of the photonic crystal. A photonic crystal-based polarization converter for Terahertz applications is realized on Si Technology [5]. This polarization converter utilizes asymmetric loaded triangular slab waveguide with square-hole. It achieved more than 15dB extinction ratio in the frequency range of 198-208GHz. A three dimensional (3D) photonic crystal polarization converter was proposed which converts transverse electric (TE) mode to the transverse magnetic (TM) mode via a hollow-core waveguide for a 25µm long device and 98% conversion efficiency [6]. Other polarization converters are also realized in various materials and technologies such as $LiNbO_3$ [7], InP [2, 8, 9], silicon-on-insulator (SOI) [10-12], and membrane technologies [2, 13, 14]. These polarization converters utilize periodic loaded waveguide [15, 16], slanted-sidewall [17, 18] and asymmetric cross-section bend waveguide [19]. Recently, we have reported the smallest polarization rotator with a length of about 1µm on hybrid technology of silicon-on-insulator and InP [20].

In this paper, a photonic crystal-based polarization rotator on hybrid technology of

SOI/InP is presented. The main objective of this paper is to take advantage of strong guiding characteristic and compactness of a photonic crystal slab waveguide with a slanted-sidewall waveguide to implement an ultra-compact TE to TM polarization rotator. To accomplish this goal, for the first time, the proposed device is analyzed using rigorous finite-element method (FEM) on a three-dimension (3D) structure.

II. POLARIZATION CONVERTOR GEOMETRY

The 2D and 3D-geometry of the photonic crystal having a hexagonal lattice with a lattice constant of *a* is shown in Fig. 1. It consists of air holes (with radius *r*) in a high index dielectric medium. The layer stack of background medium is composed of an InGaAsP core layer with a thickness of *h* and a refractive index of n_f=3.5323 on SiO_2 substrate with a refractive index of n_s=1.444 and cladding layer of air. The light confines in InGaAsP layer and propagates in z-direction.

The triangular polarization rotator shown in Fig. 2(a) exhibits a scalene right-angled triangle whose altitude, side length, and interior angle are *h*, *w*, and θ, respectively. The first and second modes have the optical axes plotted in Fig. 2(b) that are tilted with respect to the usual TE and TM polarization orientation.

The photonic crystal based polarization converter is created with a combination of the hexagonal lattice photonic crystal and by removing one row of holes and then replacing of the line defect with a structure of the scalene right-angled triangle with a side angle of θ. This asymmetric structure brings about huge birefringence and generates two eigenmodes. These modes propagate with different propagation constants. After half of beat length, the rotated modes recombine to a TM (or TE) mode in an output waveguide.

III. SIMULATION RESULTS

The bandgap of photonic crystal-based polarization converter is determined using plane wave expansion method for transverse electric (TE) and transverse magnetic (TM) modes. In this method, we solve the Maxwell's equations by formulating an eigenvalue problem out of the equation. This method determines the dispersion relation of specific photonic crystal geometries and calculate the modal solutions of Maxwell's equations.

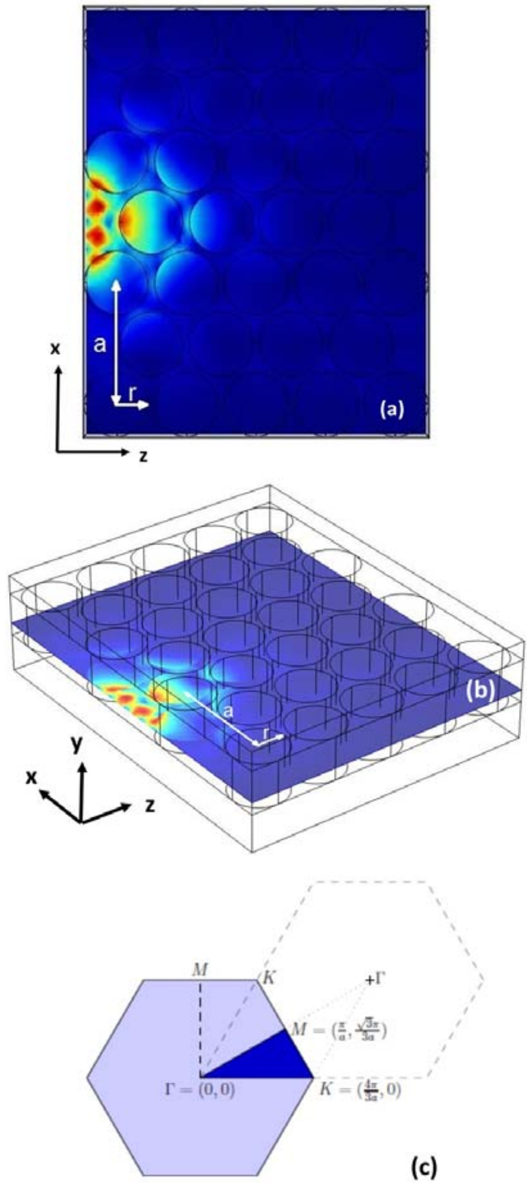

Fig. 1. (a) The triangular 3D-photonic crystal slab waveguide. (b) top-view (c) layer specification. The propagation of incident light in bandgap wavelength of 1.55µm is shown which cannot propagate through the air-hole photonic crystal structure. (c) primitive unit cell with the corresponding Brillouine zones.

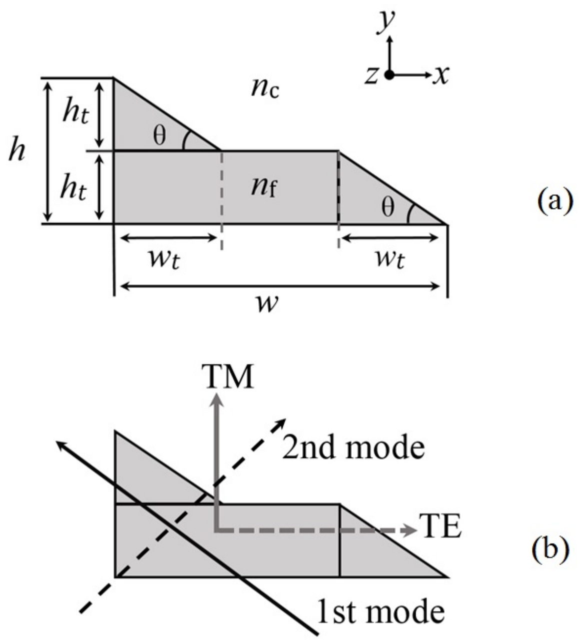

Fig. 2. (a) 2D lateral cross-section of the proposed polarization converter. (b) The direction of first and second modes.

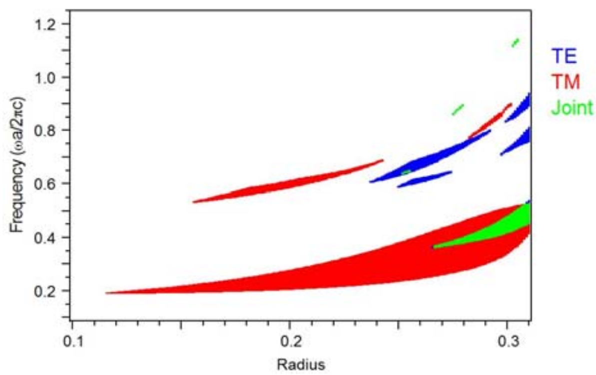

Fig. 3. Photonic bandgap versus radius for TE and TM modes.

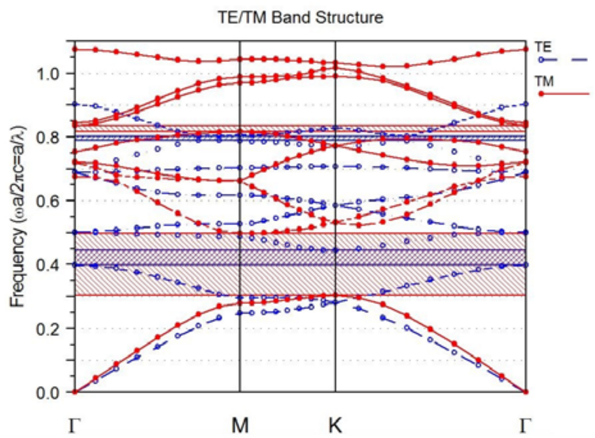

Fig. 4. Band diagram of both TE (dashed) and TM (solid) modes.

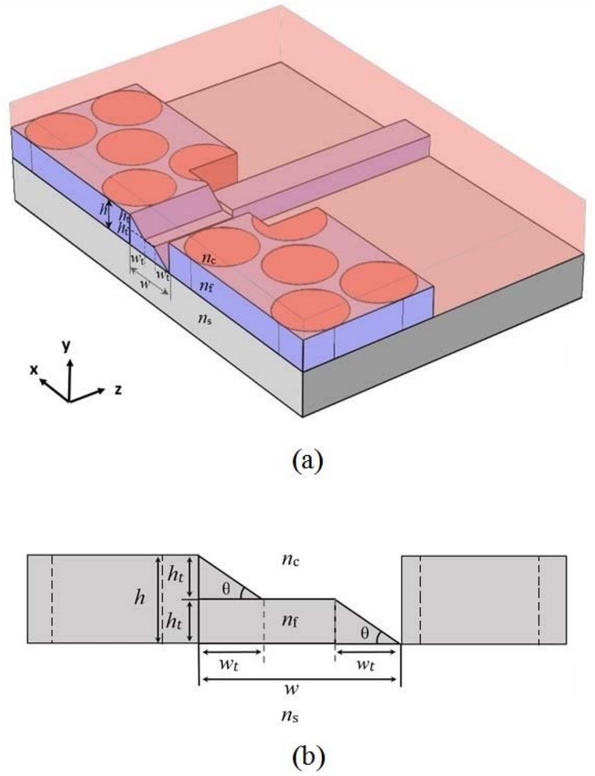

Fig. 5. The sketch of slanted-sidewall polarization rotator in photonic crystal structure (a) 3D-view (b) lateral cross-section.

The bandgap of this structure is determined using plane wave expansion method for transverse electric (TE) and transverse magnetic (TM) modes having a radius range of 0.01 to 0.31 and a lattice constant of a=640nm utilizing RSOFT Bandsolve software shown in Fig. 3. This figure illustrates that the photonic bandgap is larger for a hole with a radius of 291nm for TE and TM polarizations. At this radius, the normalized frequency lays between 0.36 and 0.42 (equal to a wavelength range of 1.523μm to 1.77μm). Also, the band structure is determined for a lattice constant of a=640nm and a radius of r=291nm in K-direction (Γ-M-K-Γ) for TE and TM modes (Fig. 4). To have maximum accuracy the grid size in the x- and z-directions (Δx and Δz) are set to Δx=Δz=0.035a=20nm. A 6 ×6 supercell has been used for the FEM calculations reported in this section. The estimated errors are kept less than 10^{-9} in all simulations.

Figure 5(a) shows 3D-schematic view of the photonic crystal-based triangular TE to TM polarization converter which is composed of a dielectric triangular waveguide. The cross-section of the TE to TM polarization converter is a polygon (shown in Fig. 1(b)) with a right angle and the altitude, side length, and interior angle of h, w, and θ, respectively. Two right-angled triangles inside the polygon have the altitude and side length of h_t and w_t, respectively. The slanted sidewall is considered 35^o for InGaAsP materials due to using wet chemical etch on the crystallographic plane of (001).

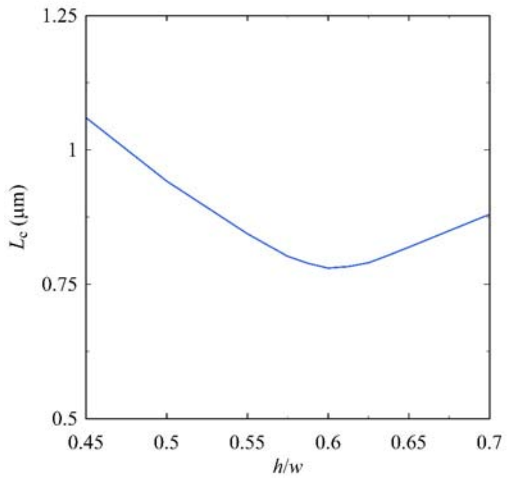

Fig. 6. Polarization conversion length as a function of h/w for w=528nm.

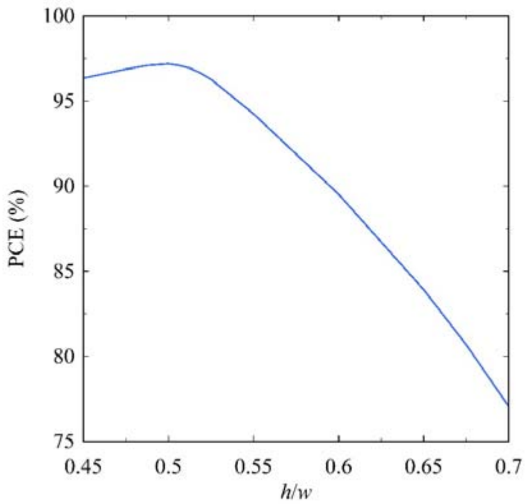

Fig. 7. Polarization conversion efficiency as a function of h/w for w=528nm

In Fig. 6, the conversion length is calculated as a function of h/w using 3D-finite element method (FEM) utilizing Comsol software for w=523nm at 1.55µm wavelength. The FEM area is surrounded by a perfect conductor and the mesh size used for analysis is chosen to be 20 nm for the x-, y-, and z-directions. Also, the mesh-size is chosen large enough so that increasing it further does not have any noticeable impact on the numerical results. It demonstrates that the conversion length has a minimum value of 720nm for h/w=0.6. The polarization conversion efficiency (PCE), defined as PCE(%)= $P_{TE}/(P_{TE}+P_{TM})$, reaches to a maximum of 92% for h/w=0.5 shown in Fig. 7.

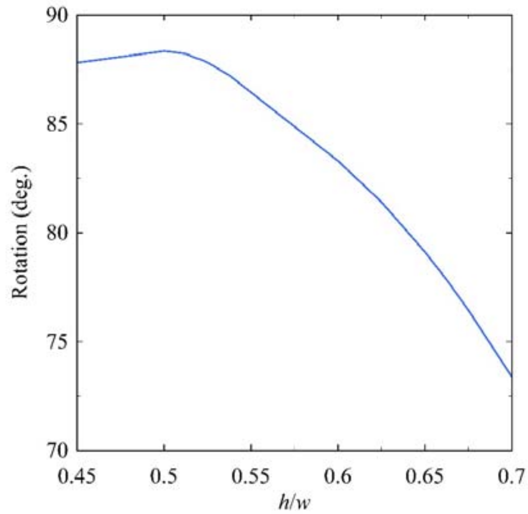

Fig. 8. The maximum rotation angle as a function of h/w for w=528nm

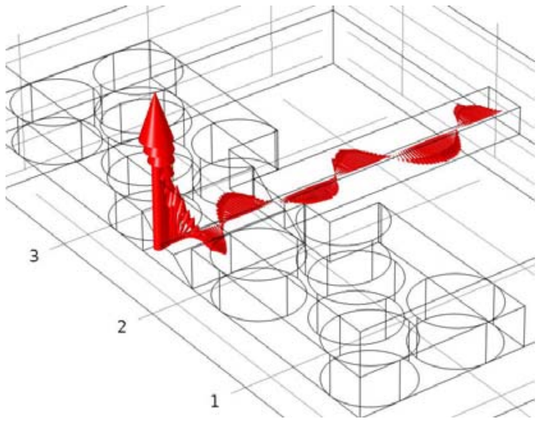

Fig. 9. The rotation of electric field through the polarization converter and photonic crystal defect for h/w=0.6

The maximum rotation as a function of h/w is presented in Fig. 8 whose behavior is similar to PCE. It can be seen that for the minimum conversion length of L_c=720nm, the PCE and maximum rotation are 89.51% and 83.3^o, respectively.

The electric field rotation in the propagation direction (z-axis) is demonstrated in Fig. 9. It can be observed that the incident TE-electric field has been rotated into TM mode for a conversion length of 750nm for w=528nm, h=0.6w=317nm, and w_t=226nm.

IV. Conclusion

In this work, we have presented a photonic crystal-based TE to TM polarization converter for optical communication applications. The proposed device is suitable for hybrid integration of silicon on insulator (SOI) and InP technologies. This structure has simulated using finite element method in a 3D structure. We have demonstrated numerically that the polarization converter length can be decreased up to 750nm, the smallest value which have reported so far.

References

[1] N. Ouchani, D. Bria, B. Djafari-Rouhani, and A. Nougaoui, “Transverse-electric/transverse-magnetic polarization converter using 1D finite biaxial photonic crystal,” J. Opt. Soc. Am. A, Vol. 24, pp. 2710-2718, 2007.

[2] J. Pello, J. van de Tol, G. Roelkens, H. Ambrosius, and M.K. Smit, “Design of a new ultra-small polarization converter in InGaAsP/InP membrane,” in 15th European conference on Integrated Optics (ECIO 2010), 2010.

[3] J. Yamauchi, M. Yamanoue, and H. Nakano, “A short polarization converter using a triangular waveguide,” J. Lightw. Technol. Vol. 26, pp. 1708-1714, 2008.

[4] M. Laroche, F. Marquier, C. Vandenbem, and J.-J. Greffet, “Polarization conversion with a photonic crystal slab,” J. the Europ. Opt. Soc.-Rapid Pub. Vol. 3, pp. 08038 (1-4), 2008.

[5] K. Bayat, G.Z. Rafi, G.S. Shaker, N. Ranjkesh, S. K. Chaudhuri, and S. Safavi-Naeini, “Photonic-crystal-based polarization converter for terahertz integrated circuit,” IEEE Trans. Microwave Theory Techn. Vol. 58, pp. 1976-1984, 2010.

[6] J. Wang and M. Qi, “Design of a compact mode and polarization converter in three-dimensional photonic crystals,” Opt. Express, Vol. 20, pp. 20356-20367, 2012.

[7] R. Alferness and L. Buhl, “High-speed waveguide electro-optic polarization modulator,” Opt. Lett. Vol. 7, pp. 500-502, 1982.

[8] F. Groen, Y. Zhu, and J. van der Tol, “Compact polarisation converter on InP/InGaAsP using an asymmetrical waveguide,” in 11th European Conference on Integrated Optics (ECIO’03), pp. 141-144, 2003.

[9] Y. Zhu, F. Groen, D. Maat, X. Leijtens, and M.K. Smit, “Design of a short polarization converter on InP/InGaAsP using asymmetrical waveguides,” in Proceedings 2000 IEEE/LEOS Symposium Benelux Chapter, pp. 227-230, 2000.

[10] K. Bayat, S. K. Chaudhuri, S. Safavi-Naeini, and M.F. Baroughi, “SOI based photonic crystal polarization converter for terahertz frequency applications,” in Integrated Photonics and Nanophotonics Research and Applications, p. ITuC3, 2009.

[11] C. Brooks, P.E. Jessop, H. Deng, D.O. Yevick, and G. Tarr, “Passive silicon-on-insulator polarization-rotating waveguides,” Optical engineering, Vol. 45, pp. 044603-044603-5, 2006.

[12] H. Deng, D. O. Yevick, C. Brooks, and P. E. Jessop, “Fabrication tolerance of asymmetric silicon-on-insulator polarization rotators,” J. Opt. Soc. Am. A, Vol. 23, pp. 1741-1745, 2006.

[13] J. Pello, J. van der Tol, H. Ambrosius, P. van Veldhoven, M. Smit, S. Keyvaninia, and G. Roelkens, “Demonstration of an ultra-short polarization converter in InGaAsP/InP membrane,” in 16th European Conference on Integrated Optics (ECIO-2012), 2012.

[14] J. Pello, J. van der Tol, S. Keyvaninia, R. van Veldhoven, H. Ambrosius, G. Roelkens, and M. Smit, “High-efficiency ultrasmall polarization converter in InP membrane,” Optics letters, Vol. 37, pp. 3711-3713, 2012.

[15] W. Huang and Z. Mao, “Polarization rotation in periodic loaded rib waveguides,” IEEE J. Lightw. Technol. Vol. 10, pp. 1825-1831, 1992.

[16] Y. Shani, R. Alferness, T. Koch, U. Koren, M. Oron, B.I. Miller, and M.G. Young, "Polarization rotation in asymmetric periodic loaded rib waveguides," Appl. Phys. Lett. Vol. 59, pp. 1278-1280, 1991.

[17] M.F.O. Hameed and S.S. Obayya, "Design consideration of polarization converter based on silica photonic crystal fiber," IEEE J. Quantum Electron. Vol. 48, pp. 1077-1084, 2012.

[18] S.S. Obayya, B. Rahman, K.T. Grattan, and H.A. El-Mikati, "Improved design of a polarization converter based on semiconductor optical waveguide bends," Appl. Opt. Vol. 40, pp. 5395-5401, 2001.

[19] T. Cao, S. Chen, Y. Fei, L. Zhang, and Q.Y. Xu "Ultra-compact and fabrication-tolerant polarization rotator based on a bend asymmetric-slab waveguide," Appl. Opt. Vol. 52, pp. 990-996, 2013.

[20] M. Nikoufard and M. Hatami, "Ultra-short novel transverse magnetic to transverse electric polarization rotator in hybrid integration of InGaAsP/silicon-on-insulator technologies," Ind. J. Phys. Vol. 90, pp. 211-217, 2016.

Mahmoud Nikoufard received his B.Sc. degree in Electrical Engineering (Telecommunication Engineering) from Sharif University of Technology in 1990 and his M.Sc. degree in Telecommunication Engineering (fields and waves branch) from Tarbiat Modares University in 1994. He received his Ph.D. degree on the design and fabrication of monolithic integrated InP-based wavelength division multiplexing receivers at the Eindhoven University of Technology, Holland. He is a member of the academic staff of Kashan University, Iran, since 1995. His current research interests are focused on active and passive photonic integrated devices, hybrid integration of SOI and InP devices, photonic crystals, and plasmonics.

Mohsen Hatami received the master's degree in electronic engineering from University of Kashan, in 2014. His thesis research was carried on the hybrid integration of the silicon-on-insulator (SOI) and InP based polarization converter.

SCOPE

Original contributions relating to advances, or state-of-the-art capabilities in the theory, design, applications, fabrication, performance, and characterization of: Lasers and optical devices; Laser Spectroscopy; Lightwave communication systems and subsystems; Nanophotonics; Nonlinear Optics; Optical Based Measurements; Optical Fiber and waveguide technologies; Optical Imaging; Optical Materials; Optical Signal Processing; Photonic crystals; and Quantum optics, and any other related topics are welcomed.

INFORMATION FOR AUTHORS

International Journal of Optics and Photonics (IJOP) is an **open access** Journal, published online semiannually with the purpose of publication of original and significant contributions relating to photonic-lightwave components and applications, laser physics and systems, and laser-electro-optic technology. Please submit your manuscripts through the Web Site of the Journal (**http://www.ijop.ir**). Authors should include full mailing address, telephone and fax numbers, as well as e-mail address. Submission of a manuscript amounts to assurance that it has not been copyrighted, published, accepted for publication elsewhere, and that it will not be submitted elsewhere while under consideration.

MANUSCRIPTS

The electronic file of the manuscript including all illustrations must be submitted. The manuscript must be in double column with the format of **IJOP Paper Template** which for ease of application all over the world is in MS-Word 2003. The manuscript must include an abstract. The abstract should cover four points: statement of problem, assumptions, and methods of solutions, results and conclusion or discussion of the importance of the results. All pages, including figures, should be numbered in a single series. The styles for references, abbreviations, etc. should follow the IJOP format. For information on preparing a manuscript, please refer to the IJOP webpage at: **http://www.ijop.ir**.

Prospective authors are urged to read this instruction and follow its recommendations on the organization of their paper. References require a complete title, a complete author list, and first and last pages cited for each entry. All references should be archived material such as journal articles, books, and conference proceedings. Due to the changes of contents and accessibility over time, Web pages must be referenced as low as possible.

Figure captions should be sufficiently clear so that the figures can be understood without referring to the accompanying text. Lettering and details of the **figures** and **tables** should be large enough to be readily legible when the drawing is reduced to one-column width of the double column article. **Axes of graphs** should have self-explanatory labels, not just symbols (e.g., Electric Field rather than E). **Photographs** and **figures** must be glossy prints in electronic files with GIF or JPEG Formats.

Article Keywords are mandatory and must be included with all manuscripts. Please choose approximately 4 to 8 keywords which describe the major points or topics covered in your article.

COPYRIGHT TRANSFER FORM

Authors are required to sign an IJOP copyright transfer form before publication. *Authors must submit the signed copyright form with their manuscript.* The form is available online at **http://www.ijop.ir**

ISSN: 1735-8590

http://www.ijop.ir