International Journal of Optics and Photonics (IJOP)

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

WINTER-SPRING 2016 VOLUME 10 NUMBER 1

Papers' Titles and Authors **Pages**

Design and Construction of a Seismometer Based on the Moiré Technique: Detailed Theoretical Analysis, Experimental Apparatus, and Primary Results *3-10*

Saifollah Rasouli, Shamsedin Esmaeili, and Farhad Sobouti

Simulation of Light-Nanowire Interaction in the TE Mode Using Surface Integral Equations *11-18*

Masoud Rezvani Jalal and Maryam Fathi Sepahvand

All-Optical Reconfigurable-Tunable 1×N Power Splitter Using Soliton Breakup *19-29*

Amin Ghadi and Saeed Mirzanejhad

Tunable Schottky Barrier in Photovoltaic BiFeO3 Based Ferroelectric Composite Thin Films *31-35*

Seyed Mohammad Hosein Khalkhali, Mohammad Mehdi Tehranchi, and Seyedeh Mehri Hamidi

Self-Fields Effects on Gain in a Helical Wiggler Free Electron Laser with Ion-Channel Guiding and Axial Magnetic Field *37-46*

Hasan Ehsani Amri and Taghi Mohsenpour

Use of Zernike Polynomials and SPGD Algorithm for Measuring the Reflected Wavefronts from the Lens Surfaces *47-53*

Roghayeh Yazdani, Sebastian Petsch, Hamid Reza Fallah, and Morteza Hajimahmoodzade

A Systematic Approach to Photonic Crystal Based Metamaterial Design *55-64*

Saeed Pahlavan and Vahid Ahmadi

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)
P O Box 14395-115
Tehran, 1439663741, Iran
Phone: (+98) 21-44255936
Fax: (+98) 21-44255937
Email: info@ijop.ir

Use of Zernike Polynomials and SPGD Algorithm for Measuring the Reflected Wavefronts from the Lens Surfaces

Roghayeh Yazdani[a *], Sebastian Petsch[b], Hamid Reza Fallah[a c], and Morteza Hajimahmoodzade[a c]

[a]Department of physics, University of Isfahan, Isfahan, Iran.
[b]Gisela and Erwin Sick Chair of Micro-Optics, Department of Microsystems Engineering, University of Freiburg, Germany
[c]Quantum optics research group, University of Isfahan, Isfahan, Iran

[*]Corresponding Author Email: rh.yazdani@gmail.com

Received: Nov. 8, 2015; Revised: Jan. 3, 2016; Accepted: Jan. 19, 2016; Accepted: Apr. 30, 2016

ABSTRACT— **Recently, we have demonstrated a new and efficient method to simultaneously reconstruct two unknown interfering wavefronts. A three-dimensional interference pattern was analyzed and then Zernike polynomials and the stochastic parallel gradient descent algorithm were used to expand and calculate wavefronts. In this paper, as one of the applications of this method, the reflected wavefronts from two surfaces of a spherical lens are experimentally reconstructed.**

KEYWORDS: Interference pattern, Lens parameters; SPGD algorithm, Wavefront reconstruction.

I. INTRODUCTION

Various noninterferometric and interferometric methods have already been proposed for wavefront reconstruction because of its importance in a number of fields such as adaptive optics [1], optical testing [2], and microscopy [3]. The most commonly used noninterferometric techniques are based on the transport of intensity equation [4,5], moiré deflectometry [6,7], Shack–Hartmann wavefront sensor [8], pyramid wavefront sensor [9], and Gerchberg–Saxton algorithm [10]. A large variety of interferometric techniques is known, in which the wavefront is reconstructed by processing the interference patterns, such as shearing interferometry [11], phase conjugating method [12], and interfering with a known reference wavefront [2].

Reconstructing two unknown interfering wavefronts, without the reference wavefront, has already received much attention [13]–[18]. Two reconstructed interfering wavefronts can be applied to simultaneously test two surfaces of an optical element from which the interfering wavefronts are reflected or transmitted, and to find the parameters of an optical element such as the lens [13]. The measurements of lens parameters, such as focal length, radius of curvature, thickness, and refractive index of the lens material as well as the shape of the wavefront produced by a lens, are important for their proper selection in various applications.

Recently, we introduced and implemented a fast and accurate method for reconstructing two unknown interfering wavefronts based on Zernike polynomials and analyzing the interference patterns [17]. Here, we present another experimental verification of the proposed method, as one of its applications. In this application, the reflected wavefronts from two surfaces of a spherical lens are experimentally reconstructed. These reconstructed wavefronts can provide useful information to find the lens parameters or to test its surface's quality. In the following sections, we briefly describe the proposed method, and then report the experimental results.

II. THEORY

To reconstruct φ_1 and φ_2, the unknown phase distributions of two interfering waves in the paraxial approximation, we do the following steps:

1- Interference patterns at two parallel planes are recorded. These planes are perpendicular to the average propagation direction of these waves (z-axis) and located at z_1 and z_2.

2- Analyzing the recorded fringe patterns with a proper method, such as phase shifting and Fourier transform (FT) [2,19], the phase difference distributions (PDDs), $\Delta\varphi_{1\exp} = \varphi_{2z_1} - \varphi_{1z_1}$ and $\Delta\varphi_{2\exp} = \varphi_{2z_2} - \varphi_{1z_2}$ are derived at these two planes. φ_{iz_j} denotes the phase distribution of the ith wave at plane $z = z_j$.

3- φ_{1z_1} is expanded in terms of N Zernike polynomials [20]:

$$\varphi_{1z_1}(r,\theta) = \sum_{i=1}^{N} a_i Z_i(r,\theta), \tag{1}$$

where a_i is the coefficient of Zernike polynomial $Z_i(r,\theta)$. To start, guess the expansion coefficients, say $a_i = 0$. Therefore, φ_{1z_1} is determined from Eq. (1) and then φ_{2z_1} is obtained by

$$\varphi_{2z_1} = \varphi_{1z_1} + \Delta\varphi_{1\exp}. \tag{2}$$

4- Propagating two obtained wavefronts to the second observation plane at $z = z_2$, φ_{1z_2} and φ_{2z_2} can be reconstructed. Then, the PDD at the second plane is calculated by

$$\Delta\varphi_{2cal} = \varphi_{2z_2} - \varphi_{1z_2}. \tag{3}$$

5- Cost function C based on the difference between the measured and calculated PDDs $(E = \Delta\varphi_{2\exp} - \Delta\varphi_{2cal})$ is defined, such that if $E = 0$, then C is minimized. Cost function can be defined as

$$C = \overline{E} = \frac{\sum_{i=1}^{K}\sum_{j=1}^{L} E_{ij}}{KL}, \tag{4}$$

or

$$C = \sqrt{\overline{M}} \quad , \quad M = (E - \overline{E})^2, \tag{5}$$

where K and L are the number of pixels along the x and y directions at the observation planes, respectively.

6- The stochastic parallel gradient descent (SPGD) algorithm [21,22] is used to find the optimum Zernike coefficients of φ_{1z_1} in order to minimize the cost function.

III. EXPERIMENTS

A. *Experimental details and results*

We experimentally reconstructed two interfering wavefronts which were reflected from two surfaces of a spherical lens. A schematic of our experimental setup is shown in Fig. 1. The collimated laser beam with wavelength of 638nm (light source: RO-638-PLR-30, Ondax, USA) was focused by the lens L_1, and then was reflected from the test lens L_2 (Thorlabs, N-BK7 Plano-Convex Lens, focal length=60mm and diameter=25.4mm). Superimposing two spherical wavefronts, reflected from the surfaces of test lens, produced the required interference field. A camera (lw115, Lumenera Imaging Corp., Canada) was used to record the interference pattern. The camera plane, considered as the x–y plane, was perpendicular to the average propagation direction of wavefronts (z-axis). We displaced the camera along the z-axis with the precision of 0.01mm and recorded another interference pattern after an arbitrary displacement of $\Delta z = z_2 - z_1 = 3mm$. Finally, we selected a grid with 830 × 830 pixels from every recorded pattern for analyzing. The selected pattern at the first plane located at $z = z_1$ is shown in Fig. 2. The radial profile of interference intensity was obtained by averaging along every fringe (Fig. 3). The FT method [19] was used to calculate the PDDs at both observation planes. Figures 4 and 5 show the measured PDDs along the radius of fringe patterns at observations planes, and the quadratic curves fitting on them.

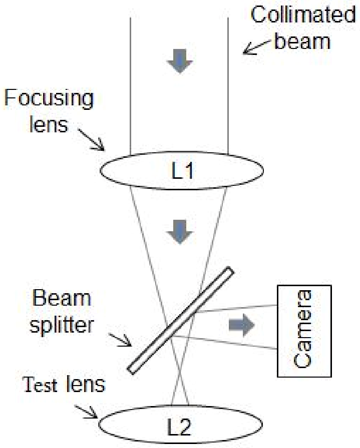

Fig. 1 Schematic diagram of the experimental setup.

In using the FT method to derive the PDD, if the fringe pattern includes low and different spatial frequencies, then its first harmonics in the Fourier space overlap the bias. So, separating the harmonics and consequently reconstructing the PDD are not accurate. To obtain a good result with FT method, a fringe pattern with a high carrier spatial frequency is a good option. Due to the finite aperture of camera and setup situation, if we selected a symmetric interference pattern around the central fringe, we missed the high spatial frequency fringes which were located far from center. This selection could reduce the accuracy of results. This limitation does not exist in the phase shifting method, which works with any fringe pattern. However, we did not have the required components to implement phase shifting, like a tunable light source.

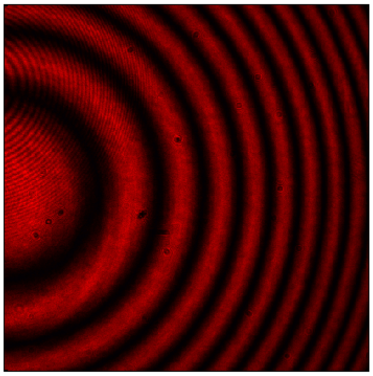

Fig. 2 Interference pattern at the first observation plane.

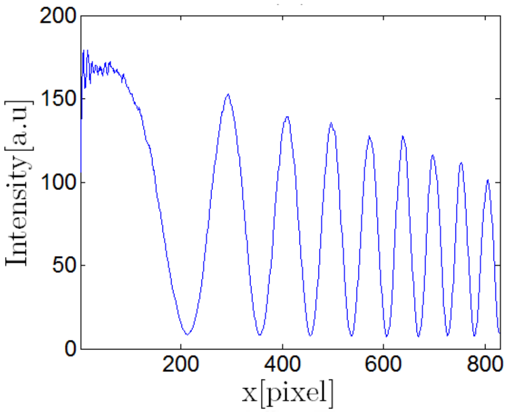

Fig. 3 Radial profile of intensity at the first observation plane.

According to the described technique in Section II, the interfering wavefronts were reconstructed from the PDDs which were multiplied by a circle function with diameter of 830 pixels. To start, a plane wavefront was selected as the initial guess for one of the wavefronts. The coefficients of the first 5 Zernike polynomials and Eq. (5) were considered as the unknown variables and the cost function in the SPGD algorithm, respectively. The ray-tracing method was used for wavefront propagation [23,24]. Figure 6 shows the cost function during the reconstruction process with the solid line. As expected, the cost function decreases with higher iteration number of the algorithm. The difference between the measured and reconstructed PDDs in the second plane decreases simultaneously. After 350 iterations, the peak to valley (PV) of this difference is 0.37rad which results in a relative error of 0.8% compared to the experimental PDD in the second plane with PV=46.64rad.

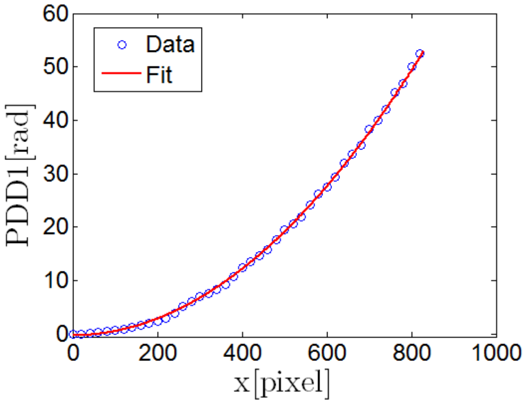

Fig. 4 Measured PDD (circles) and the fitted quadratic curve (solid line) along the radius of fringe pattern at the first observation plane.

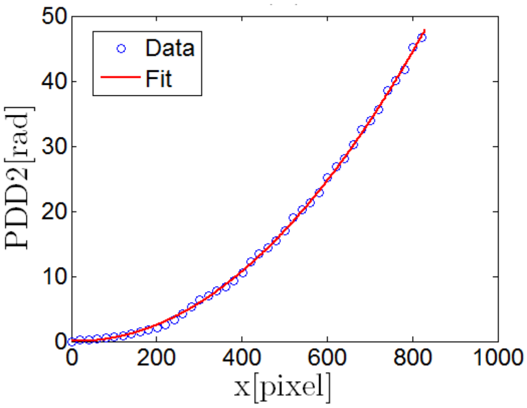

Fig. 5 Measured PDD (circles) and the fitted quadratic curve (solid line) along the radius of fringe pattern at the second observation plane.

The reconstructed phase distributions of interfering wavefronts in the first plane after 350 iterations are shown in Figs. 7 and 8. These results show two spherical wavefronts with different curvatures, which agree well with our predictions and so validate the proposed method.

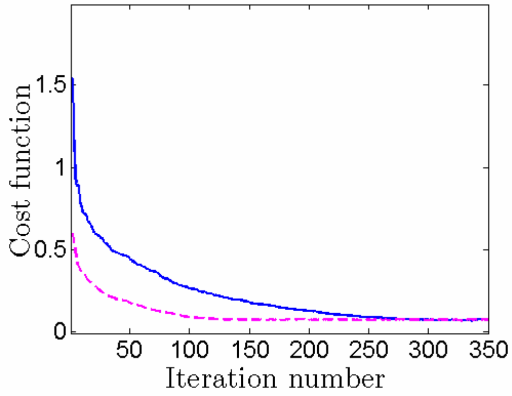

Fig. 6 Cost function during the reconstruction process, when the initial guess for one of the wavefronts is a plane wavefront (solid line) and a spherical wavefront with an arbitrary value of tilt (dashed line).

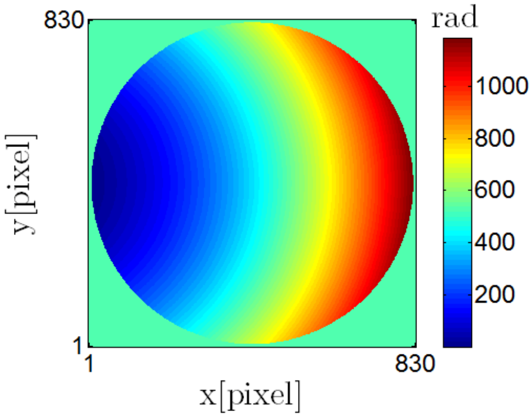

Fig. 7 Reconstructed phase distribution of the first wavefront.

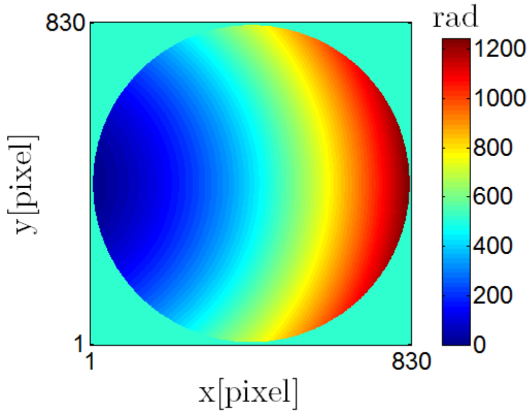

Fig. 8 Reconstructed phase distribution of the second wavefront.

B. *Convergence speed of algorithm*

In the obtained results, we considered a plane wavefront as the initial guess for one of the wavefronts in the beginning of algorithm. As this guess is close to the real wavefront, the convergence speed of algorithm is much faster. So, in the next step, we selected a spherical wavefront with an arbitrary value of tilt as the initial guess, and repeated the reconstruction process. The decreasing cost function in this case is shown with the dashed line in Fig. 6. Comparing the curves shown in Fig. 6, it is seen that after about 160 iterations, we can get the same results which were obtained after 350 iterations in the first experiment. This result verifies that the convergence speed of algorithm and consequently the reconstruction time are strongly dependent on the initial guess for one of the interfering wavefronts.

IV. CONCLUSION

In this paper, we have simultaneously reconstructed two interfering wavefronts reflected from two surfaces of a lens. These wavefronts can provide the useful information to find the lens parameters, and test the quality of lens surfaces without a reference wavefront. In fact, the deviations in every reconstructed wavefront compared to an ideal spherical wavefront show the aberrations of surface from which the wavefront is reflected. In our results these aberrations disappear because we used the fitted quadratic curves on the PDDs obtained from the FT method. In addition phase shifting with a tunable light source would permit calculation of the surface aberrations.

REFERENCES

[1] F. Roddier, *Adaptive Optics in Astronomy*, Cambridge University, 2004.

[2] D. Malacara, *Optical Shop Testing*, Wiley, 1998.

[3] A. Barty, K.A. Nugent, D. Paganin, and A. Roberts, “Quantitative optical phase microscopy,” Opt. Lett. Vol. 23, pp. 817-819 (1998).

[4] M.R. Teague, “Deterministic phase retrieval: a Green’s function solution,” J. Opt. Soc. Am. A, Vol. 73, pp. 1434–1441, 1983.

[5] R. Yazdani, M. Hajimahmoodzadeh, and H.R. Fallah, “Application of the transport of intensity equation in determination of nonlinear refractive index,” Appl. Opt. Vol. 53, pp. 8295– 8301, 2014.

[6] S. Rasouli, M. Dashti, and A.N. Ramaprakash, “An adjustable, high sensitivity, wide dynamic range two channel wave-front sensor based on moiré deflectometry,” Opt. Express, Vol. 18, pp. 23906–23915, 2010.

[7] S. Rasouli, “Use of a moiré deflectometer on a telescope for atmospheric turbulence measurements,” Opt. Lett. Vol. 35, pp. 1470–1472, 2010.

[8] J.M. Geary, *Introduction to Wavefront Sensors*, SPIE Press, 1995.

[9] J. Ragazzoni, “Pupil plane wavefront sensing with an oscillating prism,” J. Mod. Opt. Vol. 43, pp. 289–293, 1996.

[10] R.W. Gerchberg and W.O. Saxton, “A practical algorithm for the determination of phase from image and diffraction plane pictures,” Optik Vol. 35, pp. 237–246, 1972.

[11] K.R. Freischlad, “Absolute interferometric testing based on reconstruction of rotational shear,” Appl. Opt. Vol. 40, pp. 1637–1648, 2001.

[12] R. Kowarschik, L. Wenke, T. Baade, M. Esselbach, A. Kiessling, G. Notni, and K. Uhlendorf, “Optical measurements with phase-conjugate mirrors,” Appl. Phys. B, Vol. 69, pp. 435–443, 1999.

[13] A. Darudi and M.T. Tavassoly, “Interferometric specification of lens (single and doublet) parameters,” Opt. Lasers Eng. Vol. 35, pp. 79–90, 2001.

[14] M.T. Tavassoly and A. Darudi, “Reconstruction of interfering wavefronts by analyzing their interference pattern in three dimensions,” Opt. Commun. Vol. 175, pp. 43–50, 2000.

[15] E.A. Akhlaghi, A. Darudi, and M.T. Tavassoly, “Reconstructing the phase distribution of two Interfering wavefronts by analysis of their nonlocalized fringes with an iterative method," Opt. Express Vol. 19, pp. 15976–15981, 2011.

[16] C. Bourassin-Bouchet, M.M. Mang, I. Gianani, and I.A. Walmsley, "Mutual interferometric characterization of a pair of independent electric fields," Opt. Lett. Vol. 38, pp. 5299–5302, 2013.

[17] R. Yazdani, H.R. Fallah, and M. Hajimahmoodzade, "Reconstruction of two interfering wavefronts using Zernike polynomials and stochastic parallel gradient descent algorithm," Opt. Lett. Vol. 39, pp. 1505–1508, 2014.

[18] J. Amiri, A. Darudi, S. Khademi, and P. Soltani, "Application of transport-of-intensity equation in fringe analysis," Opt. Lett. Vol. 32, pp. 2864–2867, 2014.

[19] M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am. Vol. 72, pp. 156-160, 1982.

[20] R. J. Noll, "Zernike polynomials and atmospheric turbulence," J. Opt. Soc. Am. Vol. 66, pp. 207–211, 1976.

[21] M.A. Vorontsov, G.W. Carhart, and J.C. Ricklin, "Adaptive phase-distortion correction based on parallel gradient-descent optimization," Opt. Lett. Vol. 22, pp. 907–909, 1997.

[22] R. Yazdani, M. Hajimahmoodzadeh, and H.R. Fallah, "Adaptive phase aberration correction based on imperialist competitive algorithm," Appl. Opt. Vol. 53, pp. 132–140, 2014.

[23] M. Born and E. Wolf, *Principles of Optics*, Cambridge University Press, 2003.

[24] M. Bass, *Handbook of Optics*, McGraw-Hill, Vol. I, 1995.

Roghayeh Yazdani, born in Shiraz, Iran in 1984, received her BSc degree from Valieasr University of Rafsanjan, Rafsanjan in 2006, MSc degree from Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan in 2009, and PhD degree from the University of Isfahan, Isfahan in 2015, all in Physics. Her research interests include interferometry, optical metrology, and adaptive optics.

Sebastian Petsch, born in Freiburg, Germany in 1987, studied micro systems engineering at the University of Freiburg and concentrated on Materials, Sensors and Actuators. He finished his Bachelor and Master degree he earned in 2009 and 2011 at the Laboratory for Micro-Optics, respectively, on his work on tunable elastomeric lenses, their actuation and optical characterization.

After internships at the Fraunhofer Institute of Applied Solid State Physics and at the Testo Ag, he rejoined the Gisela and Erwin Sick Chair of Microoptics, Freiburg as a scientific employee in autumn 2011 and investigates Liquid Crystal Elastomer actuators as actuation concepts for micro-optical systems in the framework of the priority program "Active Micro-Optics", funded by the German Research Foundation (DFG).

Hamid Reza Fallah is a professor of physics at physics department, University of Isfahan, Isfahan, Iran. He received his B.Sc in Applied Physics from University of Isfahan in 1988, his MsSc and PhD in Applied Optics from Imperial College, London in 1993 and 1997 respectively. His research interests include Optical system design, Optical Thin Films and Applied Optics.

Morteza Hajimahmoodzadeh, born in Tehran, Iran (1964), received his BSc and MSc degrees in Physics from University of Isfahan, Isfahan (1988 and 1992) and PhD degree in Physics from Moscow State University, Moscow, Russia (2005). He was a lecturer in University of Isfahan since 1992. His fields of interest are Dynamical Systems, Optical Thin Films and Computational Physics.

THIS PAGE IS INTENTIONALLY LEFT BLANK.

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.**

Optics and Photonics Society of IRAN

انجمن اپتیک و فوتونیک ایران

ISSN: 1735-8590

http://www.ijop.ir