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Quantitative measurement of displacement in photopolymer layers during holographic recording using phase shifting electronic speckle pattern interferometry

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ABSTRACT

The aim of this study is to determine the displacement profile due to shrinkage in acrylamide-based photopolymer layer during holographic recording. Using phase shifting electronic speckle pattern interferometry the displacement at each pixel in the image of the object is measured by phase shifting technique so that a complete displacement profile of the object can be obtained. It was observed that the displacement profile is Gaussian and resembles to the profile of the recording beam. We observed an increase in shrinkage from 2 μm at 20 seconds of recording to 7.5 μm after 120 seconds of recording. The technique allows for real time measurement of the shrinkage profile.

Keywords: Holography, interferometry, photopolymer, shrinkage

1. INTRODUCTION

Photopolymers are under investigation for applications including LCD displays¹, holographic data storage²⁻⁴, holographic optical elements⁵ and sensors^{6,7} because of their easy processing, high photosensitivity, relatively high refractive index contrast and reasonable cost. Polymerisation induced shrinkage is one of the main reasons why photopolymer materials are not widely used in some holographic applications. The aim of this study is to evaluate the change in displacement profile due to shrinkage during holographic recording using speckle interferometry. Shrinkage occurring in an acrylamide based photopolymer developed at the Centre for Industrial and Engineering Optics⁸ has been previously determined using real time holographic interferometry, a non-destructive technique that measures small static or dynamic changes occurring in an object^{9,10}. Shrinkage in photopolymer layers has also been determined^{11,12} by measuring the shift in the angular position of the Bragg peak. The ability to measure in-plane and out of plane displacement components independently of each other makes Electronic speckle pattern interferometry (ESPI) a suitable technique for determining whole field surface deformations.

Electronic Speckle Pattern Interferometry (ESPI), also known as DSPI or TV holography, is a whole-field, non-contact, high-sensitivity tool widely used for deformation and shape measurements of rough surfaces¹³⁻¹⁹. It allows real-time visualization of deformation fringes which can provide qualitative deformation information. Fringe counting technique gives information regarding real time shrinkage but it could not produce complete phase information relating to object deformation. The quantitative phase contours can be obtained by adopting multiple frame methods such as phase shifting methods or single frame methods such as Fourier / Hilbert transform methods. Phase shifting techniques can provide highly accurate quantitative data about object displacement and hence they have been widely used²⁰⁻²⁷. The displacement at each pixel in the image of the object is measured by phase shifting technique so that a complete displacement profile of the object can be obtained. Temporal phase shifting methods, in which a PZT mirror in the reference beam is moved, is one of the most common techniques for introducing phase shift¹³⁻¹⁸. In our current work, we present whole field displacement profiles due to shrinkage in an acrylamide based

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photopolymer layer during holographic recording. The shrinkage is measured using a (5, 5) phase shifting algorithm. The displacement at each pixel in the image of the object is measured so that a complete displacement profile of the object can be obtained. The ESPI measurement system, the real-time fringes due to shrinkage and quantitative whole field profiles of the photopolymer film are presented.

2. EXPERIMENTAL PROCEDURES

2.1 SAMPLE PREPARATION

A green sensitive photopolymer layer was prepared as described in⁸. Briefly, 0.6 g of acrylamide monomer was added to 17.5 ml stock solution of polyvinyl alcohol (20% wt). Then 2 ml of triethanolamine was added. To this solution 0.2 g of *N, N*-methylene bisacrylamide and finally 4 ml of Erythrosine-B dye was added (0.11% wt. water stock solution). 0.4 ml of photopolymer solution was spread on a 25 mm × 35 mm glass plates. The samples were allowed to dry for 24 hours. The sample thickness after drying was approximately $160 \pm 3 \mu\text{m}$.

2.2 EXPERIMENTAL TECHNIQUE

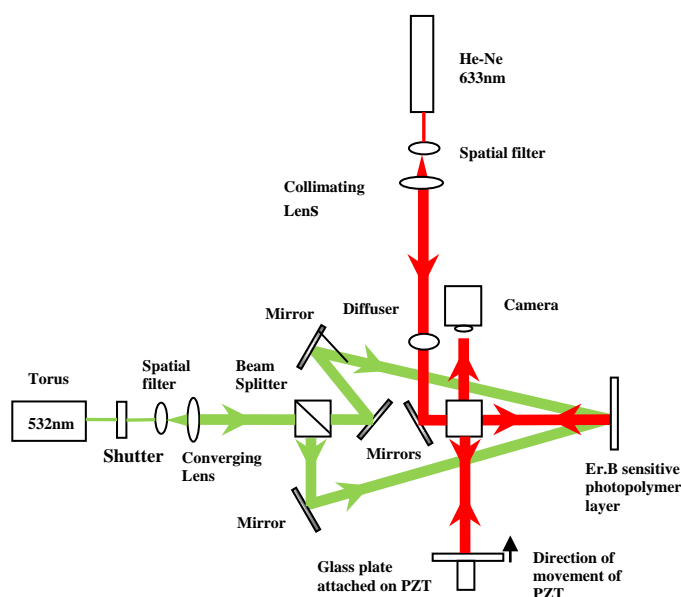


Fig. 1. Schematic of the Electronic speckle pattern interferometry (ESPI) system

The ESPI system is as shown in Fig. 1. It utilizes a red He- Ne laser (632.8 nm) to which the photopolymer layer has a negligible sensitivity. An Erythrosine B sensitized photopolymer film (ErB sample) is the object under study in this system. The photopolymer substrate is the glass plate coated with non-reflective paint to prevent back reflection of light from the glass substrate. Similarly a glass plate coated with reflective paint was attached to a piezoelectric transducer whose motion was controlled by a programme designed in LabView. The beam reflected from the Erythrosine B sample (object beam) and the beam partially reflected from a glass plate attached to a piezoelectric transducer (PZT) (reference beam) were allowed to interfere and the interference pattern was captured by a CMOS camera. The field of view of the camera was 25 mm. The optical path length difference of the two arms in the interferometer was 11 cm. After recording the reference frame and phase shifted specklegrams the photopolymer layer was then polymerised using a green beam and phase shifted speckle patterns corresponding to shrinkage in the object position were obtained. The holographic recording was carried out at 532 nm wavelength using a standard two beam interferometric set up as shown in Fig. 1. The output of a Torus laser was spatially filtered, expanded, collimated and split into two beams which were recombined at the sample under study. The spatial frequency of the recorded interference pattern was 1000 lines/mm. A constant phase difference of $\pi/2$ between consecutive frames

was introduced by changing the input voltage to the PZT. These phase shifted specklegrams were used to obtain the wrapped phase map.

3. EXPERIMENTAL RESULTS

The prepared sample as discussed in Section.2.1 was mounted in the ESPI system as shown in Fig. 1. The polymer film was exposed to green (532 nm) beams for different exposure times in a controlled manner. The shrinking of the film results in visible speckle fringes as shown in Fig. 2a. For quantitative phase analysis, temporal phase shifting method was used. Here the PZT was calibrated for a known phase shift of 90° at red-wavelength (632.8 nm). Before exposure, 5 phase shifted frames were stored for the initial state of the film, and then the film was exposed for a predetermined time interval. After that another 5 phase shifted frames were captured and stored. This procedure was repeated for different exposure time intervals. The phase maps corresponding to the sample surface before and after exposure were calculated using a 5-frame algorithm. The error-compensating 5-step phase evaluation equation was used as introduced in²⁵⁻²⁷.

$$\phi = \tan^{-1} \left[\frac{2(I_4 - I_2)}{I_1 - 2I_3 + I_5} \right] \quad (1)$$

Where, I_1, I_2, I_3, I_4, I_5 are the intensities of the phase shifted frames corresponding to phase steps of

$$-\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi$$

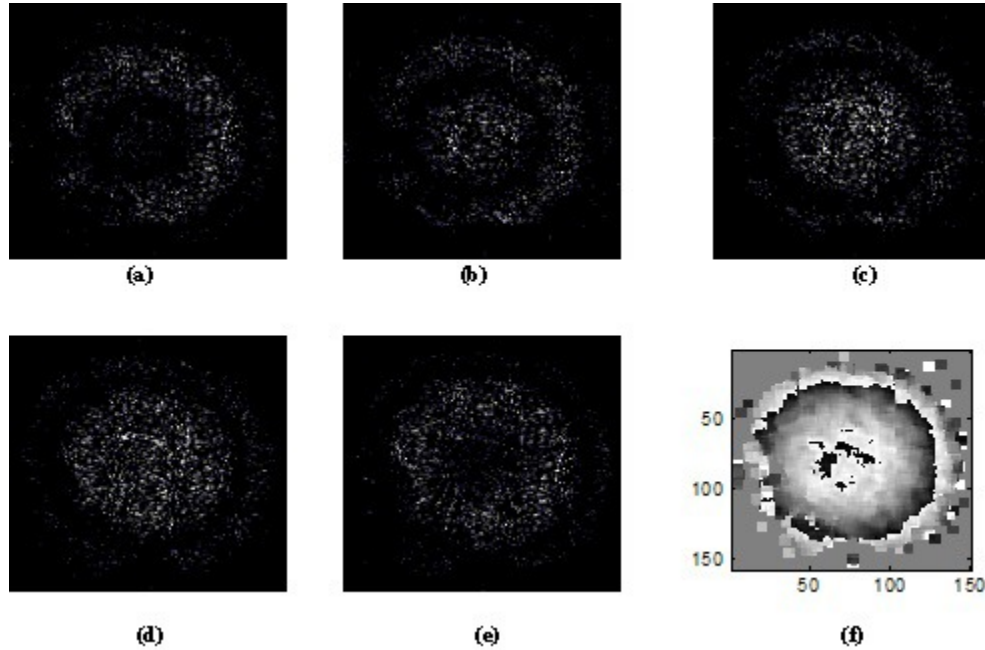


Fig. 2. Phase stepped speckle fringes (a) 0° (b) 90° (c) 180° (d) 270° (e) 360° (f) wrapped phase map

Figs. 2 (a-e) show the five phase shifted frames obtained after holographic recording for 120 s seconds with total intensity of both beams 10 mW/cm^2 . The layer thickness was $160 \pm 3 \text{ }\mu\text{m}$ and it was 1.3 cm in diameter. The phase map calculated from these 5 phase shifted frames is shown in Fig. 2(f). The phase values corresponding to each pixel within the image are wrapped between $-\pi$ and $+\pi$ due to the nature of the arctangent function that has been used for phase calculations. The wrapped phase map contains 2π phase discontinuities. But, in reality the phase is continuous. Thus, to make the wrapped phase continuous a 2D unwrapping algorithm was used. The process of removing these 2π phase steps is called phase unwrapping or integrating the phase^{28, 29}. The most common method of unwrapping is by scanning pixels sequentially along a row or column. Wherever the phase jumps are detected, an

offset of 2π is either added to or subtracted from the pixel's phase value depending on the sign of the jump. Starting at the top of any column in the phase map the offset is set to zero. Scanning down the pixels in the column, the phase jumps are examined by calculating the phase difference between adjacent pixels. The wrapped phase maps before and during exposure were unwrapped using the 2D-SRNCP unwrapping algorithm³⁰ in order to obtain smooth phase maps. The 2D SRNCP algorithm belongs to the class of quality guided path algorithms. In order to prevent error propagation, this algorithm will unwrap the highest quality pixels with highest reliability values first and lowest quality pixels with lowest reliability value last. The reliability of a pixel in this algorithm is defined based on the second differences (meaning difference of phase gradients) between a pixel and its neighbours. By using second differences of phase values of the adjacent pixels, detection of inconsistencies in the phase map can be improved. The 2D SRNCP algorithm follows non-continuous or discrete paths for unwrapping. The phase maps still contain some errors which cannot be detected, but the algorithms are very robust in practice compared to continuous path unwrapping algorithms. The two unwrapped phase maps corresponding to the sample surface before and after exposure to green light were subtracted from one another in order to get the displacement profile due to shrinkage in the photopolymer.

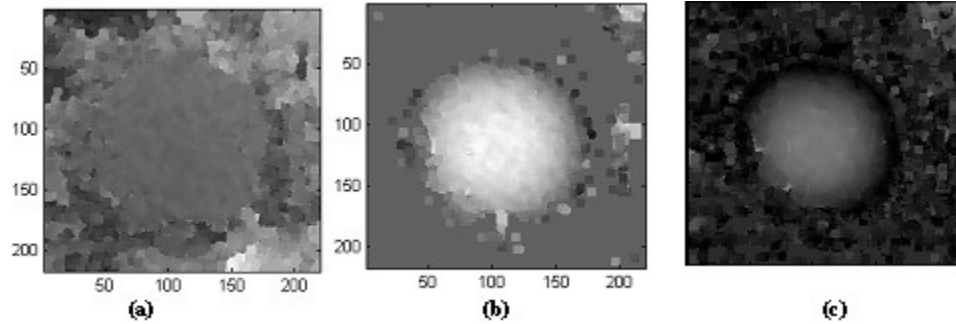


Fig. 3. Unwrapped phase map (a) before exposure, (b) after 80s exposure, (c) shrinking phase obtained by subtracting 3(a) and 3(b).

The unwrapped phase map of the wrapped image [Fig. 2(f)] is shown in Fig. 3(b). The phase value at each pixel lying in the range $[-\pi, +\pi]$ is represented by a grey level within the dynamic range of the CMOS camera enabling display of the phase map as a gray level image. The dark pixels correspond to a phase value of $-\pi$ and white pixels which are saturated correspond to phase value of $+\pi$. The unwrapped phase map of the photopolymer before exposure is shown in Fig. 3 (a).

In order to determine shrinkage in photopolymer layers the phase map corresponding to the time of recording, in this case 80 sec, was subtracted from that before recording. The resulting unwrapped phase map is shown in Fig. 3(c). From the subtracted phase map, a 3D displacement map of shrinkage can be calculated

$$\Delta d = \left(\frac{\lambda}{4\pi} \right) \phi \quad (2)$$

where, Δd - shrinkage in photopolymer layer; λ - wavelength of laser ; ϕ -unwrapped phase

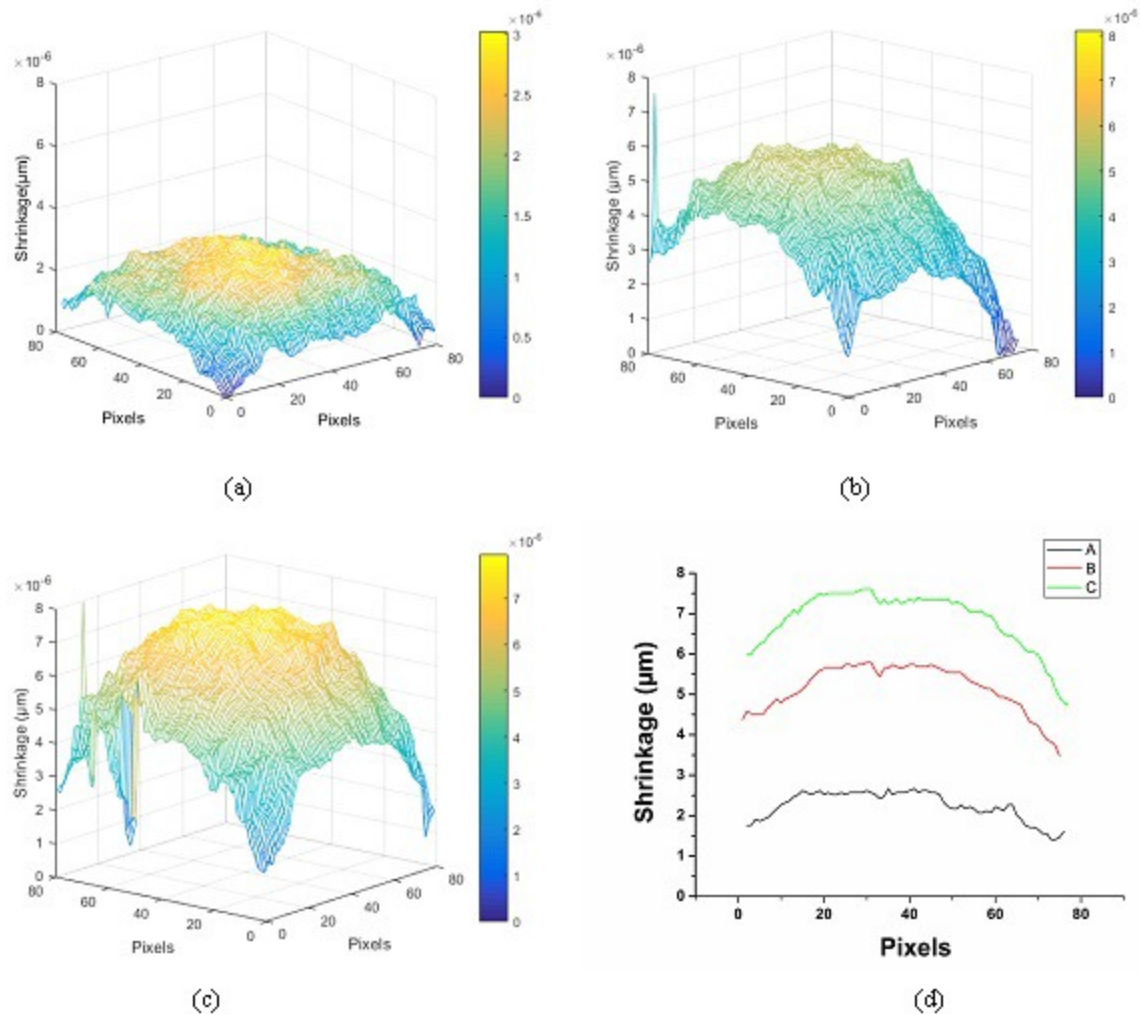


Fig. 4. A 3D map of the absolute shrinkage photoinduced in a $160 \pm 3 \mu\text{m}$ thick sample after holographic exposure for (a) 20s (b) 60s (c) 120s. Recording intensity was 10 mW/cm^2 .

Figs. 4 (a -c) show the shrinkage measured 20 s, 60 s, and 120 s after the start of holographic recording with two beams with total intensity of 10 mW/cm^2 in a $160 \pm 3 \mu\text{m}$ layer. It can be seen that the shrinkage increases with exposure time. Fig. 4(d) shows the line profile of shrinkage for the three different phase maps. We can clearly see from the line profile that the shrinkage is around $2 \mu\text{m}$ after 20 sec of recording. With increasing time at around 60 s the maximum shrinkage of around $5.5 \mu\text{m}$ and at 120 s it is $7.5 \mu\text{m}$. In the displacement maps 100 pixels corresponds to 7 mm . The line profiles in Fig. 4(d) present the shrinkage values across the middle of the 3D map. From these lines it can be seen that the shrinkage is non uniform across the illuminated area that was studied, with maximum shrinkage observed at the centre of the spot. This could be explained by the higher intensity in the centre (the recording beams had a Gaussian profile) and by the fact that there will be an influx of monomer molecules from the unpolymerised regions outside the illuminated spot. It could also be observed that the dynamics of the shrinkage in the middle and at the edges of the illuminated spot are different. A detailed analysis of the data is currently being carried out and will be published elsewhere.

4. CONCLUSIONS

We have demonstrated a whole-field deformation measurement (caused by the photoinduced shrinkage of photopolymer film) using a phase shifting ESPI system. Recording was made in a $160 \pm 3 \mu\text{m}$ thick layer. Phase

shifted specklegrams were captured before holographic recording as well as after different times of recording. These phase shifted specklegrams were used to obtain unwrapped phase maps of the 3D before and after profiles which were then subtracted from each other to obtain the shrinkage profile as a phase map and finally the actual shrinkage 3D profile. It was observed that the shrinkage has its maximum in the center of the illumination spot and increases with the recording time. The dynamics of the shrinkage depends on the intensity of exposure, a result that was previously observed in acrylamide based photopolymers, but there the shrinkage was larger when a lower intensity was used. In the results presented here the diffusion of material from outside the illumination area will also influence the final result and could be the reason why the shrinkage at the edge, where the intensity is lower appears to be lower than the shrinkage at the middle of the illuminated spot. Further analysis of the results is required, including experiments in which the illumination spot is larger than the photopolymer sample area in order to eliminate the effect of diffusion from the unilluminated area. The current study will find an useful applications for the characterization of photosensitive polymer materials for holographic applications.

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REFERENCES

- [1]. Biles, J., "Holographic Color Filters for LCDs", SID 94 Digest, 403-406 (1994).
- [2]. Pu, A. and Psaltis, D., "High-density recording in photopolymer based holographic three-dimensional disks," *Appl. Opt.* 35, 2389–2398 (1996).
- [3]. Rhee, U. S., Caulfield, H. J., Shamir, J., Vikram, C. S. and Mirsalehi, M. M., "Characteristics of the DuPont photopolymer for angularly multiplexed page-oriented holographic memories," *Opt. Eng.* 32, 1839–1847 (1993).
- [4]. Naydenova, I., Sherif, H., Mintova, S., Martin, S. and Toal, V. "Holographic recording in nanoparticle doped photopolymer," *Proc. SPIE* 6252, 625206 (2006).
- [5]. Hemmer, P., Shahriar, S., Ludman, J. and Caulfield, H. J., "Holographic Optical Memories," in "Holography for the New Millennium" eds. J. Ludman, H. J. Caulfield, and J. Riccobono, Springer-Verlag New York, 179-189 (2002).
- [6]. Yetisen, A. K.; Naydenova, I.; da Cruz Vasconcellos, F.; Blyth, J.; Lowe, C. R. *Chem. Rev.* 2014, 114 (20), 10654;
- [7]. Naydenova, I.; Grand, J.; T. Mikulchyk, Martin, S.; Toal, V.; Georgieva, V.; Thomas, S.; Mintova, S. *Chem. Mater.* 2015, 27, 6097.
- [8]. Martin, S., Feely, C.A. and Toal, V., "Holographic recording characteristics of an acrylamide based photopolymer," *Appl. Opt.* 36, 5757-5768, (1997)
- [9]. Mohesh Moothanchery, Izabela Naydenova, Viswanath Bavigadda, and Vincent Toal, "Shrinkage during holographic recording in photopolymer films determined by holographic interferometry," *Applied Optics*. 52, pp. 8519-8527, Dec 2013
- [10]. M. Moothanchery, I. Naydenova, V. Bavigadda, S. Martin and V. Toal, "Real-time shrinkage studies in photopolymer films using holographic interferometry," *Proc. SPIE*, Vol. 8437, 8437I, (2012)
- [11]. Moothanchery, M., Naydenova, I., and Toal, V., "Study of the shrinkage caused by holographic grating formation in acrylamide based photopolymer film," *Optics Express*. 19, 13395-13404 (2011).
- [12]. Mohesh Moothanchery, Izabela Naydenova, and Vincent Toal, "Studies of shrinkage as a result of holographic recording in acrylamide based photopolymer film", *Appl. Physics*, A.104, pp.899-902, May 2011
- [13]. Paul Kumar, U., Krishna Mohan, N., and Kothiyal, M. P., "Measurement of static and vibrating microsystems using microscopic TV holography" *Optik*, 122, 49-54 (2011).
- [14]. Rastogi, P.K., "Digital speckle pattern interferometry and related techniques," Wiley, New York, 2001.

- [15]. Paul Kumar, U., Krishna Mohan, N., and Kothiyal, M. P, "Microscopic TV sheroigraphy for microsystems characterization," *Optics Letters*, 34, 1612-1614(2009).
- [16]. Sirohi, R. S., "Introduction to Optical Metrology," CRC(2015).
- [17]. P. K. Upputuri, Y. Kalyani, N. Krishna Mohan, and M. P. Kothiyal, "Time-average TV holography for vibration fringe analysis," *Applied Optics*, 48, 3094-3101(2009).
- [18]. Paul Kumar, U., Krishna Mohan, N., and Kothiyal, M. P, "Red-Green-Blue wavelength TV holography and interferometry for Microsystems metrology" *Journal of Optics*, 40, 176-183(2011).
- [19]. U. P. Kumar, N.K. Mohan, M.P. Kothiyal, A.K. Asundi, Deformation and shape measurement using multiple wavelength microscopic TV holography, *Optical Engineering*, 48 (2009) 023601.
- [20]. Creath, K., "Phase shifting speckle interferometry," *Appl. Opt.* 24, 3053-3058 (1985).
- [21]. Malacara, D., "Optical Shop Testing," John Wiley & Sons, Inc.2007.
- [22]. Paul Kumar, U., Krishna Mohan, N., and Kothiyal, M. P, "Characterization of micro-lenses based on single interferogram analysis using Hilbert transformation" *Optics Communication*, 284, 5084-5092(2011).
- [23]. U. Paul Kumar, Wang Haifeng, N. Krishna Mohan and M. P. Kothiyal, "White light Interferometry for surface profiling with colour CCD," *Optics and Lasers in Engineering*, 50, 1084-1088(2012).
- [24]. U. Paul Kumar, U. Somasundaram, M. P. Kothiyal, and N. Krishna Mohan, "Single frame digital fringe projection profilometry for 3-D surface shape measurement," *Optik*, 124,166-169(2013).
- [25]. Paul Kumar, U., Krishna Mohan, N., and Kothiyal, M. P, "Multiple wavelength interferometry for surface profiling," *Proc. SPIE*, 7063, 70630W (2008).
- [26]. P. Hariharan, B.F. Oreb, T. Eiju, Digital phase-shifting interferometry: a simple error-compensating phase calculation algorithm, *Applied Optics*, 26 (1987) 2504-2505.
- [27]. Paul Kumar, U., Bhaduri, B., Krishna Mohan, N., Kothiyal, M.P., Asundi, A.K., "Microscopic TV holography for MEMS deflection and 3-D surface profile characterization," *Optics and Lasers in Engineering*, 46 (2008) 687-694.
- [28]. O. J. Lokberg and K. Hogmoen, "Use of modulated reference wave in electronic speckle pattern interferometry," *J. Phys. E: Sci. Instr.*, Vol. 9, 847-851, (1976)
- [29]. J. Schwider, R. Burow, K. E. Elssner, J. Grzanna, R. Spolaczyk and K. Merkel, "Digital wavefront measuring interferometry--some systematic error sources," *Appl.Opt.* Vol. 22, No. 21, 3421-3432, (1983)
- [30]. M. A. Herraiez, D. R. Burton, M. J. Lalor, M. A. Gdeisat "Fast two-dimensional phase unwrapping algorithm based on sorting by reliability following a noncontinuous path," *Appl. Opt.*, Vol. 41, No. 35, 7437-7444, (2002)