International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-13, Issue-7; July, 2026
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.137.2

Experimental Assessment of Compact Holographic Lens Imaging Systems for In-Plane Displacement Measurements

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Received: 03 June 2026,

Received in revised form: 01 July 2026,

Accepted: 05 July 2026,

Available online: 10 July 2026

***Keywords*— Speckle metrology, in-plane displacement, diffractive optical elements, holographic lenses, coherent imaging.**

***Abstract*— *Coherent imaging systems using holographic lenses have demonstrated significant potential in speckle metrology for diffraction-limited imaging performance free of all monochromatic aberrations. In this work, a compact four-hololens system has been investigated for in-plane displacement measurement and compared with two-hololens and double-aperture two-hololens imaging systems. Experimental results obtained using holographic lenses with a typical f-number 7.1 demonstrate that by employing an appropriate recording and reconstruction geometry for holographic lenses, the four-hololens configuration provides higher measurement sensitivity, reducing the minimum measurable in-plane displacement than the existing two-hololens systems.*

I. INTRODUCTION

Precise measurement of in-plane displacement is essential in precision engineering, structural analysis, and advanced manufacturing applications. Various optical techniques have been developed for this purpose, including speckle photography and interferometry [1], moiré interferometry [2], holography interferometry [3], and grating interferometry [4].

Nowadays, holography has been established as a superior technique for fabricating lightweight, inexpensive optical elements such as gratings, lenses, mirrors, beam splitters, etc. A holographic lens is the hologram of a point source [5-6]. It can be recorded using the interference pattern of a coherent plane wave and a spherical wave [5-6]. The interference pattern is recorded on a high resolution holographic film. When holographic lenses are reconstructed with coherent beam of monochromatic light, they show focusing properties like conventional lenses. However, unlike their conventional counterparts, which work on the phenomenon of refraction, holographic lenses achieve their required function through the phenomenon of diffraction [6]. Equivalence of holographic lenses as zone plates has been established [7]. Recent works uses holographic lenses in speckle metrology [8-11], laser Doppler anemometry [12], optical fiber communication [13], head up display [14], photovoltaic concentrators [15-16], and many other fields [17-20].

Holographic lenses have been employed in different recording and reconstruction geometries for measuring in-plane displacements in speckle metrology. Shakher et. al [21] first demonstrated the use of a single holographic lens for in-plane displacement measurement. However, in speckle metrology, one usually deals with an extended object and a single holographic lens gives aberration-free imaging performance only for a single point [6], which is the source of spherical wave during holographic lens recording [6]. Therefore, to obtain aberration-free imaging performance over an extended object field, Shakher [22-23] proposed a two-hololens coherent imaging system in speckle metrology. In this configuration, aberrations introduced by the first holographic lens for various points on the extended object are nullified by the second holographic lens. Based on this aberration-compensation imaging principle [23-24], four identical holographic lens based systems have been investigated by Yadav et al. [25]. Later, Jayaswal et al. [26], use a double-aperture two-hololens system for simple alignment procedure.

In the two-hololens imaging system reported in Ref. [22-23], the minimum measurable in-plane displacement, i.e., the measurement sensitivity (σ), is given by average speckle size, $\sigma = 1.22\,\lambda\,F\#$ [22-23], where F# is the f-number of the lens defined as ratio of focal length to diameter. In the double-aperture two-hololens system [26], each speckle is modulated by plane grating structure of period $\frac{\lambda}{2\sin\phi}$. Therefore, the measurement sensitivity of the double-aperture two-hololens system is given by $\sigma = \frac{\lambda}{2\sin\phi}$, where ϕ is the semi-angle subtended by each aperture at the image-plane [26]. For a lens of diameter D and focal length f, $sin\phi = \frac{D}{2f} = \lambda F\#$, when using the entire lens aperture [27]. This limits the measurement sensitivity of double-aperture two-hololens system to $\sigma = \lambda\,F\#$ [27]. Further, one can record a holographic lens with a limited F# only that depends on the size of the pinhole used to obtain spherical beam in holographic lens recording [27]. Thus, the measurement sensitivity of both two-hololens and double-aperture two-hololens imaging systems is governed by the f-number (F#) of holographic lenses. In the four-hololens system, each and every speckles formed at the image plane is also modulated with a planar grating pattern, therefore measurement sensitivity of the four-hololens system is also equal to $\frac{\lambda}{2\sin\phi}$ [10, 27].

In this work, experiments were carried out using holographic lenses recorded with a typical f-number 7.1 with lens diameter 25 mm, focal length 178 mm, and inter-beam recording angle of 18° between plane and spherical beams, in a two-hololens system and in a double-aperture two-hololens system, and a four-hololens system to measure in-plane displacements. The performance of these configurations was comparatively investigated in terms of their minimum measurable in-plane displacement (measurement sensitivity). The experimental results demonstrate that when holographic lenses recorded with a typical F# are used in a four-hololens system, the measurement sensitivity is not limited by the F# of the holographic lenses. Thus, the use of holographic lenses recorded with a typical F# in a four-hololens system is advantageous for measuring smaller in-plane displacement over the two-hololens and double-aperture two-hololens systems.

II. EXPERIMENTAL

2.1 Lens Recording and Playback Geometries

All the holographic lenses used in this work were recorded by interfering spherical beam originating from a point source (pinhole) and plane beams of laser light on high-resolution holographic plate. To obtain on-axis imaging performance in the two-hololens system, the spherical beam was incident normally on the recording plane and a plane beam was incident at a typical angle of 18° with the spherical beam, as illustrated in Fig. 1.

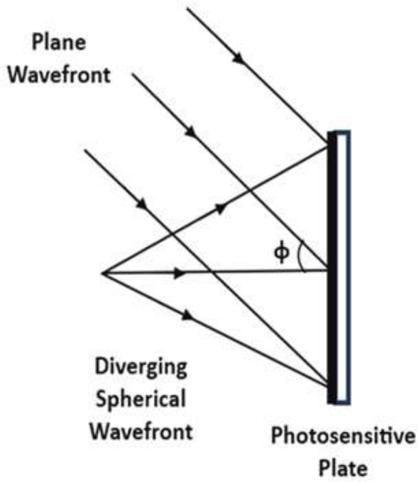

Fig. 1: Simplified holographic lens recording geometries using plane and spherical wavefronts for two-hololens system

However, to record the holographic lenses for the four-hololens system, the plane beam was incident normally on the recording plane and the spherical beam was incident a typical angle of 18° with respect to normal to the recording plane, as shown in Fig. 2.

A 12 mW He-Ne laser (Newport make) operating at a wavelength of 0.6328 µm was used to generate both the spherical and plane beams. During recording, the 5 µm diameter pinhole (Newport make), which was the point source for generating spherical beam, was positioned at a distance of 178 mm from the recording plane. Consequently, the recorded holographic lenses had a focal length of 178 mm. PFG-01 silver halide holographic plates [28] were used in recording. After giving proper exposure to the plates, they were developed using standard procedure [29-30].

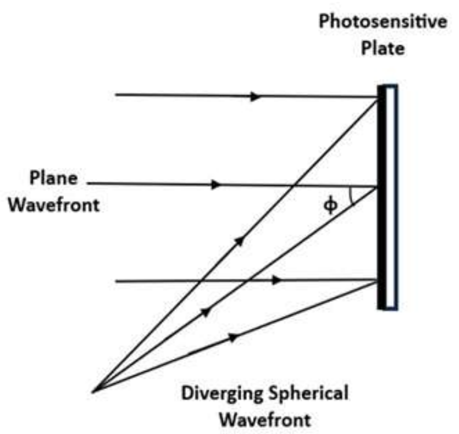

Fig. 2: Simplified holographic lens recording geometries using plane and spherical wavefronts for four-hololens system

2.1 In-Plane Displacements Measurement Using Compact Two-Hololens, Double-Aperture Two-Hololens, and Four-Hololens Coherent Imaging Systems

Fig. 3(a) and Fig. 3(b) illustrate the experimental configurations employed for in-plane displacement measurement using the two-hololens and double-aperture two-hololens systems, respectively. Both configurations utilize two identical holographic lenses recorded as shown in Fig. 1 with F# 7.1. Fig. 4 illustrates the experimental setup of the four-hololens system for in-plane displacement measurement, which employs the holographic lenses recorded as shown in Fig. 2 with the same F#. An expanded and spatially filtered laser beam with a wavelength of λ = 0.6328 µm was incident on an optical diffuser plate mounted on a linear translation stage connected with motion controller (XPS series, Newport make). The diverging speckle field emerging from the diffuser was directed onto holographic lens systems. The holographic lens systems formed image of the diffuser plate, which contains the speckle pattern generated by the diffuser.

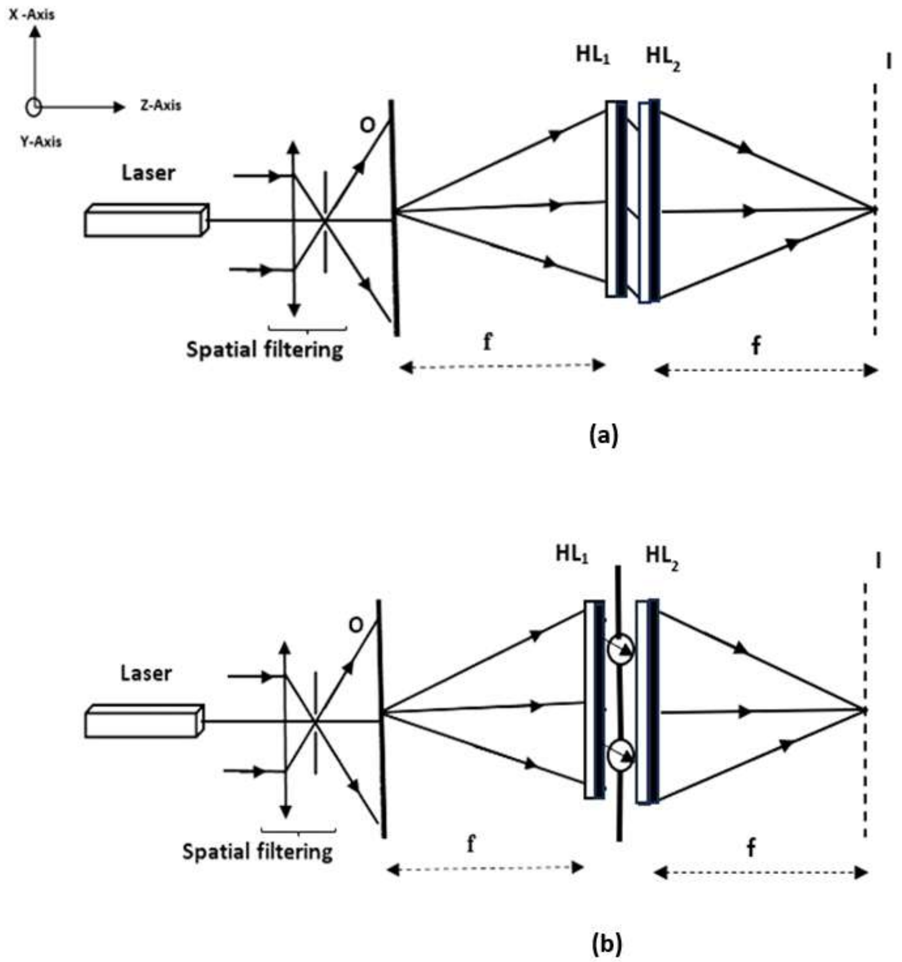

Fig. 3: Schematic geometries illustrating experimental setups for measuring in-plane displacements, (a) using two-hololens system, (b) using double-aperture using two-hololens system. In the figure, HL_1 and HL_2 are identical holographic lenses, O is an optical diffuser, I is the image plane, and f is the focal length of the holographic lenses

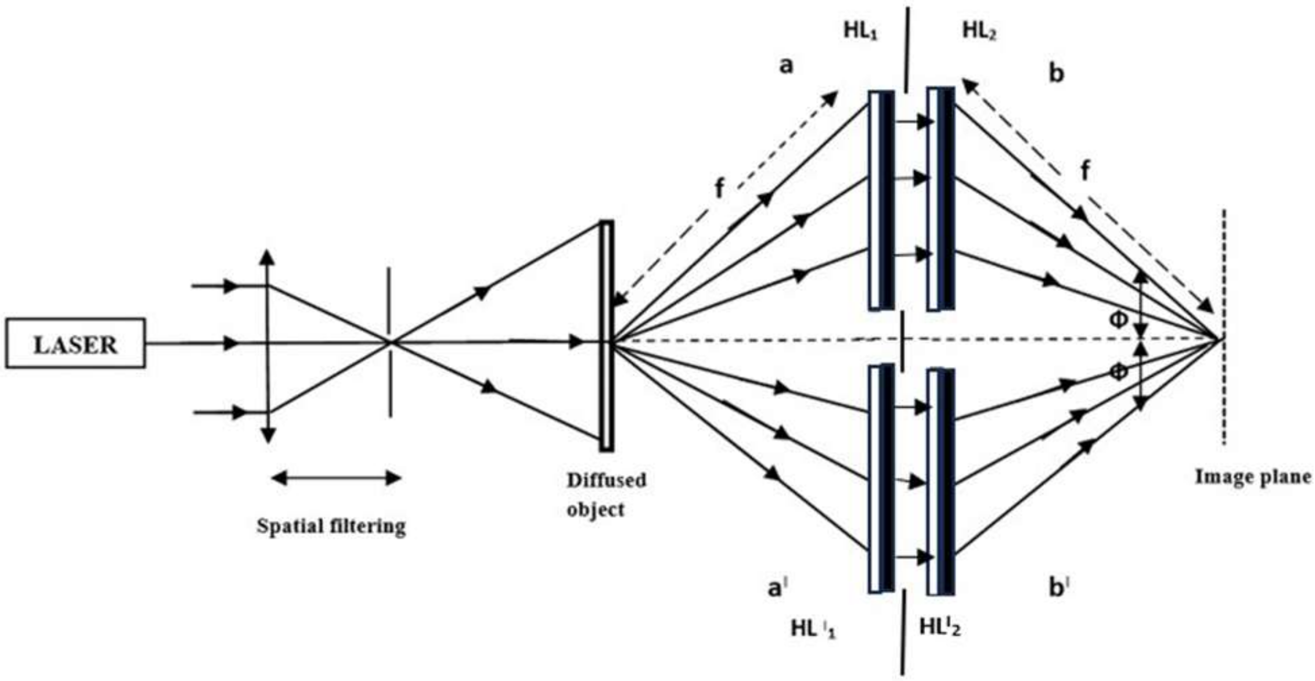

Fig. 4: Schematic of the experimental setup for measuring in-plane displacements, using four-hololens system. HL_1, HL_2, $HL_1^{|}$, $HL_2^{|}$ *are identical holographic lenses, and f is the focal length of the holographic lenses*

Double-exposure technique [24] was employed for measuring in-plane displacements that were applied to an optical diffuser. Double-exposure specklegrams corresponding to the different in-plane displacements values were recorded on PFG-01 silver halide holographic plates [28]. Silver halide recording materials possess high spatial-resolution and wide dynamic range along with high-sensitivity which help in accurately recording the fine details of speckle patterns [28]. For each measurement, the first exposure was recorded with the object in its initial position. The object was then translated by a known in-plane displacement along the x-axis, parallel to the holographic lens plane (see Fig. 3 and Fig. 4), using a precision motion controller (XPS series, Newport make), and a second exposure was recorded on the same plate. The recorded double-exposure specklegrams were subsequently processed using the point-wise filtering technique to obtain the Young's fringe patterns for displacement analysis [24].

The two-hololens imaging system produces Young 's-type speckle correlation fringes only within the central (zero-order) diffraction halo. In contrast, the double-aperture two-hololens and four-hololens imaging systems generate speckle correlation fringes in both the central (zero-order) and the first-order (±1) diffraction halos [24]. However, for comparative analysis of these imaging systems, fringe-width measurements were performed only in the zero-order diffraction halo. Schematic of point-wise filtering method of doubly exposed specklegrams shown in Fig. 5. When an unexpanded laser beam is incident on the recorded specklegram, Young's-type correlation fringes are formed within the diffraction halo, from which the in-plane displacement was determined.

The in-plane displacements can be determined by measuring the width of Young's fringes formed within the zero-order diffraction halo using the equation (1)

$$d_x = \frac{\lambda Z}{\beta} \qquad (1)$$

In this equation, d_x denotes the applied in-plane displacement of the object point in a direction parallel to the plane of holographic lenses, λ is the wavelength of the illuminating light, Z is the distance between the recording medium and the observation plane, and β represents the average fringe spacing.

Several double exposure specklegrams were obtained to determine the minimum detectable displacements with holographic lenses (F# = 7.1) in these imaging systems at a wavelength of λ = 0.6328 μm. Tables 1, 2, and 3 present the measured in-plane displacements obtained using the two-hololens system (Fig. 3 (a)), double-aperture two-hololens system (Fig. 3 (b)), and the four-hololens system (Fig. 4), respectively.

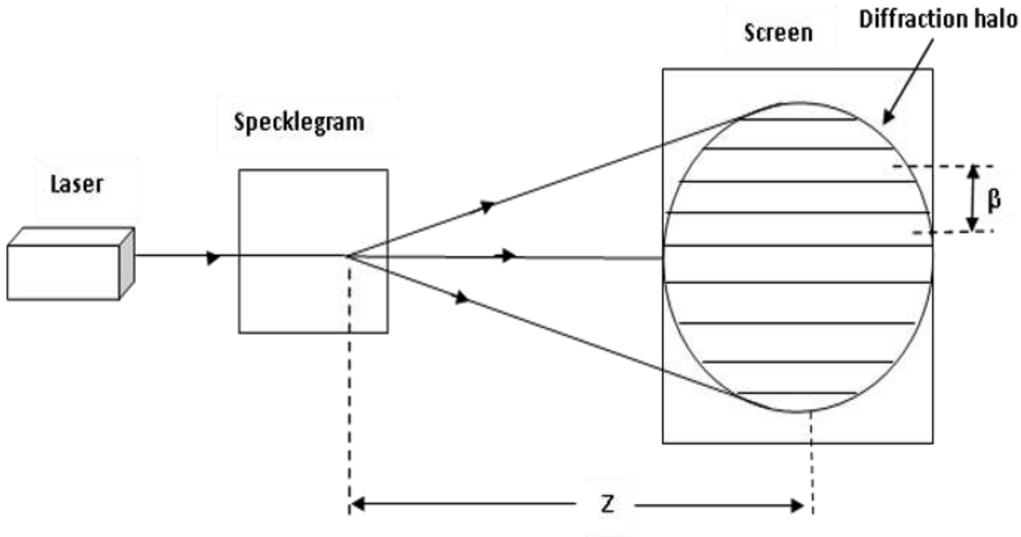

Fig. 5: Schematic illustrating fringe formation in zero-order (central) diffraction halo in the pointwise filtering method.

Table. 1: Applied and measured in-plane displacements using holographic lenses with F# 7.1 in a two-hololens system (Fig. 3 (a))

Applied In-plane displacement (in µm)	Measured In-plane displacement d_x (µm)	Distance between Specklegram and screen Z (cm)	Fringe spacing β (mm)	Percentage error in the measurement
6	5.70	30	33.30	5.0
10	9.47	30	20.10	5.3
15	14.16	30	13.40	5.6
25	23.44	30	8.10	6.2
50	46.40	30	4.10	7.2

Table. 2: Applied and measured in-plane displacements using holographic lenses with F# 7.1 in the double-aperture two-hololens system (Fig. 3 (b))

Applied In-plane displacement (in µm)	Measured In-plane displacement d_x (µm)	Distance between Specklegram and screen Z (cm)	Fringe spacing β (mm)	Percentage error in the measurement
6	5.68	30	33.42	5.3
10	9.49	30	20.00	5.1
15	14.17	30	13.39	5.5
25	23.37	30	8.12	6.5
50	46.30	30	4.10	7.4

Table. 3: Applied and measured in-plane displacements using holographic lenses with F# 7.1 in the four-hololens system (Fig. 4).

Applied In-plane displacement (in µm)	Measured In-plane displacement d_x (µm)	Distance between Specklegram and screen Z (cm)	Fringe spacing β (mm)	Percentage error in the measurement
3	2.83	30	67.08	5.6
10	9.51	30	19.96	4.9
15	14.25	30	13.32	5.0
25	23.48	30	8.08	6.1
50	46.35	30	4.09	7.3

Fig. 6 shows the diffraction halo containing Young's fringes only in the central (zero-order) halo, corresponding to an in-plane displacement of 15 µm, obtained using the two-hololens system. Whereas, Fig. 7(a) and Fig. 7(b) show diffraction halos containing Young's fringes in both the central (zero-order) and first-order halos, corresponding to the same in-plane displacement of 15 µm, obtained using the double-aperture two-hololens system and the four-hololens system, respectively.

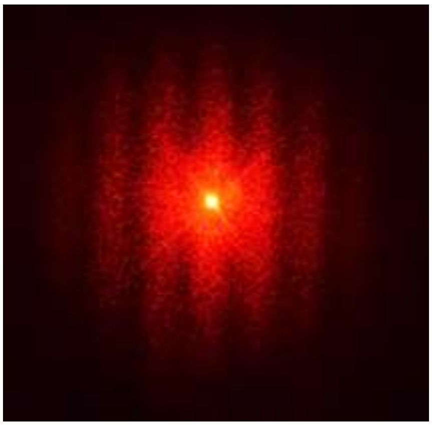

Fig. 6: Photograph of diffraction halo showing Young's fringes only in the central (zero-order) halo for an in-plane displacement of 15 µm, obtained using the two-hololens system

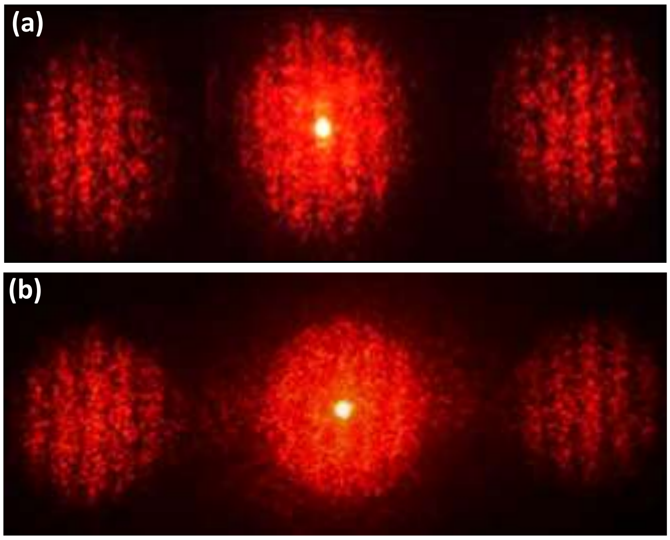

Fig. 7: Photograph of diffraction halos showing Young's fringes in both the central (zero-order) and first-order halos for an in-plane displacement of 15 µm, obtained using, (a) double-aperture two-hololens system,d (b) four-hololens system.

III. RESULTS AND DISCUSSIONS

In this work, holographic lenses recorded with a typical f-number of $F\# = 7.1$, with focal length of 178 mm, lens diameter of 25 mm, and an inter-beam recording angle of 18° between the plane and spherical recording beams were employed in a two-hololens system, a double-aperture two-hololens system, and a four-hololens system for the measurement of in-plane displacement. The corresponding experimental results are summarised in Tables 1, 2, and 3, respectively. The performance of these configurations was comparatively evaluated in terms of their minimum measurable in-plane displacement (measurement sensitivity). Theoretically, the measurement sensitivity (σ) at wavelength λ for the two-hololens system using holographic lenses of f-number F#

is $\sigma = 1.22\ \lambda\ F\#$, whereas the measurement sensitivity (σ) for the double-aperture two-hololens system is $\sigma = \lambda\ F\#$.

Thus, for holographic lenses with F# = 7.1 at a wavelength of 0.6328 µm, the theoretical measurement sensitivity is σ = 1.22 λF# = 5.48 µm for the two-hololens system and σ = λF# = 4.49 µm for the double-aperture two-hololens system. Several double exposure specklegrams were obtained to determine the minimum detectable displacements. Experimentally, the minimum measurable in-plane displacement (measurement sensitivity) was found to be 5.70 µm for the two-hololens system and 5.68 µm for the double-aperture two-hololens system using the whole lens aperture, which are in good agreement with the theoretical predictions. Whereas, when the holographic lenses with the same F# were employed in the four-hololens system, the minimum measurable in-plane displacement was 2.83 µm, representing a substantial improvement in measurement sensitivity using four-hololens system.

IV. CONCLUSION

The experimental results demonstrate that the four-hololens configuration enables significantly higher measurement sensitivity even when using holographic lenses recorded with a typical f-number, thereby overcoming the conventional limitation of measurement sensitivity imposed by the lens f-number in a two-hololens and double-aperture two-hololens systems.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Professor H. L. Yadav, Professor-in-Charge, Photonics Laboratory, NIT Jamshedpur for providing the necessary experimental facilities and for his continuous guidance, discussion, and support throughout this work.

REFERENCES

[1] Ara, M. M., & Sirohi, R. S. (2007). Speckle interferometry methods for displacement and strain measurements using photorefractive crystal. Optik, 118(9), 445–451.

[2] Salbut, L., & Kujawinska, M. (2019). Interferometry for in-plane displacement and strain measurement of microcomponents. In Optical inspection of microsystems (2nd ed., pp. 245–259). CRC Press.

[3] Nikulin, V. V., Khandekar, R., & Bedi, V. (2015). Application of holographic interferometry to in-plane and out-of-plane misalignment and deformation measurements in packaging applications. In Proceedings of SPIE (Vol. 9489, pp. 88–96).

[4] Wang, X., Dong, X., Guo, J., & Xie, T. (2003). Two-dimensional displacement sensing using a cross diffraction grating scheme. Journal of Optics A: Pure and Applied Optics, 6(1), 106–111.

[5] Schwar, M. J. R., Pandya, T. P., & Weinberg, F. J. (1967). Point holograms as optical elements. *Nature, 215*(5098), 239–241.

[6] Richter, A. K., & Carlson, F. P. (1974). Holographically generated lens. *Applied Optics, 13*(12), 2924–2930.

[7] Chau, H. H. M. (1969). Zone plates produced optically. *Applied Optics, 8*, 1209–1211.

[8] Jayaswal, R. K., Khan, A. A., & Yadav, H. L. (2025). An experimental method to minimize errors in the in-plane displacement measurements in laser speckle photography using a dual aperture compact hololens imaging system. *Russian Journal of Nondestructive Testing, 61*(11), 859–868.

[9] Khan, A. A., Yadav, H. L., & Jaiswal, R. K. (2023). Experimental method to enhance sensitivity and accuracy of measurements in measuring fracture parameters around the crack tip using compact hololens imaging system. *Russian Journal of Nondestructive Testing, 59*(6), 501–506.

[10] Khan, A. A., & Yadav, H. L. (2022). Analysis of double aperture hololens imaging system through simulation and experimentation for its application in speckle metrology. *Optics and Lasers in Engineering, 152*, 106979.

[11] Khan, A. A., & Yadav, H. L. (2023). Holographic lenses for the precision measurement of surface displacement in speckle metrology. In *Proceedings of the International Conference on Innovations in Engineering and Technology (ICIET)* (pp. 1–4).

[12] Khan, A. A., & Yadav, H. L. (2023). Design and analysis of holographic lens based optical system for laser Doppler anemometry. *Optics & Laser Technology, 167*, 109660.

[13] Singh, A. K., Yadav, A., Khan, A. A., Roy, S., & Yadav, H. L. (2022). Design and analysis of holographic optical elements for their use as couplers with appreciable efficiency at different optical transmission windows. *Optik, 261*, 169184.

[14] Wang, Y., Yang, T., Lyu, X., Cheng, D., & Wang, Y. (2024). Ultra-simplified and low-cost head-up display system enabled by freeform holographic element. *Optics & Laser Technology, 178*, 111253.

[15] Wu, H. Y., Shin, C. W., Kwon, K. C., Lee, K. Y., Gil, S. K., & Kim, N. (2024). Holographic solar concentrator with wide band using multi-wavelength transmission grating. *Optik*, *318*, 172106.

[16] Khan, A. A., & Yadav, H. L. (2023). Recording and analysis of off-axis multiplexed volume holographic lens for wavelength selective wide acceptance angle operation in concentrator photovoltaics. *Optical Engineering, 62*(8), 085103.

[17] Edwards, M. R., Munirov, V. R., Singh, A., Fasano, N. M., Kur, E., Lemos, N., ... Michel, P. (2022). Holographic plasma lenses. *Physical Review Letters, 128*(6), 065003.

[18] Nedelchev, L., Mateev, G., Nikolova, L., Nazarova, D., Ivanov, B., Strijkova, V., Stoykova, E., Choi, K., & Park, J. (2023). In-line and off-axis polarization-selective

holographic lenses recorded in azopolymer thin films via polarization holography and polarization multiplexing. *Applied Optics, 62*, D1–D7.

[19] Hsieh, M. L., Chen, Z. F., Lin, S. H., & Lin, S. Y. (2025). An efficient and wide angle coupling of light to a thin film holographic optical element. *Scientific reports*, *15*(1), 23419.

[20] Khan, A. A. (2024). *Uses of holographic lenses in interferometry and dispersive concentrating system for photovoltaics* (Doctoral dissertation, National Institute of Technology, Jamshedpur).

[21] Shakher, C., & Rao, G. V. (1984). Speckle metrology using holographic lenses. *Journal of Optics, 13*, 53–57.

[22] Shakher, C., & Rao, G. V. (1987). Use of holographic optical elements in speckle metrology: Part II. *Applied Optics, 26*, 654–657.

[23] Shakher, C. (1988). Analysis and evaluation of a two holo-lens system imaging. *Journal of Optics (Paris), 19*, 27–32.

[24] Sirohi, R. S. (1993). *Speckle metrology*. Marcel Dekker.

[25] Yadav, H. L., Kumari, N., Bhushan, R., Mallick, A., & Gupta, B. N. (2004). Fabrication of double-aperture hololens imaging system: Application to mechanics. *Optics and Lasers in Engineering, 41*(6), 869–877.

[26] Jayaswal, R. K., Yadav, H. L., & Barhai, P. K. (2015). Design and analysis of modified version of double aperture speckle interferometer consisting of holographic optical element: Application to measurement of in-plane displacement component. *Optik, 126*(18), 1700–1704.

[27] Khan, A. A., & Yadav, H. L. (2024). Experimental assessment of a low-cost aberration-free compact double aperture four-hololens imaging system: Application to the enhancement of sensitivity and accuracy of in-plane displacement measurement. *Applied Optics, 63*, 3069–3078.

[28] INTEGRAF LLC. (n.d.). *PFG-01 holographic film plates*. https://www.integraf.com/shop/pfg-01-holographic-film-plates

[29] Mehta, P. C., & Rampal, V. V. (1993). *Lasers and holography*. World Scientific Publishing.

[30] Collier, R. J., Burckhardt, C. B., & Lin, L. H. (1971). *Optical holography*. Academic Press.