Indian Journal of Pure & Applied Physics
Vol. 63, August 2025, pp. 713-718
DOI: 10.56042/ijpap.v63i8.19586

Dual Aperture Diffractive Beam Combiner Consisting of Four Holographic Lenses: Application to Visible Light Lithography

Shweta Yadav[a],[*] Rashmi Sinha[a] & Nirmalendu Deo[b]

[a]Department of Electronics and Communication Engineering, National Institute of Technology, Jamshedpur 831 001, India
[b]Semiconductor Research and Product Development Division, Next Generation Technology Inc, Schaumburg, Illinois 1386, USA

Received: 15 May 2025; accepted:4 July 2025

Diffractive beam combiners are preferred over reflective beam combiners in interference lithography so far as tolerance to spectral bandwidth of the laser source is concerned. Dual aperture interferometer consisting of four holographic lenses has been used advantageously by several researchers in speckle metrology and laser Doppler anemometry. In Present work, an innovative application of the dual aperture interferometer consisting of four holographic lenses has been proposed and investigated for its use as a diffractive beam combiner for visible light lithography to obtain periodic patterns of high spatial frequency in a very small area equal to focal spot of the lens system. Such cost-effective patterning of semiconductor wafer with periodic arrays over very small area may find its potential application in the production of high density integrated circuited and data stores media. Spatial frequency of periodic pattern can be varied by considering proper recording and playback geometry of holographic lenses.Lightweight and low-cost holographic diffractive beam combiner using visible light may be used advantageously to reduce the present high cost of extreme ultraviolet lithography.

Keywords: Beam combiners, Holography, Lithography, Spatial frequencies, Diffraction, Visible radiation, Fringe analysis, Fabrication, Wavefronts, Lenses, Laser sources

1 Introduction

Semiconducting chips are required to be appropriately patterned to accommodate several features over very small areasfor manufacturing miniaturised ICs. Nowadays, uniform and precise periodic array pattering of high spatial frequency has gained importance in manufacturing various scientific instruments like planer and multi-axis optical surface encoders[1-5], optical sensors[6-7], photonics crystals[8-9],etc. Both masked and mask-less techniques are used by industries to fabricate periodic patterns of high spatial frequency on semiconductor wafers. The masked technique utilizes the concept of projection of the image of a suitable photomask on the substrate coated with a photoresist using good quality diffraction-limited imaging optics. After post-exposure processing of the exposed wafer, the desired periodic patterns are obtained. Projection lithography[10-12], nanoimprint lithography (NIL)[13-14], and soft lithography (SL)[15-16] are the popular masked techniques. On the other hand, electron beam lithography (EBL)[17-18] and holographic photolithography or laser interference lithography (LIL)[19-23] are categorized as mask-less techniques.

Mechanical machining for fabrication of periodic patterns of high spatial frequency is cumbersome and time consuming.However, precise narrow periodic patterns can easily be fabricated in a short time using projection lithography and laser interference lithography. In usual projection lithography, the aerial image of the photomask is strongly influenced by mask defects[24,25]and errors in the optical system.Further, based on investigation, Burner[26] and Bruce W. Smith *et.al*[27]pointed out that aberration of the optical systems may lead to imperfection, causing deterioration in the quality of projected fringes/images. Whereas,errors of the optical system and mask defect do not come into the picture for obtaining good quality periodic patterns of high spatial frequency using laser interference lithography where two coherent unaberrated wave fronts are made to interfere with each other on the substrate.

To get rid of costly precision photomask and imaging optics associated with projection lithography, laser interference lithography (LIL) is quite promising for fabrication of periodic pattern of high spatial frequency.

To reduce the present high cost of extreme ultraviolet lithography[28-31], Xiaoqing Ma *et.al*[32] and Fourkas J.T[33-34] proposed the use of visible light lithography at λ = 405 nm withsuitable photoresist

---

*Corresponding author: E-mail: 2020rsec007@nitjsr.ac.in

where the size of the Spot obtained using visible light, can further be diminished to about 1/12th of the original size utilizing the concept of nonlinear saturable absorption effect[32-36] and thereby approaching very close to theregion of nanolithography. The investigations on use of visible light lithography paved a way to reach cost effective nanoscale lithography using visible light and utilizing the concept of nonlinear saturable absorption effect. Therefore, it becomes important to develop cost effective better quality optical system for visible light lithography. Holographic lenses may be used advantageously as cost effective better alternative to their conventional counterpart to achieve diffraction limited performance almost free from all monochromatic aberrations[37-39] for visible light lithography.

Evenly spaced periodic fringe pattern of high spatial frequency over large area can be obtained using diffractive beam combiner consisting of two properly recorded sinusoidal volume phase holographic gratings. However, to generate evenly spaced fringes of high spatial frequency over a very small area as determined by spot size on focal plane of the lens, use of diffractive beam combiners consisting of two identicalholographic lenses and containing dual apertures placed diametrically opposite to each other over the lens aperture is quite promising. Investigation made on use of holographic lenses in interference lithography reveals that dual aperture interferometer consisting of compact holographic lenses can be used as cost effective diffractive beam combiner so as to obtain evenly spaced periodic pattern of high spatial frequency inside focal spot of optical system[37].

Fringewidth β formed inside the focal spot of optical system on plane of the substratein air will be= $\frac{\lambda}{2\,sin\theta}$, where θ is the semi angle subtended by the two coherent beams. This shows that for a given wavelength, larger is the semi angle subtended by the two converging beams, higher will be the spatial frequency of the periodic pattern formed within the focal spot of the lens. Therefore, for achieving alarge angle subtended by two converging beams on the focal plane, holographic lenses of large diameter and short focal length (low f-number lenses) are required.

A holographic lens is recorded on a high-resolution holographic plate by recording the interference pattern of a spherical wavefront diffracted from a pinhole of diameter ‘D’ with a mutually coherent plane wavefront. The f-number (f/#) of the holographic lenses related to the diameter ‘D’ of the pinhole through which the spherical diverging wave emerges during recording, by the relation $f/\# = \frac{D}{2.44\,\lambda}$[40-41]. Therefore, pinhole size D poses a limit on achievable f-number. To overcome the limitation imposed by the finite size of a pinhole on thefabrication of a holographic lens of large diameter and short focal length to be used in a dual aperture diffractive beam combiner , the concept of designing dual aperture interferometers for speckle metrology and laser Doppler anemometryas proposed in references[41-47] can be exploited advantageously to obtain unaberrated converging diffracted waves through the two apertures leading to formation of evenly spaced periodic pattern of very high spatial frequency. The two identical compact holographic lenses in contact gives diffraction-limited imaging performance almost free from all monochromatic aberrations under proper recording and playback geometry[41-46].

The present work focuses on investigation on a new application of a dual aperture diffractive beam combiner consisting of four identical holographic lenses for visible light interference lithography to obtain periodic patternsof high spatial frequency inside the focal spot of the lens system. Such cost effective patterning of semiconductor wafer with periodic arrays over very small area may find its potential application in the production of high density integrated circuited and data stores media. Recording geometry of holographic lenses for the fabrication of diffractive beam combiner is presented. Interference fringes obtained inside the focal spot of typical diffractive beam combiner as recorded by CCD camera after magnifying the fringes are presentedto establish the feasibility of such combiners for their use in visible light interference lithography.

2 Recording of Holographic Lenses for the Proposed Diffractive Beam Combiner

For recording holographic lenses of high diffraction efficiency dichromated gelatin is the preferable recording medium[48], however for the present investigation, due to laboratory constraints on the availability of suitable laser for hologram recording in dichromate gelatin medium, four typical identical holographic lenses (lens diameter = 26 mm, focal length =200 mm, inter-beam angle = 22^0)were recorded on high-resolution silver halide emulsion

(PFG-01) holographic plates of resolution 3000 lines per mm using a He-Ne laser of power 12 mW (Model no.30993, Newport make) operating at wavelength λ=0.6328 µm.

Schematic of the geometry for recording holographic lenses is shown in Fig. 1.The laser beam is split up into two parts using a beam splitter.One of the beams is processed to obtain a plane wavefront which falls on the recording film normally such that emulsion side faces the incident beam. The other beam is processed to obtain a spherical wavefront which falls on the recording plane (holographic plate) making a typical angle θ (θ = 22º approximately) with the collimated beam of light. Photograph of the experimental setup on which the holographic lenses were recorded is shown in Fig. 2.The post exposure processing of exposed film was done using standard procedures[49-51].

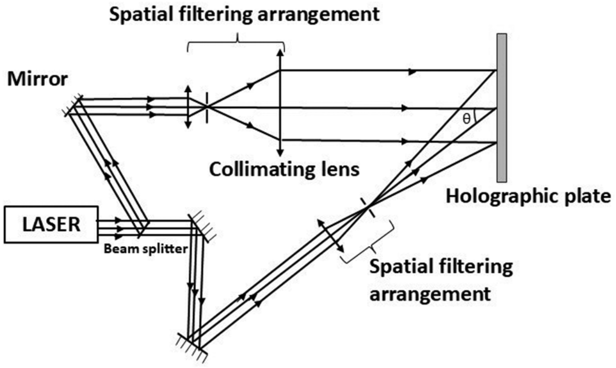

Fig. 1 — Schematic of recording geometry for holographic lenses required for fabrication of dual aperture diffractive beam combiner

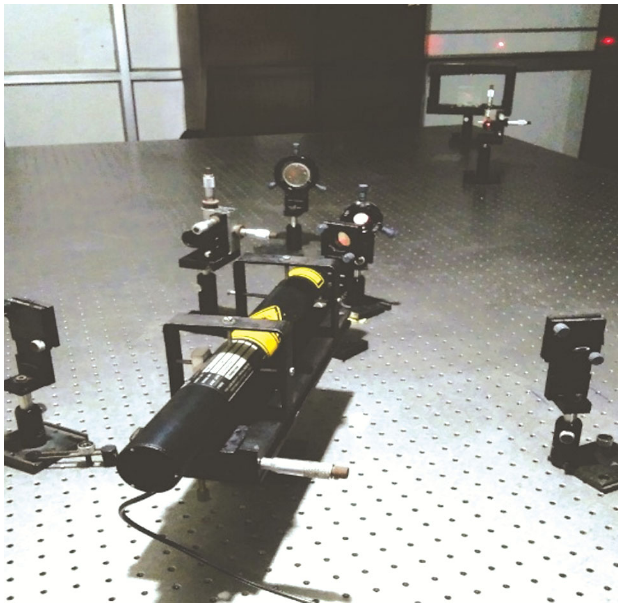

Fig. 2 — Experimental setup on which holographic lenses were recorded

3 Playback Geometry of Holographic Lenses for Fabrication of Dual Aperture Diffractive Beam Combiner Cosisting of Four Holographic Lenses

An experimental setup for realizing a dual aperture diffractive beam combiner consisting of four holographic lenses to obtain periodic structure/fringes is shown in Fig. 3. The dual aperture laser beam combiner has two identical arms. The upper arm consists of two identical holographic lenses HL_1 and HL_2. The lower arm also contains two identical holographic lenses HL_3 and HL_4. HL_1 is used in the system such that the spherical wavefront diverging from a narrow pinhole of size 5 µm illuminates the lens from the back side of the photosensitive emulsion, whereas, at the time of recording the emulsion side faces the incident spherical and plane wavefront. This arrangement ensures the generation of plane wavefront diffracted from $HL_{1,}$ which illuminates the second lens HL_2 to obtain a converging beam at the focal plane of the lens HL_2. Similarly, for the lower arm, HL_3 generates aplane wavefront which illuminates HL_4 to give rise toa converging beam on thefocal plane of HL_4. The separation between the compact holographic lenses HL_1 and HL_2 of upper armHL_3 and HL_4 of lower arm are adjusted such that spherical wavefront coming out of the pinhole the lenses of each arm at an angle 22^0fromthe same distance which was maintained at the time of recording. Here aperture B consisting of holographic lenses HL_3 and HL_4 is the mirror image of aperture A which can be generated by rotating system of lenses in aperture A through 180° about an axis XX'. The converging beams diffracted through thetwo identical arms (HL_1HL_2 and HL_3HL_4) meet at

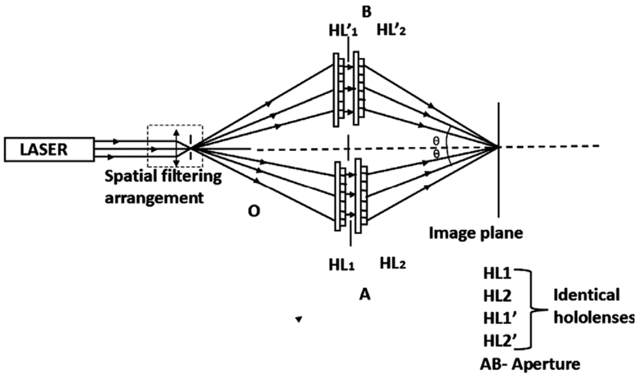

Fig. 3 — Schematic of typical dual aperture diffractive beam combiner consisting of holographic lenses

a common focal spot leading to formation of interference fringes within the focal spot.

Let us first discuss the performance of aperture A consisting of HL_1 and HL_2. For the case of identical wavelengths for the recording and reconstruction process, the radius of curvature of a wave propagated through HL_1 is given by[40-46].

$$\frac{1}{R_{I_1}} = \frac{1}{R_{c_1}} - \left(\frac{1}{R_{O_1}} - \frac{1}{R_{r_1}}\right) \quad \dots (1)$$

Where the subscript I_1, C_1, O_1,and r_1 stand for image, reconstruction, object, and reference beams for hololens HL_1.

For the present experimental setup, the spherical wavefront coming from the point source illuminates the 1st hololens HL_1 from the back side of the emulsion which behaves as a reconstructing wave. Hence,

$$R_{C_1} = R_{O_1}$$
$$R_{I_1} = R_{r_1}$$
$$\text{But} R_{r_1} = \infty \text{, therefore } R_{I_1} = \infty \quad \dots (2)$$

i.e.,theoutcoming beam from HL_1 is a plane wave.The hololens HL_2 is used in the system such that it is being illuminated from the back side of the emulsion by a plane wave coming out of 1sthololens, the radius of curvature of the wave propagated from HL_2 is given by

$$\frac{1}{R_{I_2}} = \frac{1}{R_{c_2}} - \left(\frac{1}{R_{O_2}} - \frac{1}{R_{r_2}}\right) \quad \dots (3)$$

$$\text{Hence, } R_{c_2} = R_{r_2} = \infty, \text{ and} R_{I_2} = -R_{o_2} \quad \dots (4)$$

This shows that the radius of curvature of the wave coming out of HL_2 is equal in magnitude to the radius of curvature of the object wave.The '-' sign shows that the outgoing wave is converging because the recording geometry shows that $R_{o_2}$is a diverging wave.

Aberration analysis of present configuration of holographic lenses are also fully discussed in references[36-42]

4 Formation of Fringes by a Typical Four-Hololens Dual Aperture Diffractive Beam Combiner

As discussed in section I,for a given wavelength λ, the width of the fringes formed within the focal spot depends on the semi-angleθ between the two diffracted interfering beams.The semi-angle θ can be controlled by adjusting the angle between the plane wave and spherical wave at the time of recording four identical holographic lenses required for the fabrication of a dual aperture diffractive beam combiner. Figure 4 shows the schematic of the experimental setup to generate the fringe pattern on the focal plane of the dual aperture diffractive beam combiner consisting of four identical hololens.

A mask with circular aperture was positioned between the two lenses of each arm symmetrically as shown in Fig. 4 to obtain two identical spherical converging waves coming from each arm. The interference fringes appear on the focal plane of the lenses HL_2 and HL_4 due to the superposition of these two converging spherical waves. A typical microscope objective of magnification 20-X mounted on a three-axis spatial filter (Model- M900, Newport makes) was used to magnify the fringes formed within the focal spot, and a CCD camera (Photometric Cool SNAP K4, Make - Roper Scientific) was positioned approximately 64 cm from the microscope objective to record the fringes. Figure 5 shows a section of magnified fringe pattern with their corresponding intensity profile where the intensity profile was plotted along a line perpendicular to the fringes.Further, the fringe pattern was recorded on a high-resolution silver halide film (PFG-01) after magnifying the fringe pattern. Figure 6 shows a photograph of a section of the magnified fringe pattern recorded on the holographic plate (PFG-01).

In order to measure the width of the fringes, a standard travelling microscope, whose resolution is 10 µm, was positioned approximately 64 cm from the microscope objective. The average value of the measured fringe width was found to be approximately 160.96 µm. All holographic lenses used in the experiment were recorded at a typical angle of 22°

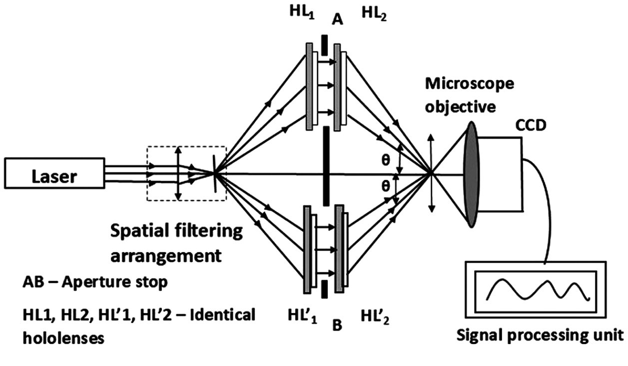

Fig. 4 — Schematic of experimental arrangement for obtaining interference fringes using a diffractive beam combiner consisting of four holographic lenses

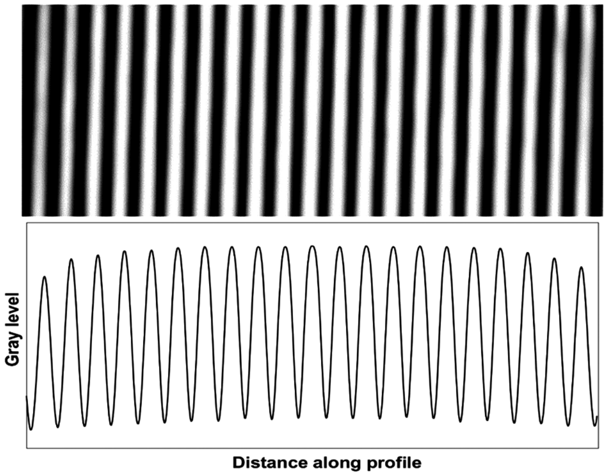

Fig. 5 — Magnifiedimage of a section of fringe pattern with their corresponding intensity profile obtained using the diffractive beam combiner

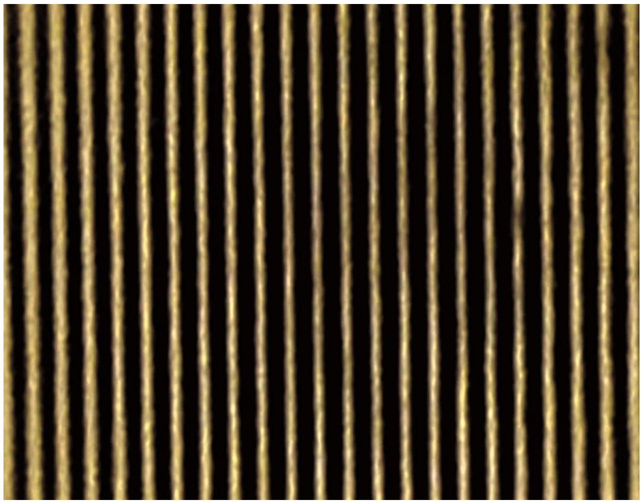

Fig. 6 — Photograph of a section of fringe patternrecorded on holographic plate PFG-01

between the plane and spherical beams (Fig. 1) hence the semi-angle(θ) formed by the diffracted beams from the two arms of the dual aperture diffractive beam combine is also 22° . Using the formula, $\beta = \frac{\lambda}{2sin\theta}$, the theoretical value of fringe width for the system used was calculated to be 0.845 μm$\left(\frac{\lambda}{2sin\theta} = \frac{0.6328}{2\,(\sin 22^0)} = 0.845\ \mu\mathrm{m}\right)$. However, after applying the demagnification formula to the average value of the measured fringe width, the observed fringe width was determined to be approximately 2.12 μm.

5 Conclusion

For patterning semiconductor wafers with periodic structures of high spatial frequency, visible light interference lithography is a cost-effective technique which does not require expensive masks and optical systems as required in projection lithography. Diffractive beam combiners consisting of holographic optical elements are cost-effective and beneficial for laser interference lithography so far as tolerance to spectral bandwidth of lasers is concerned.

Aberration-free diffraction-limited conventional lenses of large diameter and short focal length are costly, bulky and require time-consuming processing for their production. Therefore, low-cost, lightweight holographic lenses may be used advantageously as diffractive beam combiners. Present investigation shows that a dual aperture diffractive beam combiner consisting of four identical holographic lenses can be used advantageously in visible light lithography to obtain diffraction-limited performance nearly free from all monochromatic aberrations to generate undistorted converging beams diffracted through the twin apertures under proper recording and playback geometry of holographic lenses so as to obtain evenly spaced, undistorted periodic fringe pattern of high spatial frequency over a very small area equal to size of focal spot of the lens system.

Fringes shown in Fig. 5 and Fig. 6 obtained from the typical dual aperture diffractive beam combiner establishes the feasibility of advantageous use of the system in interference lithography to generate periodic pattern of very high spatial frequency over a very narrow area. In the present investigation, we could achieve fringes of width 2.12 μm on the focal plane of the system using holographic lenses recorded with an inter-beam angle of 22° between the plane and spherical beams and a He-Ne laser of wavelength 0.6328 μm. However, the fringe width can further be reduced by using holographic lenses recorded with a larger beam angle between the plane and spherical beams in the four-hololens system. Further, the fringe width obtained using visible light lithography may be utilized advantageously by researchers to reduce fringe width to about 1/12th of the original fringe width, thereby approaching very close to the region of nanolithography.

The dual aperture four-hololens diffractive beam combiner is inexpensive and gives almost aberration free performance to diffract converging wave fronts from the two apertures under proper recording and playback geometry. Tolerance to spectral bandwidth of lasers of such diffractive beam combiner is more attractive so far as cost reduction of interference lithography is concerned because lasers operating at a single frequency are costlier than lasers of finite spectral bandwidth.

Acknowledgements

Authors are thankful to Professor H.L Yadav, photonics laboratory, department of Physics, National Institute of Technology Jamshedpur for hisfruitful discussion throughout preparing this manuscript.

References

1 Li X, Gao W, Muto H, Shimizu Y, Ito S, & Dian S, *Precis Eng*, 37 (2013) 771.

2 Wang S, Luo L, Zhu J, Shi N & Li X, *Sensors,* 22 (2022) 9047.

3 Hsieh H L & Pan S W, *Opt express*, 23 (2015) 2451.

4 Gao W, Araki T, Kiyono S, Okazaki Y & Yamanaka M, *Precis Eng*, 27 (2003) 289.

5 Hong Y, Sato R, Shimizu Y, Matsukuma H & Gao W, *Sensors,* 22 (2022) 3010.

6 Zheng Y, Tang X, Yang Y, Wang W & Guoqiang Li, *Opt Lett,* 45 (2020) 4843

7 Yan N, Qiu Y, He X, Tang X, Hao Q & Chen M, *Materials,* 16 (2023) 3216.

8 Konishi K, Akai D, Mita Y, Ishida M, Yumoto J & Kuwata-Gonokami M, *Optica*, 7 (2020) 855.

9 Qi Z, Hu G, Deng C, Sun H, Sun Y, Li Y, Liu B, Bai Y, Chen S & Cui Y, *Nanophotonics*, 11 (2022) 4273.

10 Stuerzebecher L, Fuchs F, Harzendorf T & Zeitner U D, *Opt Lett*, 39 (2014) 1042.

11 Rogers J A, Paul K E, Jackman R J, & Whitesides G M, *Appl Phys Lett, 70 (1997)* 2658.

12 Jin H, Haldar S, Bruck H A, & Lu W Y, *Exp Mech*, 51 (2011) 565.

13 Tang M, Xie H, Zhu J, Li J & Li Y, *Opt Express*, 20 (2012) 2942.

14 Wang Q, Kishimoto S, Tanaka Y & Kagawa Y, *Opt Lasers Eng,* 51 (2013) 944.

15 Qin D, Xia Y & Whitesides G, *Nat Protoc,* 5 (2010) 491.

16 Dai X & Xie H, J. *Micromech Microeng*, 25 (2013) 095013.

17 Kishimoto S, Egashira M & Shinya N, *Opt Eng,* 32 (1993) 522.

18 Xing Y M, Kishimoto S & Shinya N, *Exp Mech*, 44 (2004) 562.

19 Liu R, Cao L, Liu D, Wang L, Saeed S, Wang Z, *Nanomater*, 13 (2023) 1818.

20 Lu C & Lipson R H, *Laser Photonics Rev*, 4 (4) (2010) 568.

21 Shimizu Y, *NNM*, 4 (2021) 3.

22 Purvis A, Toriz-Garcia J J, Cowling J J, Williams G L, Seed N L, McWilliam R, Soulard F B & Ivey P A, *Appl Opt, 2014*, DW1B.1.

23 Kondo T, Juodkazis S, Mizeikis V, Misawa H & Matsuo S, *Opt Exp*, 14 (2006) 7943.

24 Maurer W & Donald J Samuels, *Masks for 0.25-um lithography*, (1994) 26.

25 Wong A K, Ferguson R A & Mansfield S M, *The mask error factor in optical lithography* 13 (2000)325.

26 Brunner T A, *IBM J Res Dev,* 41 (1997) 57.

27 Smith B W & Schlief R, *Optical Microlithography XIII*, SPIE, 2000.

28 Levinson H J,*Principles of Lithography,* 2ndEdn, SPIE Press (Bellingham), 2005.

29 Bakshi V, *EUV Lithography*, SPIE press (Bellingham),2018.

30 Naulleau P, *Nanofabrication Handbook*, Vol 180, edited by Cabrini S & Kawata S, Elsevier (Amsterdam, Netherlands), (2019).

31 Kazazis D, Santaclara J G, Schoot V, Mochi J & Ekinci I Y, *Nat Rev Methods Primers,* 4 (2024) 84.

32 Ma X & Wei J S, *Nanoscale*, 3 (2011) 1489.

33 Fourkas J T, *J Phys Chem Lett*, 1 (2010) 1221.

34 Fourkas J T & Tomova Z, *Optical Microlithography XXVIII*,), SPIE, (2015) 74.

35 Menon R & Smith H I, *J Opt Soc Am ,*23 (2006) 2290.

36 Tofighi S & BahrampourA R, *J Opt,* 14 (2012) 125004.

37 Yadav S, Sinha R, Deo N & Yadav H L, *Fabrication of periodic fringe pattern of high spatial frequency for visible light lithography using dual aperture compact holographic lens system,* Novel Patterning Technologies 2025 SPIE, 2025,47

38 Yadav S, Sinha R, Deo N & Yadav H L, 2022 international interdisciplinary conference on mathematics, engineering and science IEEE (MESIICON), (Durgapur) 2022.

39 Yadav S, Sinha R, Deo N & Nath V, *IETE J Res,* (2024) 1.

40 Born M & Wolf E, *Principles of optics*, 7thEdn, Cambridge university press, (1999).

41 Khan A A & Yadav H L *Opt& Lasers Technol,* 167 (2023) 109660.

42 Khan A A & Yadav H L *Opt Lasers Engg,* 152 (2022) 106979.

43 Yadav H L, Kumari N, Bhushan R, Mallick A, Gupta B N, *Opt Lasers Engg,* 41 (2004) 869.

44 Jayaswal R K, Yadav H L & Barhai P K, *Optik,* 126 (2015) 1700.

45 Khan A A & Yadav H L, *Appl Opt,* 63 (2024) 3069.

46 Ghosh A & Nirala A K, *Opt Spectrosc,* 118 (2015 482

47 Ghosh A & Nirala A K,*Opt Laser Technol,* 167 (2023) 109660.

48 Chang B J & Leonard C D, *Appl Opt*, 18 (1979) 2407.

49 Saxby G & Zacharovas S, *Practical Holography*, 4thEdn, CRC Press, (2015).

50 Collier R J, *Optical Holography*, *2ndEdn, Academic Press*, (1971).

51 Hariharan P, *Basics of holography, Cambridge University Press*, (2002).