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Self-wavefront interference using transverse splitting holography

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ABSTRACT

Manufacturing diffractive lenses with a high Numerical Aperture (NA) is a challenging task due to limitations in lithography methods and the inverse relation between the width and the radius of the zones. With low-resolution lithography techniques such as photolithography, the zone width reaches the lithography limit within a short radius, resulting in low-NA diffractive lenses. With high-resolution electron beam lithography, it is possible to manufacture high-NA diffractive lenses by prolonged writing. However, in this case, the width of the outermost zones becomes subwavelength, inducing undesirable polarization effects. In this proof-of-concept study, a holography solution has been demonstrated to enhance the imaging resolution of low-NA diffractive lenses. The light from an object is partly modulated by the low-NA diffractive lens and interfered with the remaining unmodulated light outside the area of the diffractive lens. This self-interference hologram of the object is processed in the computer with the point spread hologram to reconstruct the object with a resolution corresponding to the NA of the image sensor. This new imaging technique is called Self-Wavefront Interference using Transverse Splitting Holography (SWITSH). A resolution enhancement of ~10 times has been demonstrated using a low-NA diffractive lens and SWITSH compared to direct imaging with the same low-NA diffractive lens.

Introduction

Imaging objects with a high resolution requires lenses with a large Numerical Aperture (NA), as the lateral resolution is ~λ/NA [1]. While the challenge in manufacturing large NA refractive lenses is the requirement of a large amount of material and its weight, manufacturing large-area diffractive lenses has a different problem. The radius of the m^{th} 2π-period zone is given as $r_m \approx \sqrt{2mf\lambda}$, where f is the focal length of the diffractive lens and λ is the design wavelength [2]. Therefore, when the zone number m increases, the spacing between the zones, given as $\Delta = \sqrt{2f\lambda}\left(\sqrt{m} - \sqrt{m-1}\right)$, decreases and reaches the lithography limit of photolithography. If the lithography limit can be extended by replacing photolithography with electron beam lithography, the problem still persists due to the above relation of Δ with zone number m: as Δ reaches the wavelength limit, it causes undesirable polarization-sensitive behaviours. This is a fundamental problem in diffractive optics. Recently, a computational imaging solution to the above problem was developed by replacing a single large NA diffractive lens with multiple low NA diffractive lenses and collecting light to multiple points on the sensor instead of a single point [3]. The multiple low-resolution images were reconstructed into a single high-resolution image using computational reconstruction algorithms. Even though the above is a useful solution, the method still requires manufacturing a large-area diffractive element.

Methods

In this study, we propose a radical holographic approach that can significantly improve the lateral resolution beyond the limit imposed by the low NA of the diffractive lens. This idea originated from the fact that high-NA diffractive lenses are small with a diameter of tens of

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micrometers to a few hundred micrometers, whereas the size of a typical image sensor is a few mm. This gap allows an opportunity to improve the resolution limit from the NA of diffractive lenses to the NA of image sensors. The optical configuration of the holography system is shown in Fig. 1. Only incoherent illumination is considered in this study. When light from an object is incident on the low-NA diffractive lens, part of the light that is within the area of the diffractive lens is focused to a point, and the light from the object that lies outside the area of the diffractive lens continues to propagate without any modulation. However, at a distance beyond the focus point, the light modulated by the diffractive lens interferes with the unmodulated light, resulting in a self-interference pattern, as both waves are derived from the same object point. This self-interference pattern has higher spatial frequencies that were not collected by the diffractive lens. Therefore, if the hologram can be reconstructed, then the resulting image should have a higher resolution than the image recorded directly from the low-NA diffractive lens. In principle, the lateral resolution can be increased from $1.22\lambda z_1/D_1$ to $1.22\lambda(z_1+z_2)/D_2$, as shown in Fig. 1.

The resolution enhancement in SWITSH is due to an interference between light that goes to a regular lens and light detected with higher NA that detours the lens. This lost light contains image information with a higher resolution than that from the other beam. Therefore, the recorded hologram contains high-resolution information where the low-resolution beam is used as a reference beam in the holographic recording. The reconstruction process of the hologram restores the image with the high-resolution features stored in the hologram. With a low-NA diffractive lens, only the light that arrives within the cone with a diameter of D_1 takes part in the imaging process, so the resolution limit is given as $1.22\lambda z_1/D_1$. In the proposed new imaging concept, in addition to the light arriving within the cone with a diameter of D_1, the light arriving beyond the lens but within the diameter of the sensor D_2 participates in the imaging process. The new resolution limit is therefore $1.22\lambda(z_1+z_2)/D_2$. To achieve super-resolution, it is sufficient to satisfy the condition $D_2/(z_1+z_2)>D_1/z_1$. This new approach is called Self-Wavefront Interference using Transverse Splitting Holography (SWITSH). A previous study was reported using a ring-shaped bifocal lens to record and reconstruct incoherent digital holograms [4].

Experiments

A preliminary experiment was carried out using an optical setup, as shown in Fig. 2(a). A spatially incoherent light source (Thorlabs, 170 mW, $\lambda = 650$ nm and $\Delta\lambda = 20$ nm) was used for illumination. An SLM (Thorlabs Exulus HD2, 1920×1200 pixels, pixel size = 8 μm) was used to display the low NA diffractive lens. An image sensor (Zelux CS165MU/M 1.6 MP monochrome CMOS camera, 1440×1080 pixels with pixel size ~3.5 μm) was used for recording the holograms. A pinhole with a diameter of 10 μm was used for recording the point spread hologram (PSH). The light from an object was collimated by a refractive lens with a focal length of 5 cm and incident on the SLM on which a diffractive lens with a focal length of 4 cm and a diameter of 0.8 mm was displayed. The distance between the SLM and the image sensor was ~18 cm. An event of shifting the location of the pinhole to four different locations by ±20 μm was carried out to create a multipoint object. At every new location, the hologram was recorded, and after the shifting procedure, all four holograms were summed to obtain the hologram of the multipoint object. To reconstruct the image of the object, a recently developed computational algorithm, the Lucy-Richardson-Rosen algorithm (LRRA), was used [3,5]. The schematic of LRRA is given in Fig. 2(b). There are three parameters of the algorithm, namely, α, β and the number of iterations n. The values of α and β are tuned between -1 and 1, and n is a positive integer. Extensive details of the control and operation of LRRA are discussed in many research articles, including [3,5,7,8]. The optimal values of α, β and n for this study are 0.1, 1 and 6, respectively. The image of the PSH, object hologram, reconstruction results, direct image with a low NA diffractive lens and reference direct image with a maximum NA diffractive lens are shown in Figs. 2(c)-2(g), respectively. In direct imaging with a low NA diffractive lens, the four points could not be discriminated, but with the SWITSH with the same 0.8 mm diameter diffractive lens, the four points could be discriminated. The exposure time for recording PSH and the object hologram of four shifted points is 1.881 s. The exposure times for direct imaging with a 0.8 mm diameter diffractive lens and 9.6 mm diameter diffractive lens are 0.702 s and 20 ms, respectively. The plot of the imaging result of a point by direct imaging using a low NA diffractive lens and SWITSH are compared in Fig. 2(h). The theoretical and experimental values of resolution enhancement were 12 and 9.33, respectively.

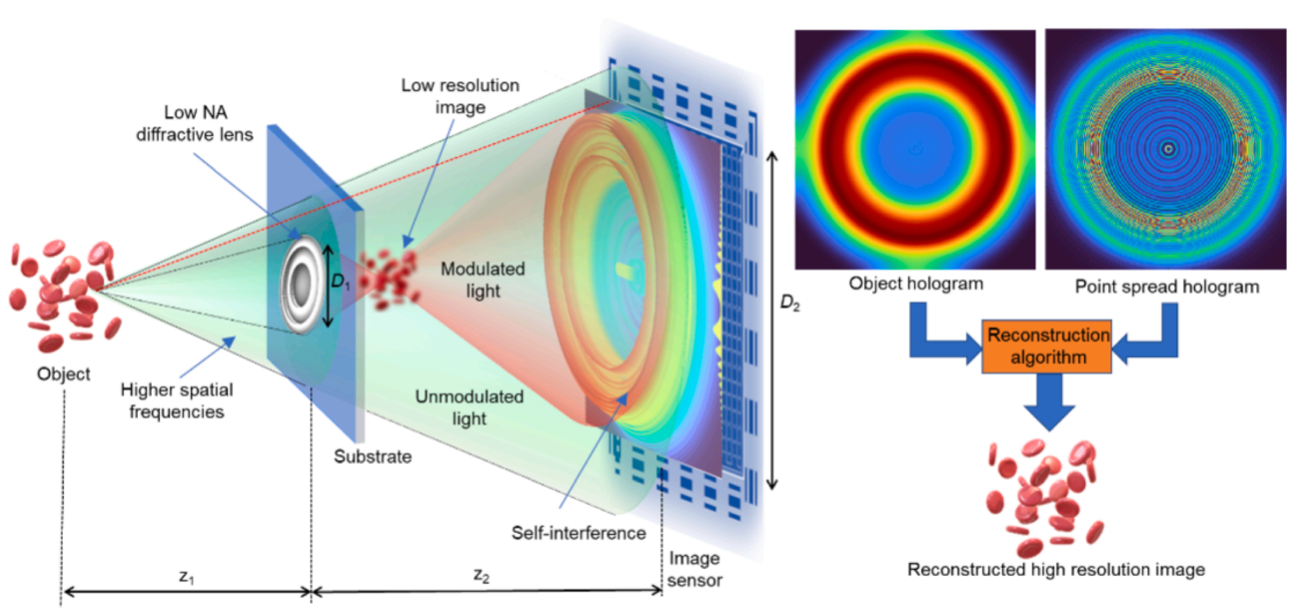

Fig. 1. Concept figure of SWITSH. Light from an object is partly modulated by a low-NA diffractive lens and interferes with the unmodulated light to create the self-interference hologram. The object hologram and the point spread hologram are processed to reconstruct a super resolution image of the object. The red dotted line indicates the inequality $D_2/(z_1+z_2)>D_1/z_1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

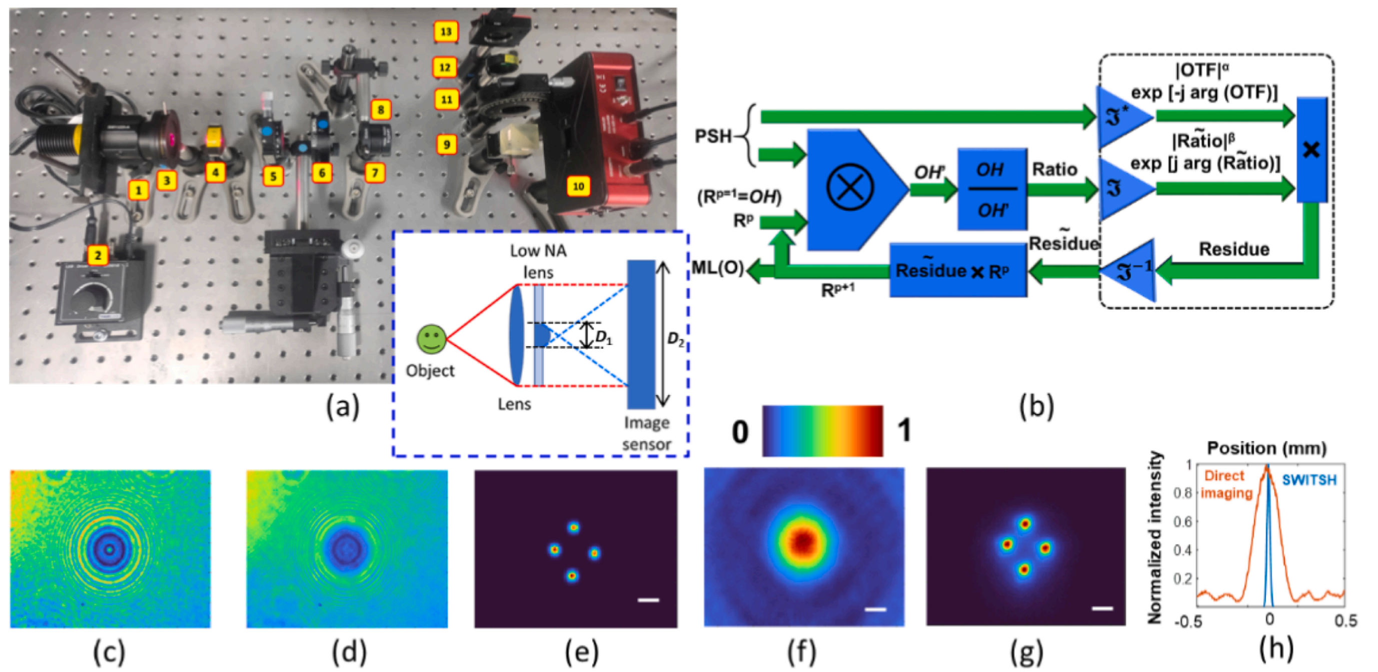

Fig. 2. (a) Photograph of the experimental set up. (1) LED, (2) LED power controller, (3) iris, (4) refractive lens (f = 50 mm), (5) polarizer P1, (6) object/pinhole, (7) iris, (8) refractive lens (f = 50 mm), (9) beam splitter, (10) SLM, (11) polarizer P2, (12) bandpass filter, and (13) image sensor. (b) Schematic of LRRA: OTF- optical transfer function, ML – maximum likelihood, *p* – iteration number, *O* - object, *OH* – object hologram, *OH'* – estimated object hologram, $\Im$ - Fourier transform, $\Im^*$ - complex conjugate operation following a Fourier transform, $\Im^{-1}$ – inverse Fourier transform, R^n and $R^{(n+1)}$ are the n^{th} and $(n+1)^{th}$ solutions, OH was used as the initial guess solution R^1, ~ Fourier transform of a variable, $\otimes$ - 2D convolution. (c) PSH, (d) object hologram, (e) reconstruction result using LRRA, direct imaging with (f) 0.8 mm diameter diffractive lens and (g) 9.6 mm diameter diffractive lens. (h) Plot of the point image obtained from direct imaging with a diffractive lens and the reconstructed point for SWITSH. The optical configuration equivalent to an object at infinity is shown as an inset.

Conclusion

A proof-of-concept study of a novel super resolution imaging technique SWITSH has been proposed and demonstrated. A resolution enhancement close to *an order* was achieved in the preliminary experiment. The area ratio between SWITSH and direct imaging was only 0.7%, which is significant. Unlike existing incoherent digital holography techniques that follow the division of the complete wavefront on a transverse aperture, SWITSH follows the division of the wavefront across a transverse aperture, making it unique compared to the existing methods. In the proposed idea, spatially incoherent illumination is used to illuminate the object at a range of angles, which redistributes low spatial frequencies along with high spatial frequencies at high diffraction angles. Consequently, some of the light arriving at smaller angles that do not contribute to the hologram does not impact the performance of the system [6].

Unlike existing incoherent holography methods that require the recording of multiple phase-shifted holograms for every object, the proposed method requires the recording of only one hologram for an object and a PSH recorded only once after building the set up. This single shot capability makes the method suitable for recording dynamic scenes with super resolution. While a proof-of-concept study has been reported in this micro article, which opens pathways to realize super resolution imaging with different architectures and phase masks, further studies are needed to fully understand the potential of SWITSH for different imaging conditions. The proposed method can be used to build super-resolution imaging systems with microlenses, ball lenses and even microdroplets of lithography resists at a significantly low cost. In all the above cases, except for the computational reconstruction as required in any indirect imaging method, the imaging process is similar to most optical microscopes. Since the recorded intensity distribution is a hologram, the 3D information can be reconstructed. We believe that the developed SWITSH will enable low NA diffractive elements in the form of diffractive lenses and coded apertures to image with a super resolution by utilizing the large area of an image sensor. Therefore, SWITSH can directly impact coded aperture imaging, digital holography and advanced manufacturing by reducing the cost and time of manufacturing large area diffractive elements.

Consent to publication

All authors consent to publication.

Availability of data and materials

The data and materials can be obtained from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Andrei-ioan Bleahu: Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Shivasubramanian Gopinath:** Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tauno Kahro:** Investigation, Validation, Writing – review & editing. **Soon Hock Ng:** Investigation, Validation, Writing – review & editing.

Kaupo Kukli: Conceptualization, Investigation, Resources, Supervision, Writing – review & editing. **Aile Tamm:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. **Saulius Juodkazis:** Funding acquisition, Conceptualization, Investigation, Resources, Supervision, Writing – review & editing. **Joseph Rosen:** Conceptualization, Investigation, Resources, Software, Validation, Supervision, Writing – original draft, Writing – review & editing, Visualization. **Vijayakumar Anand:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Supervision, Funding acquisition, Resources, Project administration, Software, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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