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Realizing Large Area Diffractive Lens using Multiple Sub-Aperture Diffractive Lenses and Computational Reconstruction

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ABSTRACT

Manufacturing large area diffractive lenses (DLs) is a challenging task, as in many cases, the outermost zone width surpasses the photolithography limit and even the wavelength limit. In this study, a computational imaging method is proposed which allows realizing a single large area strong DL with multiple sub-aperture weak DLs. The sub-aperture DLs collect light and focus it into multiple points within the area of the image sensor instead of a single point which increases the width of the zones of the DL. A computational reconstruction method was applied to reconstruct a high-resolution image from the multiple low-resolution images.

Keywords: Computational imaging, Golay telescope, Lucy-Richardson-Rosen algorithm, diffractive lens, sub-aperture, holography.

1. INTRODUCTION

Imaging systems play a vital role in the modern scientific world. There are many types of imaging systems: direct and indirect imaging systems. In direct imaging systems, the image of the object is captured directly by an image sensor in one step.¹ In indirect imaging systems, such as coded aperture imaging systems² and digital holography,³ multiple steps are involved in the imaging process. The above two methods can be executed by coherent as well as incoherent light sources. Incoherent digital holography (IDH) is one of the widely used methods for recording objects with spatially incoherent light. In IDH, the hologram is formed by self-interference, where light from an object point is split into two, differently modulated and interfered. Achieving self-interference requires complicated optical configurations such as rotational-shearing interferometry,^{4,5} multiple viewpoint projection methods,^{6,7} conoscopic holography,^{8,9} optical scanning holography,^{10,11} Fresnel incoherent correlation holography^{12,13} and coded aperture correlation holography (COACH).¹⁴ The recorded hologram can be processed using computational algorithms to obtain 3D image of the object.^{15,16} Coded aperture imaging (CAI) is another widely used indirect imaging method which has a quite interesting research history.¹⁷⁻²⁰ With the development of COACH, IDH and CAI was connected leading to the development of interferenceless COACH (I-COACH).²¹ In I-COACH, light from an object is modulated by a quasi-random coded phase mask and the scattered intensity distribution was recorded. Recently, I-COACH has been realized using deterministic optical field generated from a Cassegrain objective lens.²²

In this study, I-COACH has been attempted to improve telescopes. Telescopes, in general, require a lens with a large diameter. Considering that diffractive lenses (DLs) require lesser material compared to refractive lenses and are thinner than refractive lenses, DLs can be used for building telescopes. But the manufacturing of large DLs is challenging because the outermost zones reaches either lithography limit or wavelength limit. Golay-type synthetic aperture telescope is one of the powerful tools to obtain super resolution.^{23,24} In this approach, a single lens is replaced by multiple sub-aperture lenses. The multiple images recorded are processed using computational reconstruction methods to obtain a high-resolution image.^{25,26} In this study, the single large DL is replaced by multiple sub-aperture DLs. When a single DL

is used, it is required to bend the light to large angles to focus light to a single point. But in the case of the multiple sub-aperture DLs, light is focused at different points within the sensor area and so it is sufficient to bend light to smaller angles. The above diffractive element is called as Large Area Diffractive Lens with Integrated Sub-Apertures (LADISA). Since multiple sub-aperture DLs are used, the intensity distribution captured by the sensor consists of low-resolution images that are overlapped. Using computational reconstruction methods, the low-resolution image can be reconstructed into a high-resolution image.

2. METHODS

The optical configuration of computational imaging using LADISA is shown in Figure 1. For instance, LADISA with four sub-apertures is shown. Light from a distant object is incident on the LADISA which creates four low resolution images on the image sensor. These low-resolution images are processed with the synthesized or recorded point spread functions (PSFs) using computational reconstruction algorithms to obtain a high-resolution image of the object. In this study, two computational reconstruction methods namely non-linear reconstruction (NLR)²⁷ and Lucy-Richardson-Rosen algorithm (LRRR)²² are used for reconstructing the high-resolution image from the recorded low-resolution images. The schematic of the LRRR is shown in Figure 2 in which NLR is shown with dotted lines.

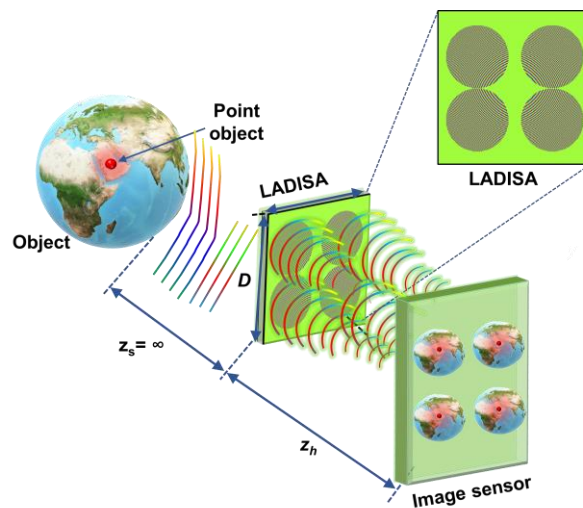


Figure 1. Optical configuration of LADISA with four sub-apertures.

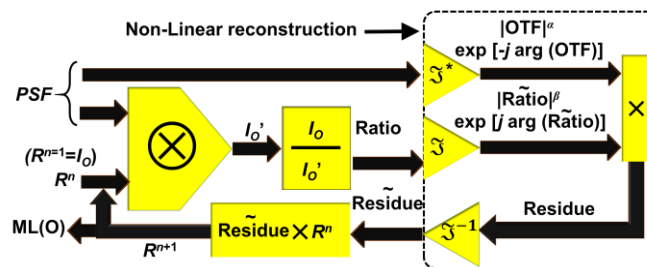


Figure 2. Representation of LRRR. ML – maximum likelihood; OTF – optical transfer function; n – number of iterations; \otimes - 2D convolutional operator; I_o – object intensity; \mathfrak{F} - Fourier transform; $*$ - complex conjugate, $^{-1}$ – inverse; R^{n+1} – $(n+1)^{\text{th}}$ solution, PSF – point spread function.

3. SIMULATION

The simulation was carried out in MATLAB with a matrix size of 500 pixels, $\lambda = 650$ nm and pixel size of $10 \mu\text{m}$. In the simulation, LADISA was constructed using eight sub-apertures as shown in Figure 3 (a). The image of the PSF, object, object intensity distribution and reconstruction results by NLR and LRRR are shown in Figures 3(b)-3(f) respectively.

As seen from the results, LRRA performed better than NLR with lesser background noise and higher resolution. The ring pattern present in the eye is resolved in the case of LRRA but the ring is seen as a single point in the case of NLR and the low-resolution images.

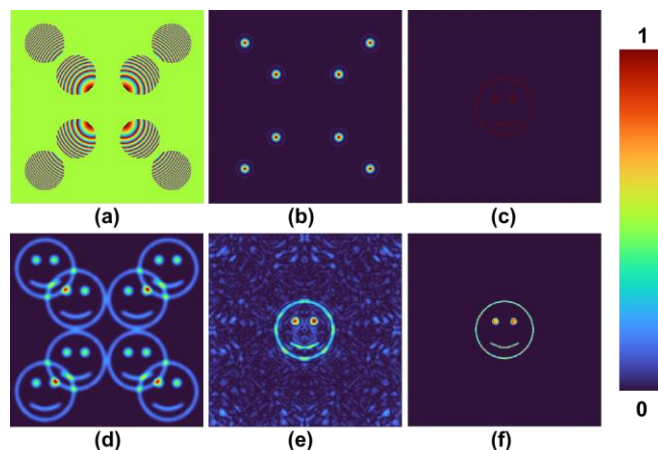


Figure 3. (a) LADISA, (b) PSF, (c) Object, (d) Low resolution images obtained from LADISA, high resolution images obtained from (e) NLR and (f) LRRA.

4. EXPERIMENTS

An optical experiment was carried out with a laboratory model of telescope.²⁸ A spatially incoherent light source (Thorlabs, 170 mW, $\lambda = 650$ nm and $\Delta\lambda = 20$ nm) was used for illumination of objects. A $10\text{ }\mu\text{m}$ pinhole was used for recording the PSF and an USAF object (Group – 5, Element 1) number 5 and gratings with a line width of $15.63\text{ }\mu\text{m}$ was used as the test object. To realize large distance, the light from the object was collimated by a refractive lens. The collimated light was incident on an SLM (Thorlabs Exulus HD2, 1920×1200 pixels, pixel size = $8\text{ }\mu\text{m}$) on which the LADISA was displayed. The light modulated by LADISA was incident on an image sensor (Zelux CS165MU/M 1.6 MP monochrome CMOS camera, 1440×1080 pixels with pixel size $\sim 3.5\text{ }\mu\text{m}$). The image of the PSF, object intensity and reconstruction results using NLR and LRRA are shown in Figures 4(a)-4(d) respectively.

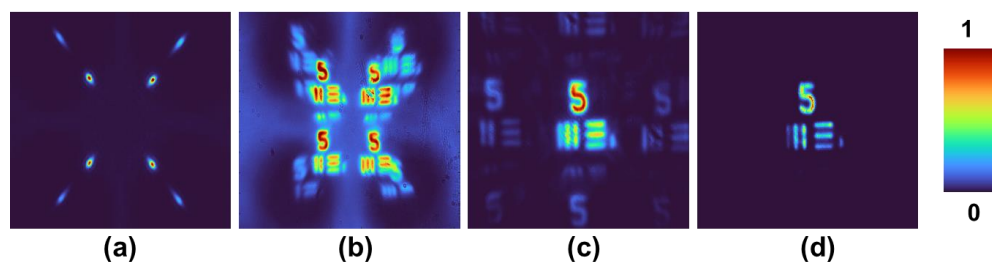


Figure 4. Images of the recorded (a) PSF and (b) object intensity distribution. Reconstruction results using (c) NLR and (d) LRRA.

5. SUMMARY AND CONCLUSION

A computational imaging approach has been used to solve a fundamental problem in manufacturing large area diffractive lenses. A large diffractive lens is replaced by LADISA which creates multiple low-resolution images on the image sensor which is then processed by the computational reconstruction algorithms such as NLR and LRRA to obtain a single high-resolution image. The performance of the system is highly dependent on the location of the sub-apertures.

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