Computational holographic camera with a dielectric metasurface diffuser

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Abstract: We experimentally demonstrate computational complex optical field imaging by a metasurface diffuser and the speckle-correlation scattering matrix method. Thus, we show that the metasurface diffuser can outperform conventional scattering media in context of computational imaging. © 2019 The Author(s)

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In the last decade, diverse speckle-based computational imaging techniques have been proposed. These speckle-based computational imaging techniques have unique advantages in capturing various types of hidden information that are otherwise difficult to obtain with conventional optical setup [1-3]. Especially, the speckle-correlation scattering matrix (SSM) method has been proposed recently to enable holographic imaging without reference beam from a single speckle intensity pattern [4]. However, the previous investigations have focused only on the optical methods or computational aspects, leaving out the scattering medium as a part of the system. As a result, many drawbacks of conventional scattering media (CSM) directly hider the potential of those speckle-based techniques for real application.

Dielectric metasurfaces composed of nano-scatterers are classified as a new category of diffractive optical element. They drew great interests due to their unique capabilities to manipulate the phase, amplitude, and polarization of light at subwavelength scales [5,6]. Recently, the concepts of random metasurfaces have been explored from various viewpoints such as wave-front shaping or random Rashba effects [7,8]. Here, we introduce the concept of a metasurface diffuser (MD) in the context of the speckle-based computational imaging and show that the MD can address many issues of the CSM [9].

Figure 1a conceptually illustrates the idea of the holographic camera based on the MD. The amplitude and phase of objects can be retrieved computationally in a single shot by a pre-calculated transmission matrix of the MD (**T**) and the SSM method. In Fig. 1b, the MD is composed of the 652-nm tall amorphous silicon nano-posts on a fused silica substrate. With a sophisticated design, the rectangular nano-posts provide independent 2π phase control coverage for *x*- and *y*-polarized light [6]. We plot the optimal width and length of the rectangular nano-posts versus the desired phase delays for two orthogonal linear polarizations in Fig. 1b. We design the MD in a cross-polarized configuration in order to suppress unscattered light components with linear polarizers. In other words, the MD is designed to operate as a half-wave plate and a diffuser at the same time. A scanning electron microscope image and an optical image of the fabricated MD are shown in Fig. 1c.

We experimentally demonstrated the complex field imaging with real objects. First, two different parts of the 1951 USAF resolution test target are exploited as amplitude objects. The objects and measured speckle patterns of the objects after passing through the MD are shown in Fig. 1d. As shown in Fig. 1e, amplitude and phase of the objects can be retrieved computationally by the SSM method and the measured speckle pattern in Fig. 1d. It should be noted that proper iteration procedures (20 times) are applied to suppress noise in the initial retrieved fields [4]. To further verify the ability of the complex field retrieval, we perform holographic imaging experiments. As shown in Fig. 1f, we retrieve the complex field at a fixed aperture (~150 µm diameter circular aperture) and reconstruct several target objects at different distances from the aperture by numerical back-propagation. The reconstructed objects are shown in Fig. 1g. In the presentation, we will further discuss the mathematical properties of the **T** matrix of the MD to expand our understandings about the MD as a scattering medium.

It is worth clearly noting the advantages of the MD comparing with CSM. Most importantly, the MD replace the laborious experimental characterization procedure of the CSM with a simple simulation procedure. Furthermore, the MD provides a large noise tolerance, robustness against misalignments, reliable reproducibility, and highly stable optical properties. In general, the MD can be easily applied to diverse existing speckle-based computational optics methods [1-3]. Thus we expect that the MD can extend the potentials of those methods for many applications such as endoscopic quantitative phase imaging [10] and holographic point-of-care devices [11].

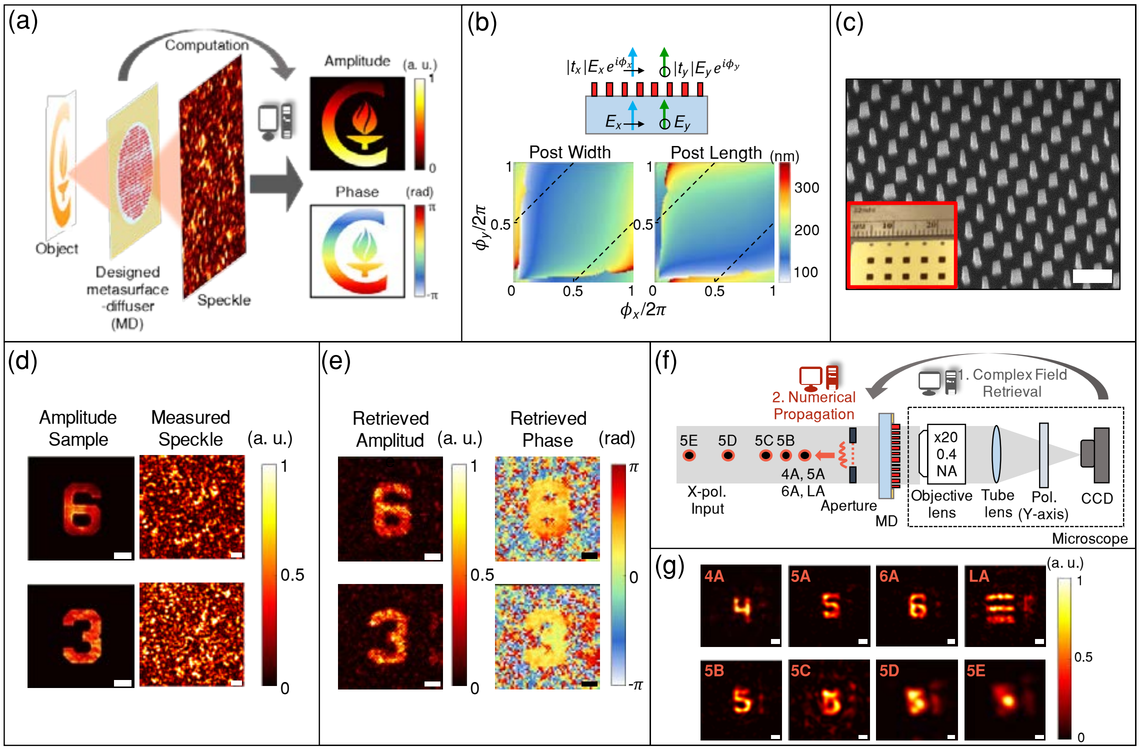

Fig. 1. a, Schematic illustration of computational complex field camera based on the metasurface diffuser (MD). **b,** Schematics of a uniform array of the nano-posts (top) and calculated optimal width and length of the rectangular nano-posts as functions of the required transmission phases for *x*- and *y*-polarized light (bottom). The dashed lines represent the nano-posts that work as a half-wave plate. **c**, scanning electron microscope image and optical image (inset) of the fabricated MD. Scale bar is 1 µm. **d**, in-focus microscope images of amplitude objects (left) and measured speckle patterns of the objects after passing through the MD (right). Scale bars are 25 µm. **e**, Retrieved amplitude (left) and phase (right) of the objects calculated from the speckle intensity patterns in d. Scale bars are 25 µm. **f**, Schematic drawing of the measurement setup for holographic imaging. The complex field is retrieved at a fixed circular aperture of the 150-µm diameter. The field is reconstructed through numerical back-propagation. **g**, Reconstructed images for different objects ('4','5','6', and lines) at a certain position ('A') and same object ('5') at different positions ('B', 'C','D', and 'E'). The distances between the reconstructed positions and the aperture are as follows: A, 1.5 mm; B, 2 mm; C, 2.5 mm; D, 3.5 mm; and E, 4.5 mm. Scale bars are 25 µm.

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