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Highly Efficient Visible Hologram through Dielectric Metasurface

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Abstract. To achieve applied aspect of metasurfaces in the visible regime, dielectric materials with low absorption are indispensable. This work presents highly efficient generation of hologram via processed amorphous silicon, which exhibits significantly low absorption in the region of interest. The phase and the polarization of transmitted light are tailored by varying the orientation of dielectric nanorods whereas their conversion efficiency is optimized by adjusting their structural parameters. Better image fidelity and higher conversion efficiency (up-to 75%) are achieved as compared to previously reported work. The proposed design methodology paves a way toward on-chip realization of various novel phenomena with substantially enhanced performance.

1. Introduction

Metasurfaces are two dimensional (2D) metamaterials with the ability to control the wavefront of light through spatial modulation of phase, amplitude and/or polarization at sub-wavelength scale [1]–[4]. This unique property of wavefront engineering facilitates in demonstrating diverse phenomena in the visible domain, like flat lensing [5]–[8] , vortex beam generation [9]–[12] and holography [13]–[17]. Meta-holograms are used to reconstruct holographic images, leading to different applications e.g. multi optical switching and image processing. Initially metallic nanoantennas were employed to realize visible meta-holograms, both in transmission [16], [18] and reflection modes [13], [14]. However, these plasmonic meta-holograms were afflicted by unavoidable Ohmic losses causing deteriorated efficiency [15]. Although reflection-type metasurfaces exhibited enhanced efficiency [14], they were impractical for transmission based applications [19].

Hence, lossless dielectric materials with high refractive index proved to be an ideal candidate to demonstrate highly efficient transmission-type metasurfaces in the visible regime. In this regard, recently Devlin et al. implemented highly efficient meta-holograms using dielectric nanoresonators made up of TiO_2 [20]. However, expensive and complex fabrication methodology of TiO_2 limit its mass-scale realization and compatibility with existing semiconductor fabrication processes. Among reported dielectric materials, silicon (Si) provides significant advantage in terms of its cost-effectiveness and CMOS compatibility. Owing to this unique advantage, Huang et al. [15] and Yoon [21] demonstrated transmission-type, Si-based, visible meta-hologram. However, significant dielectric losses of amorphous Si, in the visible spectrum, deteriorated image fidelity and efficiency (3%), hence limiting their desired applicability [15]. Therefore, low-cost, highly-efficient and CMOS compatible dielectric metasurfaces are required for the visible regime. The ellipsometry data of our processed amorphous silicon (a-Si) reveals comparatively higher refractive index and considerably lower absorption coefficient (3.25+0.047*i*) at a wavelength of 633 *nm*, hence making it a better candidate for low cost and highly efficient metasurface holograms. In this paper, we have proposed a highly efficient transmission-type hologram, using low-loss processed a-Si, for the red light (633 *nm*).

2. Methodology

To achieve 2π phase coverage for full wavefront manipulation, Pancharatnam-Berry Phase Modulation (PBPM) is implemented. Amplitude modulation of our hologram is two level. As suggested by PBPM, the orientation of the amorphous silicon nanorods with respect to x-axis (φ) is varied to achieve the desired phase. For instance, if left circularly polarized light (LCP) is impinged on nanorod (with an orientation angle φ), the transmitted wave will have one component of scattered wave with the same helicity and the other component of scattered wave with the opposite helicity, carrying an extra phase of 2φ (known as Pancharatnam-Berry (PB) phase) as shown in the Equation. 1 [22].

$$E_L^t = \frac{t_p+t_s}{2}\widehat{e_L} + \frac{t_p-t_s}{2}e^{i2\varphi}\widehat{e_R} \qquad (1)$$

To maintain highest conversion efficiency of the cross-polarized component, the optimization of unit cell (Figure. 1(a)) is performed using Finite Difference Time Domain (FDTD) analysis with periodic boundaries along x and y directions. However, perfect match layer (PML) boundary is used along the propagation direction.

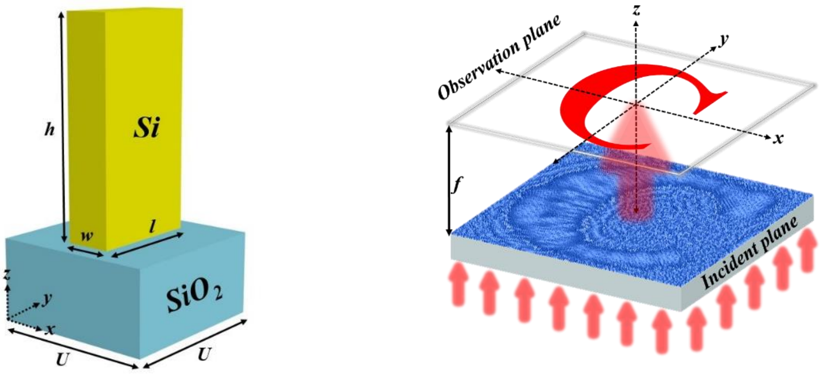

Figure 1. (a) Optimised unit cell of a-Si nanorod with glass substrate. l =200 *nm*, w=80 *nm*, and h =380 *nm* denote length, width and height of a-Si rod. Periodicity of unit cell is denoted by U = 290 *nm*. (b) A metasurface producing hologram at an observation plane (height f = 200 μm). Letter 'C' is formed when the incident light is RCP.

Length (l), width (w) and periodicity (U) of unit cell are optimized for maximum transmission (T) and maximum conversion efficiency (ξ) of the cross-polarized light at 633 *nm* wavelength. Cross-polarized ξ is defined as the ratio of power of cross-polarized light and power of incident light. An iterative method known as particle swarm algorithm is employed to optimize the structural parameters of corresponding unit cell in FDTD Lumerical. The optimization of unit cell aligns the electric and magnetic dipole resonances, i.e. their identical phase and amplitude, of nanorod as described by Mie theory [23]. This optimization also ensures maximum forward scattering for 2π phase coverage. FDTD simulations showed that the highest value of T and ξ at 633 *nm* are 76% and 75% respectively. The average value of ξ for the proposed design is 73%. Schematic diagram of our proposed hologram is shown in Figure. 1(b).

3. Results and Discussion

The phase only hologram is used to generate a metasurface using FDTD Lumerical (Figure 1(b)). Due to limited computational power, only 35 x 35 μm^2 hologram is simulated in FDTD Lumerical to prove the concept. PML boundary conditions are used along each dimension for hologram simulation. Image ('C') on the projection plane (at a distance f) can be seen if the incident light is right circularly polarized (RCP). Figures 2(a) and 2(b) depict the simulation results of the designed hologram at 633 *nm* wavelength. Letter 'C' is observed with a high image fidelity at an on-axis focal plane.

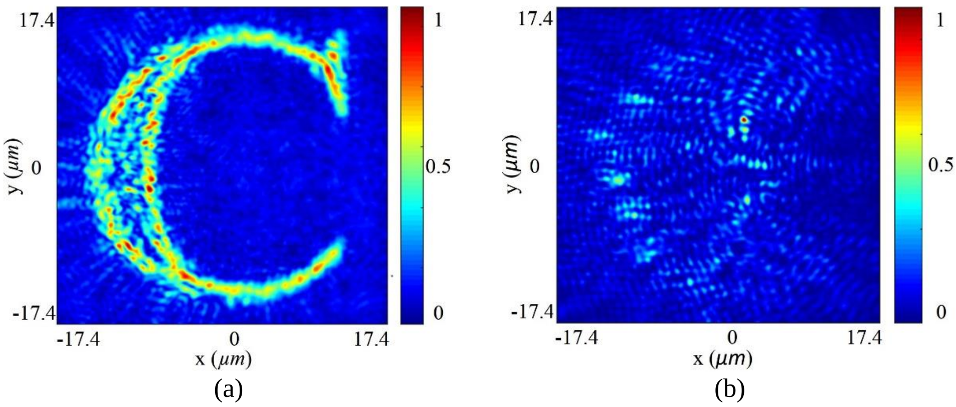

Figure 2. Result obtained from Finite Difference Time Domain (FDTD) simulations when incident light is (a) RCP and (b) LCP.

Moreover, it is clearly observed from the simulation results, that significant portion of the incident light has contributed to the target image. Only a minor portion is dissipated/absorbed due to absorption coefficient of the material. Unlike previously reported silicon based metasurfaces, this hologram possesses high quality image formation with the highest conversion efficiency at a visible wavelength (633 *nm*). Due to polarization dependency, no information is observed for incident light with left circular polarization, as shown in the Figure 2(b). FDTD Lumerical results can be further improved by increasing the size of the hologram.

4. Summary

In summary, processed amorphous silicon meta-hologram at a wavelength of 633 *nm* is demonstrated. The transmission type hologram instructs Pancharatnam-Berry (PB) phase to the transmitted wave by spatially controlling the orientation of nanorods. We have successfully presented high optical efficiency and good image quality by using a-Si nanorods, which are easy to fabricate and are compatible with CMOS fabrication. Hence, all silicon-based metasurface devices can be integrated into photonic circuits without degrading the performance, which paves a path toward applications of highly efficient integrated photonic circuits based on metasurfaces/metamaterials.

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