An Ultra-Thin Beam Splitter Design Using a-Si:H Based on Phase Gradient Metasurfaces

Hammad Ahmed1, Muhammad Mahmood Ali2, Arif Ullah1, Arbab Abdur Rahim1,∗, Husnul Maab1, and Mahmood Khan3

This paper explicates the design of an ultra-thin beam splitter based on phase gradient metasurfaces using amorphous silicon hydrogenated (a-Si:H) nano cylinders for the visible frequency of 474 THz. The a-Si:H nano cylinders exhibit low losses in the visible regime compared to standard a-Si, and small size due to reduced aspect ratio compared to other highly efficient materials such as TiO2 and GaN. In the proposed design, incident wave at a single operating frequency of 474 THz in visible regime is split into two different directions according to the generalized Snell’s law of refraction. The angles of refracted waves are controlled by choosing different phase gradients. Based on this concept, three metasurfaces are designed and simulated using finite difference time domain numerical method for various split angles (31.8°, −31.8°), (−44.6°, 31.8°) and (−44.6°, 20.5°).

Keywords: Ultra-Thin Beam Splitter, Phase Gradient Metasurfaces, Dielectric Materials, Amorphous Silicon Hydrogenated.

1. INTRODUCTION

During the past decade, metasurfaces have attained much attention because of an ultra-thin subwavelength geometry and ease of fabrication compared to three dimensional (3D) metamaterial [1]. For this reason, metasurfaces are also known as a planar analog of bulk metamaterial [2]. The interesting feature of metasurfaces is their ability to tailor amplitude, phase, and polarization at the interface of two media [3], which enabled researchers to fabricate the miniaturized conventional optical component at the nanoscale. Recently many interesting applications such as flat lenses [4], phase masks [5, 6], ultra-thin wave plates [7–9], optical vortices [10], and holography [11] have been realized. Choice of material is very crucial while designing metasurface.

In previous work, it has been observed that all dielectric based metasurfaces exhibit better performance in both transmission and reflection mode compared with metals which work well only in reflection type metasurface [12]. Choice of dielectric material for specific frequency range is essential. The complex refractive index \( n = n + ik \) must have high refractive index \( n > 2 \) and low extinction coefficient (absorption) \( k \approx 0 \) [13] for highly efficient dielectric metasurface. Commonly used high refractive index materials for an infrared region are silicon and germanium but these materials have shown a significant amount of losses at visible frequencies [14, 15]. Titanium dioxide (TiO2) and gallium nitride (GaN) with high refractive indices are used for the visible domain but these materials require high aspect ratio along with costly and complex fabrication techniques for the realization of metasurface [13, 16, 17].

In this article, we numerically presented an ultra-thin beam splitter design with gradient metasurfaces based on amorphous silicon hydrogenated (a-Si:H) nano cylinders. The a-Si:H can be deposited at low temperature via plasma enhanced chemical vapour deposition (PECVD) [18, 19] and it offers reduced absorption at visible frequencies compared with standard amorphous silicon (a-Si) because a-Si:H contains hydrogen impurities which decreases the defect density of a-Si [18, 20]. Furthermore, a-Si:H with high refractive index offers strong confinement of wave into the nano cylinder which results in full hold over the phase of refracting wave [13]. The a-Si:H nano cylinder introduces phase retardation to the refracted wave, which can be tuned over 0°–360° by varying the radius of a-Si:H
nano cylinder. Generalized Snell’s law [21] is the basic principle of the proposed beam splitter in which metasurface with different phase gradients are placed adjacent to each other to achieve variable split angle. In this article, three beam splitters are designed for different split angles along the left and right side of metasurface. This design is expected to be used in optical communication, planar light wave circuits as a multiplexer and as a demultiplexer.

2. DESIGN AND METHODOLOGY

The first step in designing phase gradient metasurface is to achieve $0^\circ$–$360^\circ$ phase by altering the geometric parameters of unit cell. In this respect, we chose hydrogenated amorphous silicon ($a$-Si:H) nano cylinder on glass substrate as illustrated in Figure 1(a). Here $R$ represents radius of nano cylinder, $H$ represents height of nano cylinder, $P$ is the periodicity of unit cell. Due to polarization independent feature, the cylindrical geometry is used [17]. Finite Difference Time Domain (FDTD) Numerical method is used for parametric optimization of the unit cell. Figure 1(b) shows that, the periodic boundary conditions are employed in $x$–$y$ direction and perfectly matched layer boundary (PML) is used along the direction of propagation ($z$). The $x$-polarized plane wave is illuminated onto cylinder from the backside. Through parametric optimization, it is observed that for the range of $R$ from 50 nm to 140 nm with $P = 300$ nm and $H = 400$ nm the maximum transmission amplitude as shown in Figure 1(c) along with full $0^\circ$–$360^\circ$ phase profile as depicted in Figure 1(d) have been achieved at 5 nm away from top of nano cylinder at operating frequency of 474 THz. Based on optimization through FDTD, $P = 300$ nm and $H = 400$ nm are fixed throughout this article. Inset Figure 1(c) shows that

![Fig. 1.](image1.png)

- (a) Schematic of $a$-Si:H nano cylinder on a glass substrate with periodicity of unit cell $P$, height of cylinder $H$ and radius of cylinder $R$.
- (b) Showing periodic boundaries are applied along $x$ and $y$ direction while PML boundary is applied along direction of propagation ($z$).
- (c) Transmission amplitude of transmitted $x$-polarized wave at distance of 5 nm away from the top of nano cylinder. Inset presents the transmission spectrum of $a$-Si:H nano cylinder with $R = 50$ nm.
- (d) Phase profile of transmitted $x$-polarized wave at distance of 5 nm away from $a$-Si:H nano cylinder.

![Fig. 2.](image2.png)

Fig. 2. Schematic design of beam splitter based on gradient metasurfaces, splits the normally incident $x$-polarized wave into two $x$-polarized wave with an angle of $\theta_1$ and $\theta_2$.
Ahmed et al.

An Ultra-Thin Beam Splitter Design Using α-Si:H Based on Phase Gradient Metasurfaces

Fig. 3. Angle of emergence as a function of frequency for different values of phase step \( N_1 \) and \( N_2 \) for left side and right side of beam splitter respectively is shown. Solid lines (pink, cyan, blue) are indicating \( \theta_1 \) for \( N_1 = 3, 4, 6 \) respectively while solid lines (black, red, green) are indicating \( \theta_2 \) for \( N_2 = 3, 4, 6 \) respectively.

α-Si:H nano cylinder for \( R = 50 \) nm can maintain high transmission efficiency in broad visible range (from 430–532 THz). The maximum transmission efficiency that can be achieved is 90% at 442 THz but here operating frequency of 474 THz is chosen with 83% transmission efficiency because this is the working frequency of Helium Neon laser normally available for experimentation. The α-Si:H is chosen in this paper because efficient dielectric metasurface realization requires negligible absorption with high refractive index. Due to this reason, α-Si:H offers reduced absorption \( (k = 0.0471) \) compared with standard α-Si \( (k = 0.4) \) with high refractive index \( (n = 3.247) \) at the operating frequency of 474 THz [18]. The high refractive index yields lower aspect ratio [19]. The minimum radius \( R \) of a nano cylinder that can be handled easily in fabrication is bounded by maximum aspect ratio \( (AR) \) given by:

\[
AR = \frac{H}{2R_{\text{min}}}
\]

where \( H \) is the height of the nano cylinder and \( R_{\text{min}} \) is the minimum radius of nano cylinder, whereas the maximum radius of cylinder must be equal to or less than the size of unit cell [19]. Nano cylinders with low \( AR \) are desired compared to high \( AR \) nano cylinders, which are susceptible to fragility and require additional metal-mask for fabrication [22, 23]. In this paper, \( AR \) is 4 for the smallest radius of 50 nm and height of 400 nm which is much smaller than TiO₂ and GaN having the smallest \( AR \) of 7.5 [24] and 12 [16] respectively.

Figure 2 illustrates the schematic of proposed beam splitter based on all dielectric gradient metasurface for visible frequency (474 THz). Designed metasurface can manipulate the direction of the refracted wave according to generalized Snell’s law of refraction [21]:

\[
n_i \sin \theta_i - n_n \sin \theta_n = -\frac{c}{2\pi f} \int dx \frac{d\phi_i}{dx}
\]

\[
n_i \sin \theta_i - n_n \sin \theta_n = -\frac{c}{2\pi f} \int dx \frac{d\phi_n}{dx}
\]

Fig. 4. Showing simulated electric field distribution recorded by placing field monitor along \( x-z \) plane of metasurface with (a) \( N_1 = N_2 = 4 \), (b) \( N_1 = 3 \) and \( N_2 = 4 \) (c) \( N_1 = 3 \) and \( N_2 = 6 \).
where $\theta_i$ is the angle of incidence, $\theta_1$ and $\theta_2$ are the angles at which the incident wave is divided. $\theta_i$ is taken as $0^\circ$ because incident wave propagates in the $z$-direction (normal incidence), $n_i$ and $n_r$ are refractive indices of two media which in this case is taken as 1 because the sample is placed in a free space while $f$ is the operational frequency (474 THz), $c$ represents the speed of light, $d\phi_r/dx$ and $d\phi_l/dx$ are the phase gradients along the $x$-direction. For convenience, $d\phi_r/dx$ is the phase gradient along the left side from center point O and $d\phi_l/dx$ is the phase gradient along right side from O. In Eqs. (2) and (3), $dx$, $d\phi_r/dx$ and $d\phi_l/dx$ are replaced by $f$, $2\pi/N_1$, and $2\pi/N_2$ respectively [25]. Where $N_1$ and $N_2$ are the phase steps on the left and right side respectively. The phase step corresponds to number of $a$-Si:H nano cylinders on left and right side in Figure 2. If $N_1 = N_2 = 4$, there will be four cylinders on left and four cylinders on right side with the phase interval of $360^\circ/4 = 90^\circ$. Radius ($R$) is varied along each side to get the desired phase. The angle of refraction can be calculated by modifying Eqs. (2) and (3) as:

$$\theta_1 = -\sin^{-1}\left(\frac{c}{N_1 f P}\right)$$

(4)

$$\theta_2 = -\sin^{-1}\left(\frac{c}{N_2 f P}\right)$$

(5)

From Eqs. (4) and (5), the angles of refraction $\theta_1$ and $\theta_2$ are purely dependent on phase steps, which means $\theta_1$ and $\theta_2$ can individually be controlled by phase steps $N_1$ and $N_2$. So, for $N_1 = N_2 = 4$, the desired angle of refraction is $-31.8^\circ$ for $\theta_1$ and $31.8^\circ$ for $\theta_2$, at 474 THz. Figure 3 shows the plot of Eqs. (4) and (5), where $\theta_1$ is represented by solid lines (pink, cyan, blue) for $N_1 = 3$, $4$, $6$ and $\theta_2$ is represented by solid lines (black, red, green) for $N_2 = 3$, $4$, $6$ as a function of frequency. It can be seen that with the increase in frequency, the angle of refraction decreases. In this article, the unit cell is optimized at fixed frequency of 474 THz with $P = 300$ nm, the only parameter that can be changed in Eqs. (4) and (5) is phase step ($N_1$ and $N_2$) to get the desired angle of emergence. For $N = 3$, radii ($R = 50$, $72.4$, and $85$ nm) are selected with phase interval of $120^\circ$, similarly for $N = 4$, radii ($R = 50$, $69.1$, $78.9$, and $92.9$ nm) are chosen with phase interval of $90^\circ$ and for $N = 6$, radii ($R = 50$, $65.1$, $72.4$, $78.9$, $85$, $99.5$ nm) are selected with phase interval of $60^\circ$. Figure 4 illustrates the simulation results of electric field distribution in $x$-$z$ plane for: (a) $N_1 = N_2 = 4$ with $\theta_1 = -31.8^\circ$ and $\theta_2 = 31.8^\circ$. (b) $N_1 = 3$ and $N_2 = 4$ with $\theta_1 = -44.6^\circ$ and $\theta_2 = 31.8^\circ$ respectively. (c) $N_1 = 3$ and $N_2 = 6$ with $\theta_1 = -44.6^\circ$ and $\theta_2 = 20.5^\circ$ respectively.

3. CONCLUSION

Here we demonstrated an ultra-thin beam splitter based on gradient metasurfaces using low loss $a$-Si:H nano cylinders with high refractive index for the visible frequency of 474 THz. Our designed all dielectric metasurface with $a$-Si:H is miniaturized and compact compared to others which are designed by SiO$_2$ and GaN due to reduced aspect ratio. Furthermore, three different designs of metasurfaces are presented using generalized Snell’s law for various split angles by generating different phase gradients on the left and right side of metasurfaces as shown in conceptual Figure 2. The Split angles are calculated analytically and verified numerically by finite difference time domain numerical method.

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References and Notes


