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Free Space Beam Shaping Using phase-change Reconfigurable metasurfaces

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***Abstract*— Metasurfaces are planar structures that enable us to manipulate electromagnetic wavefronts by using subwavelength elements. Here, we propose a new tunable metasurface based on phase change materials and graphene heaters to operate in the near-IR regime. In the proposed structure, by incorporating electrical heaters, the optical properties of the phase change material layer and, consequently, the metasurface response can be adjusted. Finally, to investigate the potential capability of the proposed metasurface as a free space beam shaper, its beam steering capability is investigated.**

Keywords—Tunable metasurfaces, Phase Change Materials, Optical beam steering

I. Introduction

In recent years, optical metasurfaces have been at the center of attention of researchers because of their exceptional ability to manipulate light wavefront in free space. These structures are composed of subwavelength nano-antenna arrays (also known as unit cells), which are designed to manipulate electromagnetic wave characteristics at subwavelength scales [1]. Early metasurfaces were made of metals in which light was trapped inside the structure through exciting surface plasmon polariton. Recently, to avoid the high optical loss provided by metals [2], high index dielectrics (e.g., silicon in optical range) have been used more commonly in visible and near-IR regimes. In contrast to metallic nano-antennas, the dielectric ones trap light inside themselves by exciting Mie resonances in the operational wavelength [3].

In simple metasurfaces, the characteristics of the reflected or refracted wave could only be manipulated by adjusting the geometry and the shape of the nanoantennas building the metasurface, meaning that the response of the designed metasurface could not be adjusted after the fabrication. To broaden the potential applications of metasurfaces, there is a need to develop reconfigurable metasurfaces to modify the metasurface response whenever needed.

Nowadays, there is an extensive effort on designing tunable metasurfaces. These efforts have led to development of different categories of tunable metasurfaces. However, each method has a limited operational wavelength range. For example, varactor diodes are only applicable at microwave ranges [4], or realizing a reconfigurable metasurface using graphene is only experimentally reported in terahertz and mid-IR range [2].

Among different methods used in near-IR regime, phase change materials like germanium-antimony-tellurium (GST, GSST) have shown promising results in controlling the metasurface response at MHz and KHz speed ranges [5]. In these methods, the optical properties of the mentioned materials can be adjusted by applying an external controlling signal. The controlling signal can be electrical (voltage or current), optical (laser pulses), or thermal (injecting thermal energy into the material). However, applying an electrical control signal seems to be the most practical method. In this paper, a novel tunable metasurface is proposed in which a relatively thin layer of GST, a phase change material whose phase can be controlled by adjusting its temperature, is used to make the metasurface tunable. In addition, to control the optical properties of the GST layer, embedded graphene heaters are used to produce the required thermal energy for changing optical properties of the GST layer. By using graphene as a heater material, we benefitted from its high electrical and thermal conductivity, while avoiding the ohmic loss caused by metallic heaters. After performing a comprehensive Electromagnetic and Joule heating analysis, we successfully designed a metasurface capable of modulating phase of the reflected wave in the range of 0° to 270°, while keeping the reflectance efficiency above 50%. Finally, to investigate the capability of the proposed metasuface as a beam shaper, its beam steering ability was studied. It was found out that the proposed metasurface is able to steer the reflected beam to different angles with relatively low sidelobe levels.

II. Design Procedure of the Proposed Tunable Metasurface

Phase change materials have been in a prominent place in both memory devices industry and research; because of significant changes in optical and electrical parameters which is realized by applying an external control signal. By adjusting the temperature of these materials, their molecular state change from totally amorphous (crystallization level= 0) to totally crystalized (crystallization level= 1). It is also possible to adjust the crystallization level to any value between 0 to 1 by heating the material to the corresponding temperature. Following that, the dielectric constant and electrical conductance vary significantly. The relation between molecular state and the dielectric constant of PCMs is determined by Lorentz-Lorenz relation [6]:

$$\frac{\varepsilon_{eff}(\lambda)-1}{\varepsilon_{eff}(\lambda)+2}=C\frac{\varepsilon_c(\lambda)-1}{\varepsilon_c(\lambda)+2}+(1-C)\frac{\varepsilon_a(\lambda)-1}{\varepsilon_a(\lambda)+2} \quad (1)$$

where λ is the wavelength, ε_{eff} is the dielectric constant of the PCM at the crystallization level *C*, and ε_c , ε_a are dielectric constants of the PCM in totally crystallized and totally amorphous states, respectively. To bring them back to fully amorphous state, their temperature should rise up to 600 $°C$ for a short time, (less than 100 ns) known as RESET process.

There are different approaches to provide the required heat for PCMs. One of the most precious strategies is using laser pulses, which provides the exact amount of the heat that we need to tune the material into our desired phase [7]. However, in real-world applications, using a laser to tune the metasurface unit cells with subwavelength dimensions does not seem to be practical. As mentioned in the introduction, using an electrical controlling signal is the most practical approach. Therefore, instead of using lasers, one can design a unit cell with embedded heaters that are controlled by an externally applied voltage. By applying the voltage to heaters, induced current causes heat generation due to resistive (Joule) heating phenomena. Consequently, the generated heat will change the crystallization level and dielectric constant of the phase change material.

Figure 1 shows the design procedure used for designing the proposed tunable metasurface using phase change materials. As shown in this figure, in addition to electromagnetic simulations, heat transfer analysis should also be performed to determine the direct relationship between the response of the metasurface and the controlling signal. Material characteristics of the PCM should also be measured experimentally. Here we used the experimentally measured data reported in [8] which is illustrated in Fig. 2C as a relation between dielectric constant of a PCM material (GST) and its temperature.

The proposed novel tunable metasurface with embedded heaters is shown in Figs. 2A, 2B. Figure 2A shows the whole metasurface, while Fig. 2B shows the designed unit cell and its parameters. The phase change material is sandwiched between two graphene and silicon layers. The graphene layers are used as embedded heaters due to their high electrical and thermal conductivity and their low loss in near-IR range. In this design, the applied voltage to each unit cell can be controlled independently. Silicon is also used to make the geometry of the unit-cell in such a way that the first order of Mie resonance occurs in the vicinity of the operational wavelength of λ=1.55µm. By applying a voltage difference to both sides of graphene heaters, the heat produced by Joule heating phenomenon changes the temperature of the GST material to its phase changing point. The results of Joule heating analysis is shown in Figs. 2D, 2E. The length of the metasurface in the y-direction is assumed to be 10 µm. Fig. 2D shows the heat distribution of 3 adjacent unit-cells while a 10V voltage difference is applied to the middle unit cell and the adjacent unit cells do not experience any applied voltage. As can be seen in this figure, the heat is mainly confined in the center unit cell. The reason behind is that the metasurface is intentionally designed in such a way that the produced heat by one unit cell would not change the temperature of adjacent unit cells significantly. Figure 2E also shows numerically

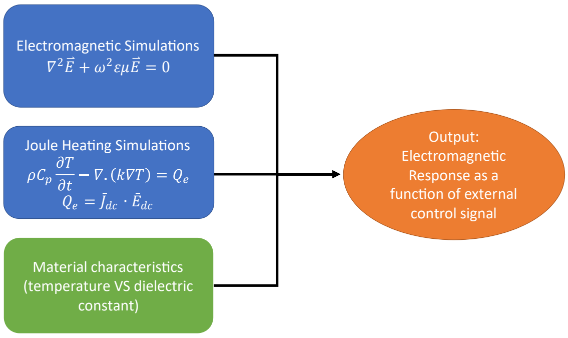

Fig. 1. The procedure required to design a PMC-based reconfigurable metasurface.

calculated relation between the applied voltage to the middle unit cell and the temperature of the phase change materials of all three unit-cells. The discussed heat confinement can be seen more clearly in this figure. In Fig. 2F, the Electromagnetic response of an infinite array of designed unit-cell as a function of crystallization level of the GST layer under the illumination of a normal TE plane-wave is illustrated. By the response, here we mean the phase and amplitude of the reflected wave when a normal TE plane-wave is incident on the structure. As demonstrated in this figure, by adjusting the crystallization level of the PCM, the phase and the amplitude of the reflected wave can be adjusted to the desired level.

In the final stage, by merging material parameters with Joule heating and electromagnetic simulations results, we can determine the direct relationship between the applied voltage and the metasurface response. Figure 2G shows the phase and amplitude variations as a function of the externally applied voltage.

III. Digital Beam Steering Using the Proposed Metasurface

Here, to study the ability of our proposed metasurface as a beam steering device, we performed full-wave analysis on a metasurface with 80 unit cells. To steer the main lobe of an array of antenna to the angle of θ, phased array theory states that the following equation should be established [9]:

$$\theta=sin^{-1}(\frac{\lambda_0\Delta\phi}{2\pi d}) \quad (2)$$

where $\Delta\phi, d$ *and* λ_0 are phase difference between adjacent antennas, the distance between antennas and, wavelength in free space, respectively. In this case, we assume that the phase difference between adjacent antennas are fixed to $\Delta\phi = \frac{\pi}{2}$, while the variable parameter in equation 2 is d = nw_1, where w_1 is the width of unit cells, and *n* is an integer ($n \in \mathbb{N}$). Actually, *n* is the number of adjacent unit cells that have equal phase shifts. In this case, it is only needed to tune the crystallization level to 4 values: 0 °, 90 °, 180 °, and 270 °, by applying their corresponding voltages (see Fig. 2G). Figs. 3(A-C) show the numerically calculated electric field magnitude of the reflected wave for n = 1, n = 2, and n=3, respectively. The three mentioned cases correspond to steering degrees of 52.2° , 23.2° and 15.2°, respectively. Figs.

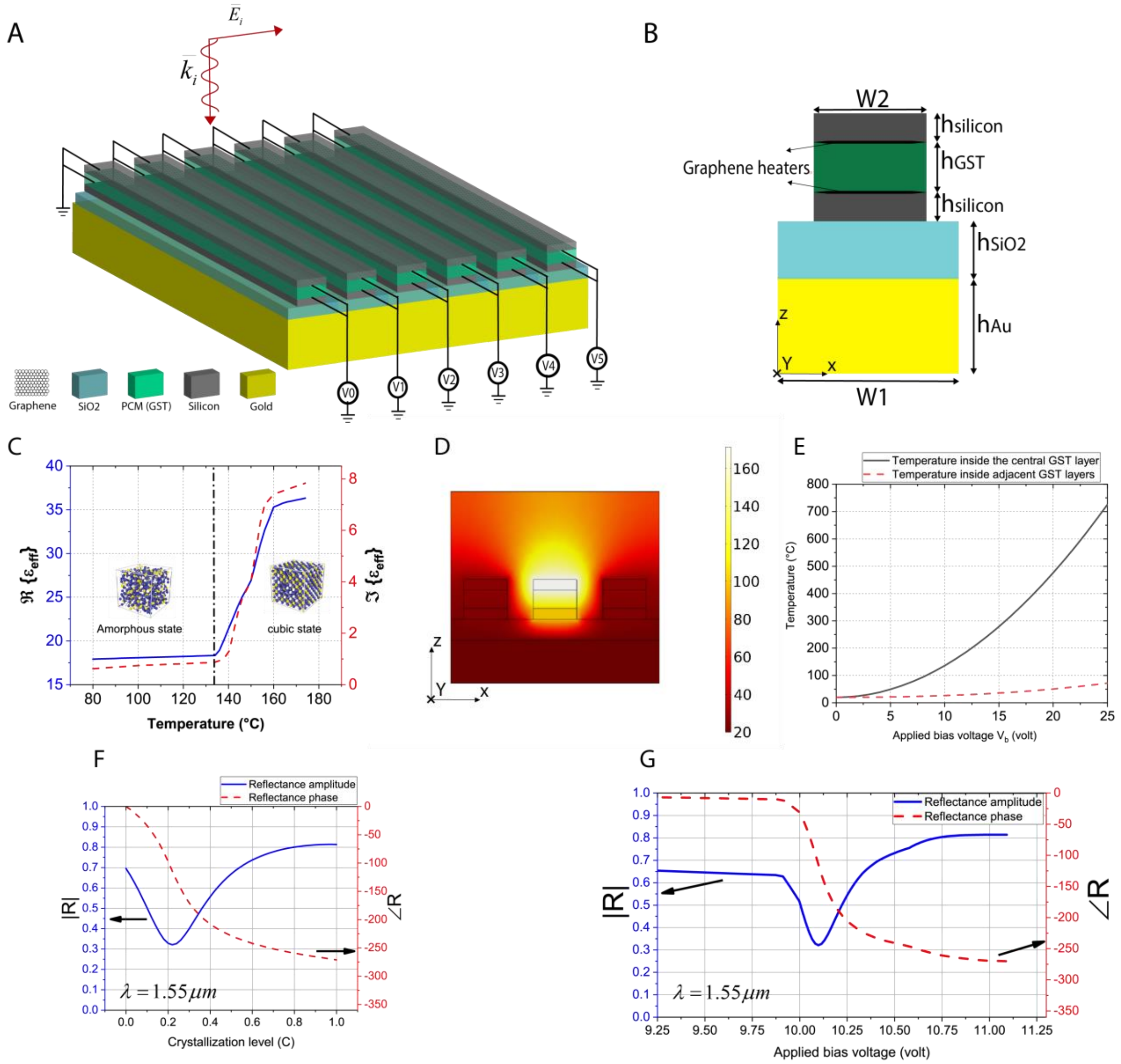

Fig. 2. A: The proposed reconfigurable metasurface, B: The unitcell of the proposed metasurface with h_{Au} = 300 nm, $h_{silicon}$ = 75 nm, h_{SiO2} = 150 nm, h_{GST} = 130 nm, W_1 = 490 nm and, W_2 = 305 nm. C: dielectric constant variation of the GST material as a function of temperature. D: Heat distribution of 3 adjacent unit cells when a 10v voltage is applied to the middle unit cell graphene heaters. E: temperature of the GST material as a function of applied voltage to embedded heaters. F: Reflected wave characteristics as a function of the crystallization level C. G: Reflected wave characteristics as a function of applied bias voltage to embedded heaters

3 (D-F) also show the normalized radiation pattern intensities for the three mentioned cases. In order to compare the radiation pattern of the proposed structure with an ideal case, we calculated the array factor of an ideal phased array antenna. The array factor of an ideal antenna array consisted of 80 antennas is given by [9] :

$$AF = \sum_{n=1}^{80} e^{j(n-1)(kd\cos(\theta)+\Delta\phi_n)} \tag{3}$$

The normalized calculated array factors are also depicted in Figs. 3(D-F) and compared with the numerically calculated patterns. Fortunately, the main lobes of our proposed metasurface and ideal case have the same characteristics, but the Sidelobe levels for the proposed metasurface are higher. The reason behind this difference, is amplitude fluctuations for different phase shifts and also coupling effects between adjacent unit cells.

IV. Conclusion

A novel reconfigurable metasurface using phase change materials and graphene embedded heaters was proposed. Full wave electromagnetic simulation along with the Joule heating analysis was performed to investigate the performance of the proposed unit cell. The results of this analysis, showed that the proposed metasurface is capable of controlling the reflected wave characteristics by applying an external voltage to its heaters. Finally, the capability of our metasurface as a time-dependent free space beam shaper was demonstrated. Full wave electromagnetic simulation showed that the proposed metasurface can steer the reflected beam with low side lobe levels.

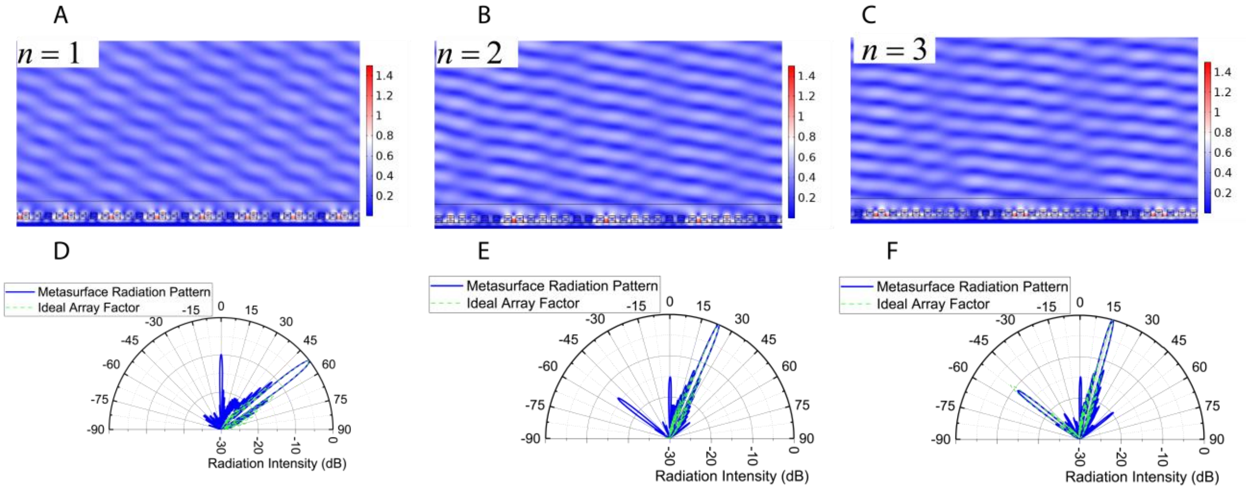

Fig. 3 Beam steering using the proposed reconfigurable metasurface. A,B,C : Full wave simulation results of the reflected electric field for n=1, 2, 3 , respectively. D,E,F: Rdiation Pattern intensity (blue solid lines) and ideal radiation pattern (dashed green lines) for n =1,2,3, respectively

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