Phase-Change Metasurfaces for Dyamic Beam Steering and Beam Shaping in the Infrared

Carlota Ruiz de Galarreta, Arseny Alexeev, Jacopo Bertolotti and C. David Wright.
College of Engineering, Mathematics and Physical Sciences, University of Exeter, EX4 4QF, UK

Abstract*— We present novel phase-change material based metasurfaces for dynamic, recnofigurable and efficient wavefront shaping in the infrared spectrum. Dynamic control and reconfigurability was obtained by incorporating an ultra-thin layer of the widely-used phase change material $Ge_2Sb_2Te_5$. Our approach exploits hybrid dielectic/plasmonic resonances to achieve local (subwavelength) phase control of light with low losses. A full 2π optical phase coverage was achieved with this approach, which allows for a wide flexibility in terms of realizable designs. To illustrate this concept, dynamic beam steering devices and reconfigurable planar focusing mirrors (both operating at optical telecommunications wavelengths) and their performance investigated. Absolute efficiencies up to 65% are achieved, significantly higher than the efficiencies of more commonly reported plasmonic-based phase-change metasurfaces.

Keywords*— 3.3 Optical Communications; 3.4 Broadband Communication Systems; 5.1 Nano Devices, Circuits, and Systems.

I. Introduction

Metamaterials and metasurfaces are engineered structures made of sub-wavelength resonant inclusions which can be either periodically or randomly arranged. By properly engineering the spacing, dimensions and electromagnetic (EM) properties of their constituent elements, metamaterials can achieve effective EM properties (ε_{reff} and μ_{reff}) beyond those found in nature [1], and/or mimic the wavefront shaping capabilities of conventional optics without the need of bulky components [2]. Since the concept of metamaterials emerged, considerable research efforts have been put into the development of novel device prototypes with unusual properties, going from the ultraviolet to the microwave spectrum. Examples of this research trend in the optical regime include devices for amplitude control (such as super absorbers [4, 5]), and phase control (e.g., holograms [2], flat lenses [2] or beam steerers [5]). Optical metasurfaces for phase control (or so-called Huygens metasurfaces [2, 3]) essentially share the same working principle of the well-established reflectarray antenna technology used in the radio frequency (RF) domain, where the phase (ϕ) of an input beam is locally controlled by means of resonant elements (antennas) to generate a particular wavefront [7]. As depicted in Fig. 1, this approach can also be exploited to create a variety of novel and compact plasmonic photonic devices, like beam steerers (Fig. 1a), or flat focusing lenses/mirrors (Fig. 1b). Such devices can however suffer from significant ohmic (plasmonic) losses, since metals are not perfect electric conductors at optical frequencies [2, 8]. As a result, the efficiency (i.e., the fraction of light re-

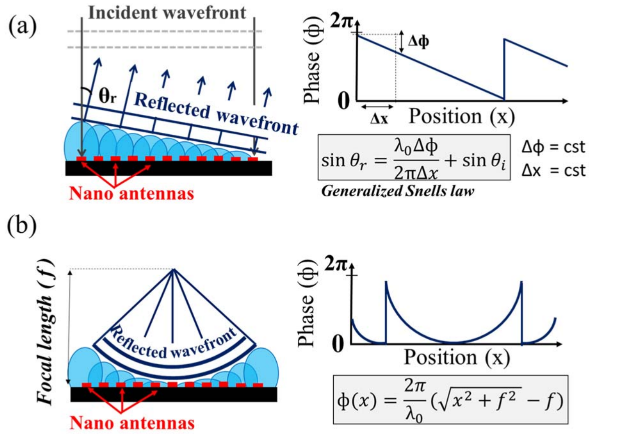

Fig. 1 Huygens principle showing the wavefront reconstruction of a normal incident beam (left), and corresponding spatial phase profile ϕ as a function of the position x (right). (a) Beam steering device: the required phase profile is linear, and can be directly determined by the Generalized Snell's law [2]. (b) Flat focusing mirror: the spatial phase profile can be spherical, parabolic or hyperbolic, and depends on the design numerical aperture (i.e. focal length and aperture) [2].

radiated to the free-space) is reduced in comparison with their RF and microwave counterparts [9]. Furthermore, the EM response of such devices is in general fixed by design, making them unsuitable for applications where light needs to be controlled dynamically or where reconfigurability is required. Chalcogenide phase-change materials, used in combination with metasurfaces, have recently emerged as one possible way of successfully realizing dynamic control and reconfigurability, as has been demonstrated for tunable absorbers, modulators and switches [10-12]. Phase-change materials (PCMs) possess the ability to switch from amorphous to crystalline states (and indeed between intermediate states) after applying a heat stimulus, which can be optically, electrically or thermally induced. Both amorphous and crystalline states are non-volatile and remain stable at room temperature for long periods (years), yet the switching between states can be achieved on sub-nanosecond time scales [13]. Fast crystallization is achieved by heating (via optical, electrical or pure thermal excitation) to a temperature below melting but at which crystal nucleation and/or growth rates are large. The amorphous phase can be recovered after crystallization via melting of the material followed by a fast cooling process (20 °C/ns) [14]. Such change in the atomic structure comes with an abrupt change in the electro-optical properties of the material (i.e. refractive index and resistivity) [15, 16]. $Ge_2Sb_2Te_5$ (GST for short) is arguably one of the most exploited materials, due to its commercial availability, fast tuning time between states (nanoseconds or less), large number of switching cycles and good optical contrast with low losses in the near infrared (NIR) [14]. Recently, the use of this materials with plasmonic Huygens metasurfaces has been proposed for reconfigurable wavefront shaping [16, 17]. Experimental verifications of phase-change plasmonic metsurfaces for dynamic beam steering [18] and lensing [19, 20] in the infrared emerged during the past year. While in such work good efficiencies of up to 40% were demonstrated (in [18]), even higher efficiencies might be achieved by moving from purely plasmonic resonators to those that also rely on Mie resonances in dielectric materials [21]. In this paper, therefore, we propose a metasurface device based on a hybrid combination of dielectric and plasmonic antennas and put forward device designs with efficiencies up to 65% in the NIR. Moreover, our device includes a phase-change (GST) layer to enable dynamic beam steering. Furthermore, our approach could be nicely re-scaled to longer wavelengths such as mid-wave infrared (MWIR) where, due to lower dielectric and plasmonic losses (coming from GST and metals respectively), even better performance (higher efficiencies) with respect to the NIR could be expected.

II. Methodology

A typical plasmonic phase-change based dynamic beam-steering device, as proposed in [18] is shown in Fig. 2(a). It consists of a metal/insulator/metal (MIM) configuration, where a SiO_2/ITO/GST/ITO multilayer stack is sandwiched between a continuous aluminum plane, and semi-infinite periodically-arranged 1D aluminum antennae of different dimensions (widths). The GST acts as a tunable dielectric environment to change the behavior of device, whereas ITO layers were proposed as top and bottom transparent electrodes or heaters, in order to allow for the phase switching of the GST layer by either electrical or optical means. When the PCM layer is amorphous, the structure was specifically designed to reflect light at a particular angle under normal incidence conditions. The required spatial phase profile for such configuration was calculated via the Generalized Snell's law [2] shown in Fig. 1(a). (Note that such approach is only accurate for target reflection angles up to ±45°, where the necessary spatial phase profile is nearly linear [22, 6]). Local phase control of light was achieved by changing the resonant frequency of each antenna (i.e. by properly varying the width of each element). However, when the GST layer becomes crystalline, the underlying resonant behavior is cancelled due to an abrupt change in the optical properties of the material (changes in n and, particularly, k). As a result, the spatial phase profile becomes flat, and thus ordinary specular reflection dominates. Such devices were designed and fabricated in [17] and achieved impressive efficiencies (for plasmonic-based systems) with around 40% of light being reflected at a pre-designed angle of 33° when the GST was in the amorphous state, and specularly reflected at 0° after crystallization, see Fig. 2(b). The remaining fraction of energy is absorbed by the array as inherent plasmonic losses coming from the aluminum, and dielectric losses from the ITO and GST layers.

To improve efficiencies beyond those achieved by MIM device structures such as that shown in Fig. 2, while still maintaining dynamic control and reconfigurability capabilities, we here propose novel phase-change material metasurfaces based on a combination of GST, silicon and a single bottom metal layer. The unit cell (or so called meta-atom) of our devices is shown in Fig. 3. It consists on a hybrid dielectric/metal plasmonic resonator, with a bottom gold (Au) plane and a top hybrid silicon/GST cubic resonator. The Au surface is coated with an ultra-thin SiO_2 layer, to avoid direct contact of Au with GST, and thus potential diffusion problems during heating of the GST layer during switching [11]. Gold possesses low plasmonic losses at NIR frequencies and provides a bottom reflective surface, which could be simultaneously used as a heating element to achieve the GST phase transition (the melting point of gold, 1064 °C, is significantly higher than that of GST, 620 °C). ITO-based heaters were therefore removed in this approach, which was found to be beneficial for the overall device efficiency, as well as for the scalability of the design to longer wavelengths (since ITO becomes extremely lossy in the mid-wave and long-wave infrared spectra). GST volumes were kept to a minimum to avoid dielectric losses without compromising the optical contrast between states. Finally, plasmonic losses coming from the top metal antenna were eliminated by replacing them by high refractive index cubic dielectric resonators, which also ensure polarization independence. Fabrication of such structures could be achieved using standard micro/nano-fabrication techniques such as thin film deposition via magnetron sputtering, and E-beam lithography with subsequent reactive ion etching to achieve cubic patterns [2, 9, 18, 21].

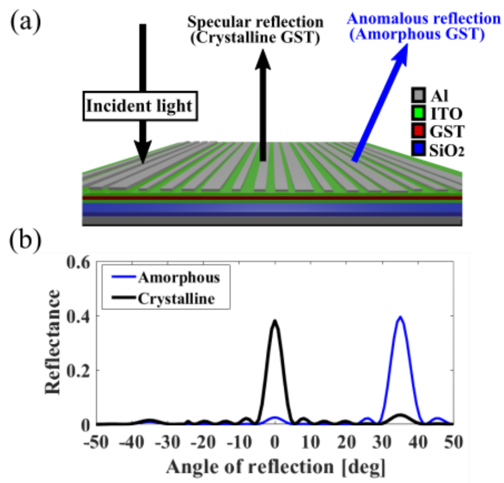

Fig. 2 (a) Schematics showing the operation principle of the phase-change dynamic beam steering meta-device reported in [17]. (b) Calculated angular reflectance for amorphous (blue) and crystalline (black) states at λ = 1550 nm).

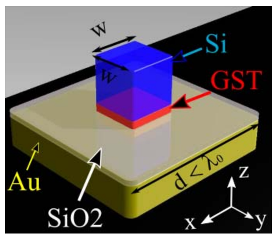

Fig. 3. Unit cell (meta-atom) structure proposed in this work. The materials employed are gold (Au), silicon dioxide (SiO_2), silicon (Si), and GST as the active element.

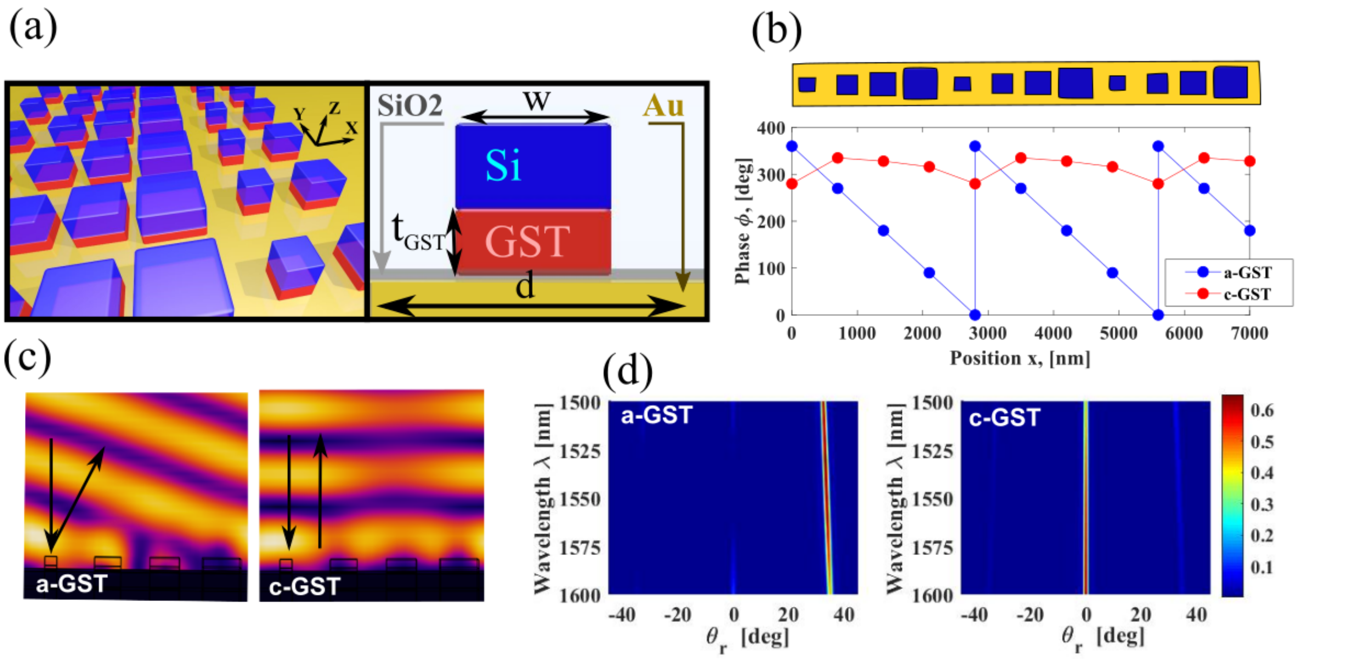

Fig. 4 (a) Dynamic beam steering device based on hybrid phase-change dielectric/metal meta-atoms (left), and schematic showing dimensions and materials employed in the unit cell (right). (b) Spatial phase profile for amorphous and crystalline states. Top inset shows the cube widths employed to achieve the necessary local phase responses, *w_1= 148 nm, w_2= 326 nm, w_3= 364 nm, w_4= 462 nm* (c) Numerically resolved instantaneous electric field distribution, showing anomalous and specular reflection at λ= 1550 nm for amorphous and crystalline states respectively. (d) Calculated angular reflectance for amorphous (left) and crystalline (right) states from λ= 1500 nm to λ= 1600 nm.

III. DESIGN & ANALYSIS

The scattering properties (phase and amplitude) of our unit-cell structure as a function of its geometrical parameters were investigated via finite element methods using the commercial software package Comsol Multiphysics®. Floquet periodic boundary conditions were applied to the sides in order to mimic infinite arrays of elements. The refractive index (n) and absorption coefficient (k) of Au, SiO2, GST and Si were taken from references [23], [24], [18] and [25] respectively.

First, a beam steering meta-device of the same characteristics as the previously described approach [18] was designed in order to compare the performance in terms of efficiency. Finally, the potential of our phase-change meta-atoms for dynamic wavefront shaping was investigated at other NIR wavelengths, towards the realization of novel device approaches, such as multifocal flat mirrors.

A. Phase-change dynamic beam steering meta-devices

The schematics of our phase-change dynamic beam steering device are shown in Fig. 4 (a). The cubic Si/GST resonator has a total height of 115 nm, with a GST thickness (t_{GST}) of 46 nm. The SiO_2 layer was fixed to 5 nm, and the lattice constant *d* is 700 nm. The cube width *w* was varied along the array to slightly detune each element from its resonant frequency, and thus generate the necessary spatial phase profile for beam steering discussed in Fig. 1(a). Fig. 4(b) shows the optical phase in reflection of each element as a function of the position *x*. Amorphous GST (a-GST) antennas were specifically arranged to induce linear phase gradients along the surface, while ensuring a near invariant spatial phase response with crystalline GST (c-GST) antennas. As a result, according the Generalized Snell's Law [2], light is anomalously reflected at a particular angle when the PCM is amorphous, and specularly reflected after crystallization (Fig. 4(c)). Finally, the angular reflectance for both amorphous and crystalline states was computed (Fig. 4(d)) within a spectral range from 1500 nm to 1600 nm. Fig. 4 shows a near invariant spatial phase response with crystalline GST (c-GST) antennas. Fig. 4 shows the results from these calculations, confirming anomalous reflection in the amorphous phase, and specular reflection after crystallization with efficiencies up to 65%. Our design thus outperforms other previously-reported approaches [18-19] by a factor of 1.5 [18] and 13.0 [19] respectively.

B. A dynamic NIR focusing meta-mirror

The optical phase in reflection of our unit cell as function of the width *w* was investigated to explore the potential of such structures for working at shorter NIR wavelengths (i.e. from λ= 1050 nm to λ= 1350 nm). The re-scaled structure is depicted in Fig. 5(a), with t_{GST} = 35 nm, t = 90 nm, and d = 700 nm. Indeed, just like in the previous spectral band (Δλ = [1500; 1600] nm), the reflection phase can be manipulated over the whole 2π range when the GST layer is amorphous (Fig. 5(b)). As a result, any kind of wavefront can be reproduced using this approach, thus allowing for a wide flexibility in terms of realizable designs, not only for beam steering, but also for reconfigurable lensing [2].

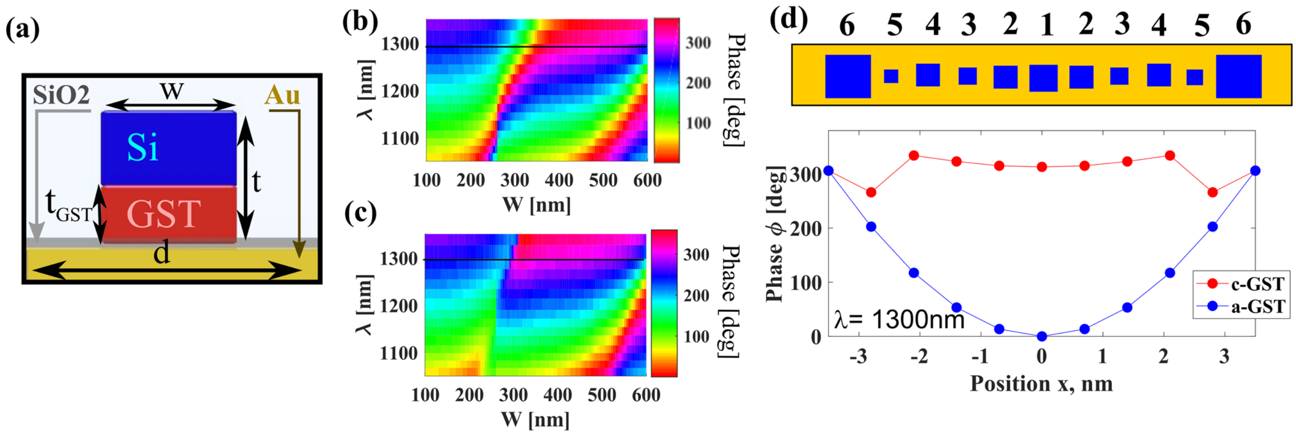

Fig. 5 (a) Schematics of the unit cell rescaled for shorter NIR wavelengths, where t_{GST} = 35 nm, t= 90 nm, and d= 700 nm. (b-c) Reflection phase of the unit cell as a function of the cube width w for amorphous (b) and crystalline (c) states. (d) Spatial phase profile from our focusing meta-mirror, for amorphous (blue) and crystalline states. Top inset shows the different sizes required to locally control the phase, w_1= 555 nm, w_2= 274 nm, w_3= 320 nm, w_4= 342 nm, w_5= 362 nm, w_6= 377 nm.

Fig. 5(c) shows the corresponding phase response after crystallization with the same previously-described characteristic near-invariant phase response at each wavelength. Again, this behavior allows for the realization of devices which can be selectively turned on and off. A reconfigurable focusing meta-mirror working at λ = 1300 nm has been designed to illustrate this principle. Fig. 5(d) shows the characteristic spatial phase profile described in Fig. 1(b), for a focal length f = 6 μm (numerical aperture NA = 0.64). Inset shows the top view of a section from our meta-mirror, where different resonator sizes provide the necessary local phase delays. After crystallization, it can be seen that the phase profile becomes nearly flat, thus the device behaves as a planar mirror.

IV. CONCLUSIONS

Hybrid phase-change dielectric/metal plasmonic meta-atoms can be exploited to create high efficiency reconfigurable devices for wavefront shaping (e.g. for dynamic beam steerering or tunable focusing mirrors) across the whole NIR spectrum. The optical phase in reflection can be manipulated over a range of 2π, which also allows for the realization of other kind of interesting and exciting metasurfaces, like reconfigurable phase-holograms or vortex beam generators [2]. Contrary to other approaches exploited to tune the optical response of metasurfaces (such as liquid crystals or gating semiconductors), the inherent fast transition times of chalcogenide phase-change materials (ns) and their non-volatile nature can provide important advantages such as ultra-fast reconfigurability with low power consumption.

Our phase-change meta-devices have shown efficiencies up to 65%, outperforming other previously-reported plasmonic-only based approaches [17, 18]. Dual configurations could be extended to multiple configurations (e.g, steering at multiple angles) by including the fraction of crystallization of GST (i.e, where refractive index takes values in between fully amorphous and fully crystalline) as another degree of freedom.

Furthermore, our meta-atoms could be potentially re-scaled to operate at larger wavelength bands, such as mid-wave IR, and even at long-wave IR by, in this latter case, replacing silicon (which becomes lossy in this regime) by germanium. It is expected that the overall performance of our hybrid dielectric/plasmonic resonator structures will be even better in this regime, due to a decrease of plasmonic losses. Our study provides the pillars for a new type of high-efficiency phase-change meta-surfaces for dynamic and reconfigurable wavefront shaping.

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