Enhancing LiDAR Performance: Mid-IR Beam Steering with a Phase-Gradient Metasurface

, **Mohmaed Elsewedy [1], Jason Midkiff [2], and Ray Chen [1,2]**

[1] *Department of Electrical and Computer Engineering, University of Texas at Austin, 10100 Burnet Rd, Austin, TX 78758, USA.*
[2] *Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, Texas 78757, USA*

[1] *mohamed.elsewedy@utexas.edu*

Abstract: The paper introduce a hybrid device that combines a passive silicon-on-sapphire metasurface (MS) with an InP-based optical phased arrays (OPA) operating in mid-IR region to overcome Its field of view's limitations. This approach expands the OPA's beam steering from ±11.5° to a wider range from 0° to 45°.

1. Introduction

Solid-state beam steering in the mid-infrared (mid-IR) 3-5 µm region is crucial for future applications in long-range LiDAR, infrared countermeasures, and chemical sensing. Optical Phased Arrays (OPAs) have become the main non-mechanical solution, providing chip-scale integration and fast operation. However, OPAs have a basic design challenge of the spacing between emitters must be large enough to reduce optical crosstalk, which limits the maximum FOV. This difficulty is highlighted by a new InP-based OPA intended for monolithic integration with Quantum Cascade Lasers [1]. Its steering range is only ±11.5° at a wavelength of 4.6 µm. For many sensing and communication scenarios, this field of view is highly restrictive. Metasurfaces (MS) have attracted alot of attention in recent years due to its ability to manipulate the phase, amplitude, and polarization of electromagnetic waves. In this work, phase-gradient MS layer is introduced to enhance the beam steering performance of the OPA device presented in []. Phase-gradient metasurfaces (PGMs) serve as an effective platform for steering a beam in a specific direction. Based on the generalized Snell's law, the direction of the refracted wave can be adjusted by changing the phase gradient term of generalized Snell's law [2].

2. Unit Cells Design and Theoretical Framework

The design of our phase gradient metasurface layer is mainly based on generalized Snell's law [2], as shown in this equation:

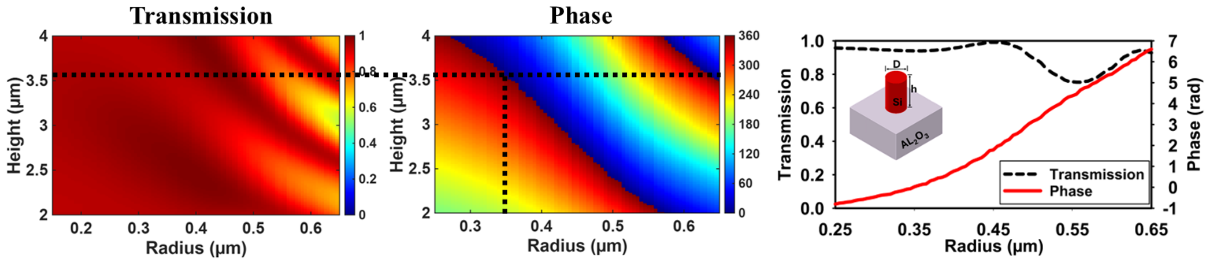
$$n_t \sin(\theta_t) - n_i \sin(\theta_i) = \frac{\lambda_0}{2\pi}\frac{d\Phi}{dx}$$

where n_i and n_t are the refractive indices of the incident medium and the transmitted medium, respectively. θ_i and θ_t are the incident and transmitted angles with respect to the surface normal of a metasurface. $d\phi/dx$ is the phase gradient term. The main goal is to construct MS supercell, which consists of multiple unit cells, that achieves a full 2π phase shift span while maintaining the transmission is efficient. The main objective of the MS layer is to improve the beam steering limit of the InP-based OPA device that has a steering window of ±11.5° [1]. To maximize the transmitted angle from the MS layer, we have a two main parameters that will control the generalized Snell's law, $d\phi$ and dx, but there are two saturation limitations. The first one is that the transmitted angle must not exceed 90° because after this angle, there is no real transmitted angle exists, which means the wave is evanescent, decaying in the transmission medium. The second limitation, the unit cell size must not be very narrow to avoid the high mutual coupling between the neighboring elements, which may distort the radiation waves. The graphical representation of the MS unit cell is shown in Fig. 1, which illustrates that a Silicon-on-Sapphire dielectric platform is utilized to design the MS layer. Silicon offers a high refractive index, which helps to provide effective light confinement at 4.6 µm, while Sapphire is transparent in the mid-IR region. Based on the calculation from the previous equation, the phase gradient term must be $\leq 0.45\,\pi$, which in turn makes the number of the unit cells in the single supercell to achieve the full 2π couverage (phase steps) must be ≥ 5 steps in order to avoid the saturation.

3. Simulation Results and Analysis

3.1. Unit-Cell Analysis and Supercell Validation

To validate the transmission behavior of silicon pillars and their ability to achieve full 2π phase control, the unit cell is simulated by using Lumerical RCWA with periodic boundary conditions. In order to generate a detailed

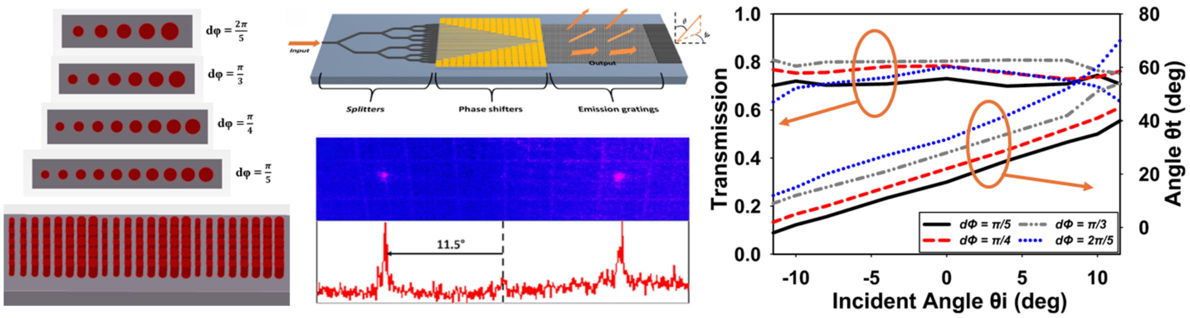


(a) (b) (c)

Fig. 1. The Transmission and the phase of the MS unit cells for (a), (b) different heights and radii (c) 3.56 μm-height.

library that connects the unit cell's geometry with the transmission phase and amplitude at 4.6 μm, the unit cell size (p) is varied from 0.3λ to 0.6λ, the radius is also swept from 0.15p to 0.6p, and the height of the unit cells is changed from 2 μm to 4 μm, as shown in Fig. 1(b), (d). An array of pillars with a thickness of 3.56 μm can achieve the highest transmission amplitudes while covering the entire spectrum of phases from 0 to 2π by adjusting the radius from 0.35μm to 0.6μm. The transmission phase and amplitude of the unit cells with thickness 3.56 μm with respect to different radii are presented in Fig. 1 (c). For the 3.56 μm height for the silicon unit cells, the minimum aspect ratio is 4.2. Based on the theoretical analysis (in section 2), the number of the unit cells in the single supercell must be larger than 5 unit cells. To validate the phase control behavior of the hybrid device, four different geometries were designed and simulated based on using four different phase gradient values as shown in Fig. 2(a). When the phase gradient value is $\pi/5$, $\pi/4$. $\pi/3$, $2\pi/5$, the supercells will consist of 10, 8, 6, and 5 unit cells, respectively, to cover the whole 2π phase range. The phase steps and the equivalent radii for each geometry are shown in Table 1. For the 3.56 μm height for the silicon unit cells, the minimum aspect ratio is 4.2.

3.2. Hybrid System Performance



(a) (b) (c)

Fig. 2. (a) MS unit cells, (b) OPA device and its beam steering results [1], (c) Transmission efficiency and the angular enhancement as a function of OPA's output.

The phase gradient MS supercells were simulated using Lumerical FDTD. The incident beam of the metasurface layer is steered from -11.5° to +11.5°, as it is the steering window of the OPA device as presented in Fig. 2(b). The diffracted angles of each geometry are shown in Fig. 2(c), which proves that the $\pi/5$-supercells, $\pi/4$-supercells, $\pi/3$-supercells, and $2\pi/5$-supercells have diffracted angles windows from -2° to 40°, 0° to 45°, 9° to 54°, and 12° to 70°, respectively, based on changing the incident angle from -11.5° to +11.5°. Furthermore, the transmission efficiency of the four different geometries is presented in Fig. 2(c). When the phase gradient is increased, the transmission efficiency is increased; on the other hand, the diffraction efficiency is decreased. So, the optimum value for the phase gradient term is $\pi/4$.

* Further graphical representations of the hybrid device and the specific radii of the unit cells used to construct the supercells will be presented at the conference.

References

1. J. Midkiff, K. M. Yoo, J. Shin, H. Dalir, M. Teimourpour, and R. T. Chen, "Optical phased array beam steering in the mid-infrared on an InP-based platform," in *Optica*, **7**, 1544–1547 (2020).
2. Nanfang Yu et al., "Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction," in *Science*, **334**, 333–337 2011).