Dielectric-Free Cells for Low-Cost Near-Field Phase Shifting Metasurfaces

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***Abstract*—This paper presents a unique dielectric-free cell configuration that is useful as a building block to design low-cost transparent phase-gradient metasurfaces required for antenna beam steering using both far-field and near-field methods. Each cell is made of a few thin metal sheets each having an asterisk-shaped slot. A phase variation of 360 degrees is possible with four metal layers, with less than 2 dB drop in amplitude. This is much greater than what is possible with the conventional cross-slot which lacks such a high degree of freedom.**

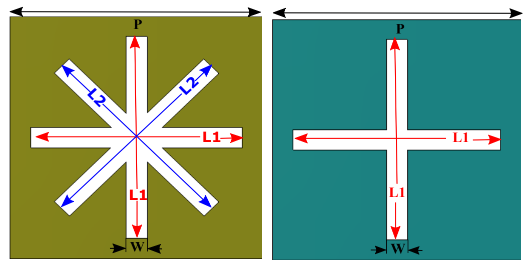
***Index Terms*—Metal-only, All-metal, Dielectric-less, Phase Gradient, Meta-Steering, Low cost, Dielectric-free, Phase Shifting Surface, PSS, FSS, Supercell, Transmitarray, Lens Antenna, Flat Lens, SATCOM, SOTM, COTM**

I. Introduction

Phase-Shifting surfaces or phase-transformation metasurfaces [1], [2] are free-standing thin surfaces made of spatially distributed cells. Often all cells have the same topology (although this is not a requirement) with different parameters. In Near-Field Meta-Steering [3], [4] these cells are arranged in a specific pattern (often in a 2D grid) to transform the near-field phase distribution created by a fixed base antenna to a more desirable phase distribution without changing the near-field amplitude distribution of the base antenna. This near-field phase transformation concept has been successfully used to make the near-field phase distribution of some antennas more uniform, thus increasing its gain and directivity by 9 dB [2], and steering in both elevation and azimuth the pencil beam of a medium-to-high gain antenna within a large conical region with an apex angle of $102°$ [2], [3].

The fundamental building block of these metasurfaces is a cell and great emphasis has been placed on developing cell topologies that can provide a wide range of phase shifts (ideally 360 degrees) with minimal change in amplitude. Most of the cell topologies have multiple layers of dielectric and metallic patterns and are fabricated using commercially available dielectric laminates [2], [3]. Therefore, when designed to steer the beam of a high-gain antenna (>30 dBi) for applications such as satellite communications, these metasurfaces are expensive and heavy. Presence of dielectric limits their applications in space due to ionization and in high-power microwave systems due to dielectric breakdown. Dielectric-free cell topologies do not have these limitations.

This paper presents preliminary results on the development of unique dielectric-free cell topology. The proposed cell configuration has an asterisk-shaped slot in a thin sheet of metal. Then, it is used to design a four-layer supercell, which is the unit cell of a phase-gradient metasurface, following the design strategy presented in [4].



(a) (b)

Fig. 1: Topology of one layer of a dielectric-free cell (a) Proposed; (b) Conventional.

II. Dielectric-free Cell Topology

The proposed cell topology, shown in Fig. 1(a), is an extension of the conventional cell with a cross slot [5]. This slot pattern is made in a very thin sheet of metal (metal thickness of $\lambda_0/80$, at $f_0 = 12.5$ GHz). To highlight superior characteristics of the proposed cell, its performance is compared here with a conventional cross-slot element shown in Fig. 1(b). The physical parameters of the unit-cells are $W = 0.5$ mm and $P = \lambda_0/2$. Both cells have been simulated in CST Microwave Studio with periodic boundary conditions. The parameter L1 is varied between 0.5 mm and 11.5 mm and the magnitude and phase of the transmission coefficient are plotted in Fig. 2. All cells used in a phase-shifting surface, and especially those used in the near field, are required to have very high transmission magnitude along with a sufficient transmission phase range. The conventional cross-slot topology can provide a limited phase range, which is mainly due to the fact that only a few physical parameters can be modified. The new topology has extra degrees of freedom.

For a fair comparison, the design parameters are the same as mentioned above whereas L1 and L2 vary independently from 0.5 to 11.5 mm and from 0.5 to 15 mm, respectively. The magnitude and phase of the transmission coefficient are pictorially depicted in colour map plots in Fig. 3. It is observed that one layer of the proposed asterisk-slot topology can provide a large phase range (nearly 90°) [6] with high transmission magnitude (> -1 dB).

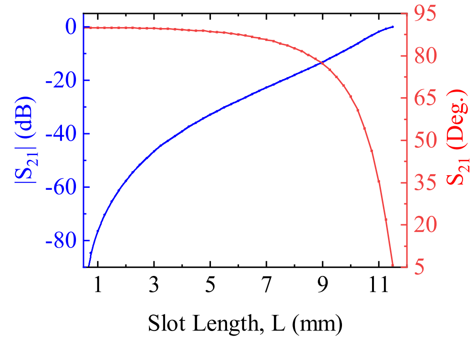


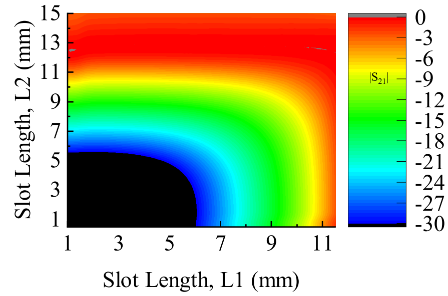
Fig. 2: Transmission characteristics for a one layer dielectric-free conventional cross-slot topology.

III. Dielectric-free Supercell

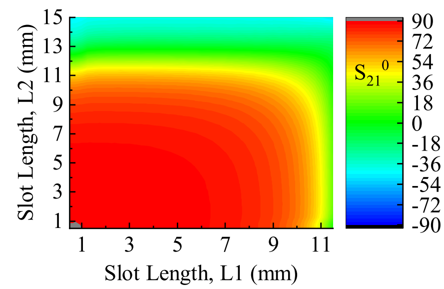
A multilayered arrangement of the proposed unit-cell, having four identical layers separated by spacing $\lambda_0/4$ is simulated and it was found that it has a phase range of 360° with a transmission magnitude greater than -2 dB. Then a supercell, which is the actual unit cell repeated in a periodic phase-gradient metasurface, was designed by cascading five asterisk-slot cells with a progressive phase advance of $2\pi/5$ between adjacent cells. The dimensions of the five cells in millimetres are : $(L_1, L_2) = (4.0, 12.5), (9, 13), (4.25, 13.75), (4.25, 11.75), (11.25, 8.25)$. This supercell was analyzed using Floquet space harmonics with periodic boundary conditions. The resulting magnitude and phase difference between output and input of the supercell, shown in Fig. 4(a), confirms its linear phase progression. Field variation through supercell, when analyzed with periodic boundary condition, indicates an output field tilted at $\theta = 23^\circ$(Fig. 4(b)). This angle was confirmed by analyzing far-field patterns.

IV. Conclusion

A new topology of the dielectric-free cell was investigated with an aim to develop low-cost near-field beam-steering metasurfaces for Near-Field Meta-Steering but they are equally useful for far-field beam steering methods as well as low-cost, lightweight lens antennas and transmitarrays. The new topology with asterisk-shaped slots cut in metal sheets can produce the required phase shifts while maintaining high transmission magnitude. It has been used to design a supercell of a phase-gradient metasurface and its performance has been verified through numerical simulations.

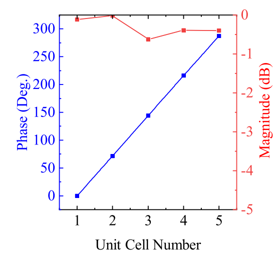


(a)

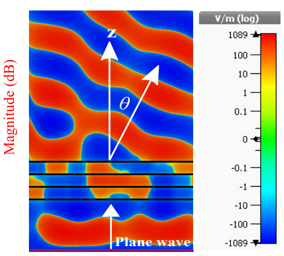


(b)

Fig. 3: Transmission characteristics for one layer of the proposed unit cell (a) Magnitude (dB) and (b) Phase (°).



(a)



(b)

Fig. 4: A Supercell (a) Showing linear phase progression and higher transmiting amplitude and (b) Electric field distribution at 12.5 GHz to verify 23° refraction.

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