URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Self-Phased Metasurface Pixels/Cells: Concept, Design and Applications

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Abstract

Metasurfaces can be categorized into two types, i.e., transmission-type and reflection-type. In general, they allow electromagnetic waves either to be transmitted or reflected with the manipulation in phase and or amplitude. The transmission/reflection phase can also be tuned by incorporating active circuit elements into the metasurface pixels/cells' design. This paper presents a self-phased metasurface pixel/cell concept that mainly focuses on the tunability in both the transmission and reflection phase without using lossy active circuit elements. The tunable phase can be realized by using constituent material as the substrate supporting the metasurface. In transmission-type, we propose a unit cell design that consists of three layers of a metallic ring surrounding a metallic patch; all are integrated into a constituent material used as substrates. In reflection-type, the presented pixel/cell design consists of a dual-circular ring, incorporating a meandered slot line, or an interdigitated line, in between. All are also integrated on a dielectric layer with a metal backing used as a constituent material. Simulation results show that the designed unit cells can achieve over 220 degrees of tunable phase with an insertion loss of less than 3 dB in the transmission configuration and 220 degrees of tunable phase with less than 2 dB loss in the reflection configuration. The proposed concept is implemented to design the reconfigurable transmit and reflectarray without lossy phase shifters or active circuit elements.

1 Introduction

The transmit/reflectarray concept has recently received significant attention in modern communication systems [1-5]. There are a few key differences between this type of antenna and a conventional phased array. In a transmit/reflectarray, there is no complex feeding network to introduce a high loss in the system. Instead, it is illuminated by a primary feed horn. The transmit/reflectarray cells receive and then reradiate the feed horn's incident energy with a given phase determined by the shape and or dimensions of the cell. The transmit/reflectarray is a simple planar structure that can also be conformed to a given surface platform, reducing its footprint.

Although arbitrary phase profile in the hybrid transmit and reflectarray cell is realizable by changing its shape or dimensions, its distinct properties are fixed once it is fabricated. To make the phase profile dynamically reconfigurable, active circuit elements, such as pin diodes or varactors, are often incorporated in designing the elements [6]. The performance of reconfigurable transmit/reflectarray is still limited due to high loss in active circuit elements.

This work presents a self-phased metasurface cell concept that can be implemented to design the reconfigurable transmit/reflectarray. To achieve the tunable transmissive phase, we present a design with three layers of an outer metallic ring surrounding an inner metallic patch with two intermediate dielectric layers in between, as depicted in Figure 1. We introduce a circular inter-digitated, CID, metasurface cell/pixel design that offers a reconfigurable reflection phase for the reflectarray configuration. A unit cell consisting of a dual-circular ring that incorporates a meandered slot or inter-digitated line in between is placed on a dielectric layer with metal backing, as depicted in Figure 2.

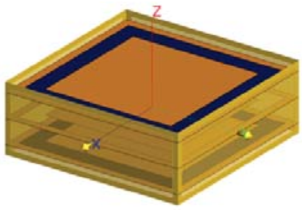

Figure 1. Metasurface pixel/cell comprises three layers of a metallic ring surrounding a metallic patch with two dielectric layers in between.

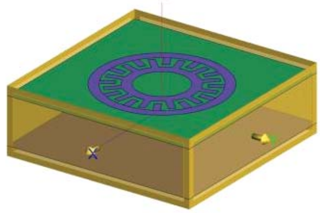

Figure 2. Metasurface pixel/cell composed of a dual-circular ring incorporating inter-digitated line, or a meandered slot, in between and placed on top of a dielectric layer.

Instead of loading the cell with active circuit elements, we use constituent material as dielectric layers to control the phase. The resonance frequency and the phase profile of the metasurface cell are affected by the surrounding medium's permittivity. Upon applying a DC voltage bias, the constituent material's permittivity can be altered, which results in a tunable phase at the cell level at the given frequency. In this work, we explore the use of Barium Strontium Titanate (BST) films [7] or nematic liquid crystals (LC) [8] in the composite as constituent materials. Both presented unit cells are designed and simulated using full-wave electromagnetics commercial software, FEKO. More than 220 degrees of tunable phase with an insertion loss of less than 3 dB in transmission-type and 220 degrees of tunable phase and a loss of less than 2 dB in reflection-type are demonstrated.

2. Design Concept of Self-Phased Metasurface Pixel/Cell

The electromagnetic properties of the cell used in the reflectarray are quite the opposite of the one used in transmit array. In reflectarray, the cells receive the incident energy and then reradiate its energy towards the feed horn. While in the transmitarray, the cells generate a focused beam in the forward direction. The relation between a reflectarray and a transmitarray is similar to the relation between a mirror and a lens. One may think designing the element in a transmitarray configuration is similar to as in the reflectarray configuration. However, this may not be the case. In the reflectarray, the magnitude of the reflection signal (S_{11}) is always approximately 1 (0 dB) due to the metal backing ground plane that reflects the entire incident energy; thus, one only needs to control the element reflection phase. In transmitarray, besides the phase control, the magnitude of the transmission (S_{21}) needs to be close to 1 (0 dB) to ensure high efficiency. Thus, this leads to a different strategy when designing elements in the reflectarray versus in the transmitarray.

Small footprint and a broad tunable phase range are two main objectives when designing cells in the reflectarray. To achieve a compact and low-profile feature, we incorporate the meander/inter-digitated line in the dual-circular-ring structure. This also enhances the resonance effect, which often results in a wider phase range and higher loss. As depicted in Figure 2, the unit cell design comprises a dual-circular-ring, incorporating a meander slot placed on top of the dielectric layer with metal backing. The outer and the inner ring have a radius of 2 mm and 1.1 mm, respectively. The width of the line is 0.3 mm. The outer ring has 12 spokes facing inward with 0.45 mm in length and 0.2 mm in width. The inner ring also has 12 spokes facing outward with the same dimensions as the outer ring. To validate the self-phased concept, we assume the dielectric constant of the supporting layer, which has a thickness of 1.5 mm, can vary from 5 to 3.5.

A broad tunable phase range while minimizing the insertion loss is the main objective when designing cells in the transmitarray. To achieve this, we utilize the concept of electromagnetic coupling between the cascaded metasurfaces. The higher number of cascaded layers leads to a wider phase range but at the expense of a thicker profile. Figure 2 shows that the proposed unit cell design comprises three metallic layers and two intermediate dielectric layers. The metallic layer contains a square-loop slot, with a side length of 11 mm and a slot width of 0.5 mm, surrounding an 8 mm inner square patch. Each of the two dielectric layers has a thickness of 1.5 mm, with a dielectric constant ranging from 2.65 to 3.65.

3. Simulation Results and Discussion

To validate the proposed concept, unit cells are designed and simulated using full-wave electromagnetics commercial software, FEKO. The unit cell is placed at the origin and excited by an x-polarized electric field (of a plane wave traveling along z-axis using 2-D periodic boundary condition. Figure 3 shows the reflection coefficient (magnitude) of the proposed unit cell depicted in Figure 1 using a dielectric constant of 5 and 3.5, as mention above. By varying the dielectric constant, the resonance frequency varies as well. Also, $|\Gamma| > 0.8$ (-2 dB) when the dielectric constant (ϵ_r) varies from 5 to 3.5. As shown in Figure 4, we can achieve up to 220 degrees of tunable reflection phase range at 12 GHz. As previously mentioned, the wider phase range often means higher loss. The range can be extended up to 330 degrees by adding more spokes in both the outer and inner ring to enhance the resonance. However, it comes with the expense of more loss in the design.

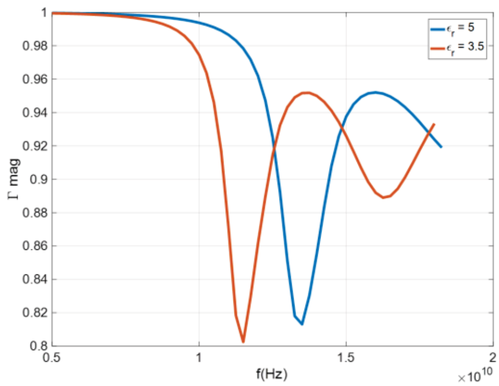

Figure 3. Reflection coefficient magnitude of the unit cell depicted in Figure 1 using ϵ_r = 5.0 and 3.5.

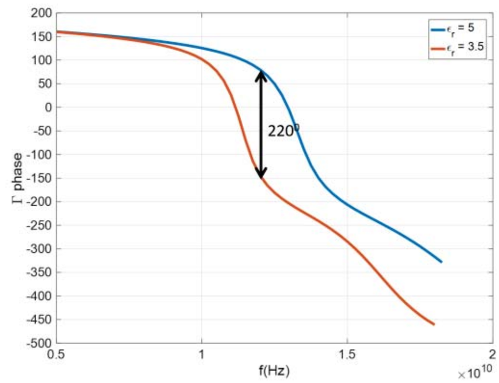

Figure 4. Reflection coefficient phase of the unit cell depicted in Figure 1 using ϵ_r = 5.0 and 3.5.

Figure 5 shows the transmission coefficient (magnitude) of the proposed unit cell depicted in Figure 2 using a dielectric constant of 2.65 and 3.65. As seen, by varying the dielectric constant, the resonant frequency varies as well. A vertical black line shows the cutoff frequency, 9.1 GHz, |T| ≥ 0.7 (-3 dB), when the dielectric constant varies from 2.65 to 3.65. Next, let us look at transmission phases, as depicted in Figure 6. At the cutoff frequency, there are up to 220 degrees of tunable phase range available. The range is reduced at lower frequencies.

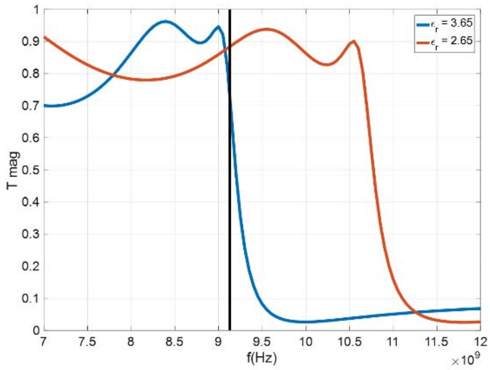

Figure 5. Transmission coefficient magnitude of unit cell depicted in Figure 2 using ϵ_r = 2.65 and 3.65.

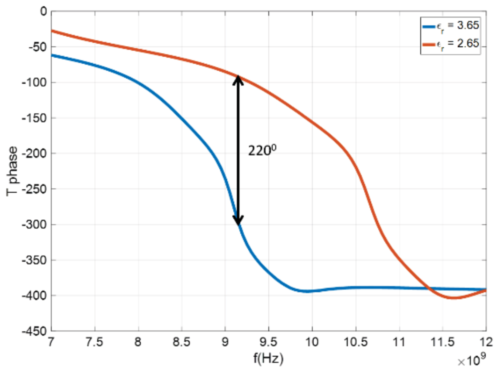

Figure 6. The unit cell's transmission coefficient phase is depicted in Figure 2 using ϵ_r = 2.65 and 3.65.

As shown in Figure 3-6, both presented unit cell designs meet criteria in terms of magnitude and phase. Based on the phase profile (Figure 4 and 6), one can tune the dielectric constant to obtain the desired phase, which can be used to control the radiated beam in transmit/reflectarray system [9-10].

4. Conclusion

In this paper, we present two unit cell designs to validate the concept of the proposed self-phased. The first design is a three-layers cascaded metallic ring surrounding a metallic patch, which can be used in transmitarray to control the radiation beam. The second design is a circular inter-digitated (CID), used in reflectarray to control the radiation beam. Both designs' simulation results confirm that more than 2200 degrees of tunable phase with less than 3 dB in loss can be achieved. The tunable phase range may be extended up to 330 degrees at the expense of more loss and or thicker profile in the design.

5. References

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