Circular Inter-Digitated Design for Self-Phased Reflective Pixel/Cell for Metasurfaces and Reflectarrays

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Abstract

A reflective metasurface cell allows electromagnetic waves to be reflected with a desired phase. The reflection phase can also be tuned by incorporating active circuit elements into the metasurface cells/pixels. In this paper, we present a design concept of circular inter-digitated (CID) self-phased reflective (SPR) metasurface pixel/cell that offers a reconfigurable reflection phase. Unlike using active circuit elements in conventional approach, we use a constituent material in dielectric layer supporting the metasurface. As the constituent material permittivity changes, the resonance wavelength of the metasurface also changes, which results in a phase change. The presented pixel/cell design consists of a dual-circular ring, incorporating a meandered slot line, or an interdigitated line, in between. All are integrated on a dielectric layer with metal backing that is used as a constituent material. The design can achieve polarization-independent phase control with 220 degrees of tunable phase and loss of less than 2 dB. The design can be applied in coding metasurfaces to control the scattering pattern, where reflection phase tuning is needed. The design can also be used in reflectarrays.

1. Introduction

Perfect electric conductor (PEC) and perfect magnetic conductor (PMC) surfaces exhibit 180 degrees and 0 degree of reflection phase, respectively. A concept with 0^0 – 360^0 adaptable phase using metasurface pixel/cell has gained significant attention in electromagnetic (EM) research community. This is due to the fact that many EM phenomena and applications are directly related to reflection phase control. For instance, in reflectarrarys, the element is designed to compensate the spatial phase delay from the feed horn to that element [1]. In other words, every reflectarrary element requires its own reflection phase to be of a value such that the radiation beam can be steered in a specific direction. In low-scattering metasurface, one can design random reflection phases for the meta-elements to create a diffused-reflection surface, resulting in low backward scattering, which is essential in EM cloaking or stealth technology [2].

Although arbitrary reflection phase profile in metasurfaces is realizable, 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 [3]. Despite technical advantages in the reconfiguration capability, conventional designs are usually polarization-dependent, where their performances may be limited in practical scenarios.

In this paper, we propose a circular inter-digitated self-phased reflective, CID-SPR, metasurface cell/pixel design, which can offer polarization-independence, along with reconfigurable reflection phase. Instead of loading the cell/pixel with active circuit elements, as in the conventional approach, we use a constituent material as dielectric supporting layer to control reflection phase. Upon applying a DC voltage bias, the permittivity of the constituent material can be tuned, which results in a tunable reflection phase. In this work, we study the use of Barium Strontium Titanate (BST) films as the constituent material. A unit cell consisting of a dual-circular ring that incorporates a meandered slot or inter-digitated line in between, is placed on a dieletric layer with metal backing, as depicted in Figure 1. The proposed design is simulated using full-wave electromagnetics commercial software, FEKO. Polarization-independence with 220 degrees of tunable phase and a loss of less than 2 dB are demonstrated.

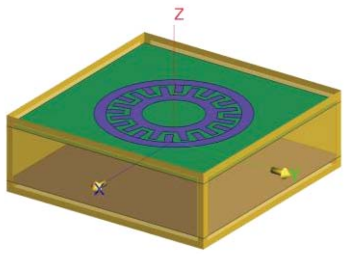

Figure 1. Metasurface pixel/cell composed of a dual-circular ring incorporating inter-digitated line, or a meandered slot, in between and placed on top of dieletric layer.

2. Ferroelectric BST Film

As is well known, the resonance frequency and the reflection phase profile of metasurface are affected by permittivity of surrounding media. In other words, the resonance frequency shifts higher if one uses lower dieletric constant material as a substrate, and vice versa. To utilize this concept for reconfigurable capability, we consider ferroelectric Barium Strontium Titanate (BST) film, which can offer permittivity tuning under applying a voltage bias. In [4], authors reported that the relative permittivity of BST varies from 200 to 50 under applying 0-9V, which is approximately 75% of tunability. To study the tunability of BST film in a substrate, we assume that the BST film has a relative permittivity, ε_r, of 200 before applying a DC bias voltage. Its relative permittivity, ε_r, drops to 100 when a 5V DC bias voltage is applied. The loss tangent value is assumed to be 0.02 over the frequency range 5-15 GHz. Figure 2 shows the effective permittivity with and without applying a DC bias voltage on the three-layer slab that has BST film embedded between two layers of RT/duroid 5880.

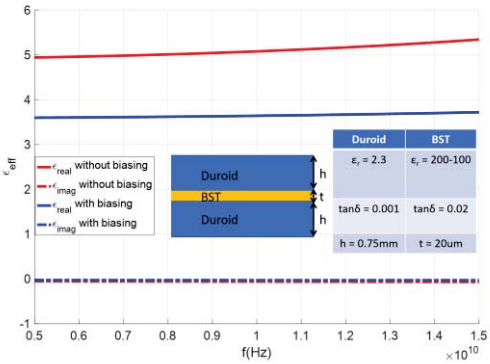

Figure 2. Effective permittivity with and without applying DC bias voltage on the three-layer slab incorporating a BST film.

The thickness and dieletric constant of each layer are also depicted in Figure 2. As seen in the figure, the effective permittivity of the slab can be tuned from 5 to 3.5 upon applying a DC bias voltage. This is equivalent to approximate 30% tunability.

3. Reflection-Type Metasurface Design

In this section, we present a reflection-type metasurface cell/pixel design, incorporating constituent dieletric layer materials for controllable capability. To achieve polarization-independence with a decently tunable phase range while minimizing the loss, we utilize the dual-circular-ring structure. To achieve a compact and low-profile feature, we incorporate the meander/inter-digitated line in the design. As shown in Figure 1, the unit cell design is composed of a dual-circular-ring, incorporating meander slot in between placed on top of dieletric 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. The dieletric supporting layer has a thickness of 1.5 mm, with a dieletric constant that can be tuned from 5 to 3.5 using a BST film, embedded between two layers of RT/duroid 5880, as mentioned in the previous section. The unit cell is placed at the origin and excited by a 45^0-polarized electric field (with respect to x axis) of a plane wave traveling along z axis.

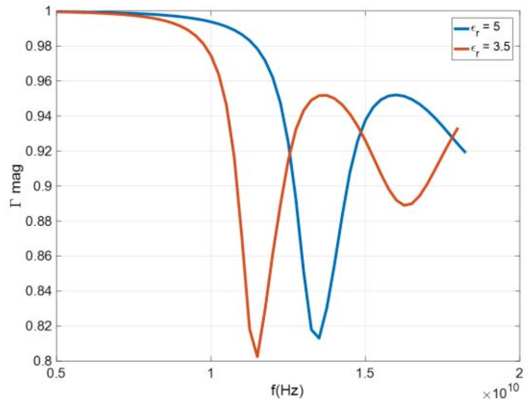

Figure 3. Reflection coefficient magnitude of unit cell depicted in Figure 1 using dieletric constant of 5 and 3.5.

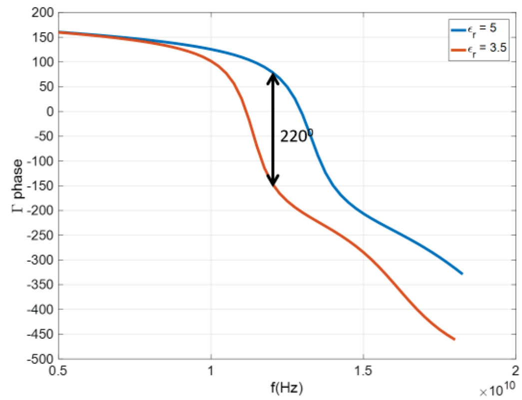

Figure 4. Reflection coefficient phase of unit cell depicted in Figure 1 using dieletric constant of 5 and 3.5.

Figure 3 shows reflection coefficient (magnitude) of the proposed unit cell using dieletric constant of 5 and 3.5. By varying the dieletric constant, the resonance frequency varies as well. Also, $|\Gamma| > 0.8\ (-2\ dB)$ when the dieletric constant varies from 5 to 3.5. As shown in Figure 4, we can achieve up to 220^0 of tunable reflection phase range at 12 GHz. The range can be extended up to 330^0 by adding more spokes in both outer and inner ring. However, it comes with the expense of more loss in the design. There is a tradeoff between tunable phase ranges versus loss. Depending on the application requirements, one can optimize the structure to achieve the desired criteria. The proposed pixel/cell design can be used as element in relfectarray to control the radiation beam [5]. It can also be used in coded metasurface [6] to control the scattering pattern.

4. Conclusion

In this paper, a design of CID-SPR metasurface cell/pixel, which can be used in reflectarry or metasurface to control the radiation beam or scattering pattern respectively, is presented. The simulations results confirm that the polarization-independence with 220 degrees of tunable phase and loss of less than 2 dB can be achieved. The tunable phase range can be extended up to 330 degrees at the expense of more loss in the design.

5. References

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