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Reflective Beam Steering of Metasurface Using Circular Inter-Digitated Self-Phased Pixels/Cells

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Abstract

Metasurfaces (MTSs) are well-known for manipulating electromagnetic (EM) waves by controlling the local phase of subwavelength elements. In this work, we present a reconfigurable MTS (R-MTS) design for reflective beam steering. By introducing the circular inter-digitated self-phased structure as the controlled tunable element in the array, the proposed MTS can dynamically change individual phases of its elements to generate beam steering. Rather than using active circuit components in the design, we use constituent material in the dielectric layer supporting the MTSs' unit elements to achieve tunable phase shifting in an extremely electrically thin ($\lambda_0/23.4$) profile. As the constituent material permittivity changes, the resonance frequency of the element also changes, which results in a local phase change. The circular inter-digitated self-phased (CID-SP) structure consists of dual-circular-ring, incorporating a meandered slot or interdigitated lines in between, all are integrated over a dielectric layer (used as a constituent material) with metal backing. Key features of our R-MTS design are polarization independence, a miniaturized meta-atom footprint, and an electrically controllable phase response using a tunable material, rather than embedded circuit elements, such as diode. The simulated scattering pattern is shown to able to deflect the beam ±26 degrees with respect to $\hat{z}$-axis for any arbitrary polarization. This work paves the way towards the realization of adaptable MTS, which can be digitally reprogrammed to fit different radar and or communication applications.

1 Introduction

Recently, single-layer MTSs, have received significant attention in EM research community. Unlike their multi-layer-structure counterpart, they have low-profile planar structure while still maintaining their distinct EM properties. The MTS can be considered as a periodic/non-periodic array of subwavelength resonant elements placed on ultra-thin surface. By introducing the local phase/magnitude changes at each element, the EM waves can be manipulated at desired. As a result, MTSs can be utilized in novel EM devices, such as beam deflectors [1], polarizer [2], reflect-array [3], and so on. Very recently, R-MTSs have been proposed for use in radar and wireless communication systems in next-generation networks [4]. Additionally, deep learning techniques have been utilized to assist in the design of MTS elements with desired amplitude, phase, and polarization responses [5].

In this paper, we present a reflective beam steering MTS design, shown in Fig. 1, that offers the capability to steer the radiated beam at will. We introduce circular inter-digitated self-phased (CID-SP) structure as elements in MTS [6]. It has a polarization-independent response and smaller footprint compared to current shapes (dipole, square, circular, etc.) used in the literature. The reconfigurable capability can be achieved by utilizing the constituent material in dielectric layer that supporting the structure. Since, the resonant wavelength of elements in MTS are affected by the permittivity of surrounding medium, by tuning its permittivity, one can design local phase changes at each element as desired. This provides a tunable mechanism to steer the reflected beam. The proposed reflect-array MTS is designed and simulated using a commercial full-wave EM solver, HFSS. Beam steering to ±26 degrees at 12.8 GHz is demonstrated, however, a broader scan volume can be achieved with this design. Similarly, the same beamforming approach that we apply to a reflect-array system can also be applied to a direct-radiating transmit system [7].

2 Reflective Beam Steering MTS Design

The proposed reflective beam steering MTS design composes of 8x8 CID-SP cell places on top of dielectric layers which uses a constituent material. The key concept is to design MTS element that allows polarization-independent EM waves to totally reflect with 2π phase control. This is a quite challenging task since most of current designs are a polarization-dependent. In other words, the design may only work with certain polarized EM waves which limits the number of potential EM applications. Furthermore, using active circuit elements in the design to achieve the tunability is also polarization-dependent. To address this issue, we present two-step approach. First, we use constituent material as dielectric supporting layer of the element to control the permittivity which results in controlling reflection phase. In this work, we consider the use of ferroelectric Barium Strontium Titanate (BST) film which can offer permittivity tuning under applying voltage bias. In [4], it is shown that the three-layer slab, which has BST film embedded between two layers of RT/duroid 5880, can

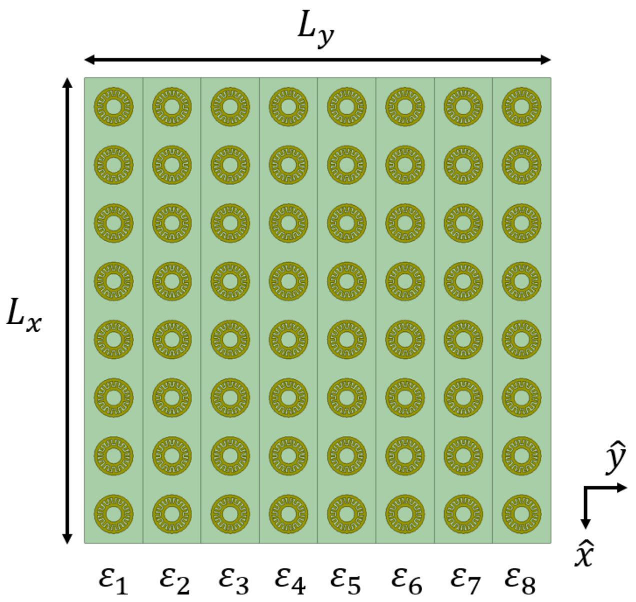

Figure 1. The proposed MTS composes of 8-by-8 circular inter-digitated self-phased (CID-SP) cells. Each column has an independently tunable BST substrate permittivity ε_r. By changing the by a bias voltage applied to the BST, the desired reflection (Rx) phase can be achieved. The dimensions of the 8-by-8 are $L_x = L_y = 48$ mm. The height of the R-MTS is $h = 1$ mm, which is $\lambda_0/23.4$ at the operating frequency of $f_0 = 12.8$ GHz

offer approximately 30% tunability (ε_r $3.5-5$). Second, we introduce CID-SP element that composes of a double-circular-ring with incorporated meander slot in between, all places on top of dielectric layer with metal backing. The dimensions of CID-SP are reported in [6]. Each CID-SP meta-atom unit-cell has planar grid dimension in the $\hat{x}$ and $\hat{y}$ dimensions of 6mm-by-6mm. At an operating frequency of 12.8 GHz, each meta-atom is subwavelength with electrical dimensions of $\lambda_0/3.9$-by-$\lambda_0/3.9$. This sub-wavelength spacing of each meta-atom allows finer pattern control can a traditional reflect-array with $\lambda_0/2$ element spacing.

A limitation of many MTS meta-atom designs are that they only provide the desired phase response for a single polarization. A unique feature of our CID-SP element design is the element's radial symmetry, which provides the benefit of providing the same phase response to any arbitrary polarization including linear, circular, and elliptical polarizations. In an operational environment, this feature removes polarization sensitivity of the feed or incoming wave. To demonstrate of the polarization-independent reflection phase response of our CID-SP MTS, we consider horizontal ($1\hat{x} + 0\hat{y}$ V/m), vertical ($0\hat{x} + 1\hat{y}$ V/m), and slant ($0.707\hat{x} + 0.707\hat{y}$ V/m) polarizations.

We use the R-MTS to dynamically scan the reflected wave in an electrically thin form factor without the use of conventional phase shifters. The reflection phase coding of the R-MTS is varied by changing the bias voltage applied to the tunable BST material in the substrate of each column. Following Fermat's principle, the anomalous reflection of a reflect-array MTS is governed by the generalized law of refraction [8],

$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_0}{2\pi n_i}\frac{d\phi}{dy}, \tag{1}$$

where θ_r and θ_i are the respective reflective and incident angles, λ_0 is the operating free-space wavelength of the incident wave, n_i is the refractive index of the medium of the MTS ($z > 0$), and $\frac{d\phi}{dy}$ is the rate of change of the reflection phase across the MTS in the $\hat{x}$ direction. By setting the incident wave θ_i to a fixed angle and wavelength λ_0, we are able to reconfigure the reflection phase of each each R-MTS column to achieve a progressive phase $\frac{d\phi}{dy}$ that results in a reflected beam at the desired scan angle θ_r. Assuming that $\theta_i = 0$ and $n_i = 1$, this equation becomes,

$$\theta_r = \sin^{-1}\left(\frac{\lambda_0}{2\pi}\frac{d\phi}{dy}\right). \tag{2}$$

Since our R-MTS has tunable columns of CID-SP meta-atoms, we have the ability to control the progressive phase shift across the surface ($\frac{d\phi}{dy}$) by controlling the bias voltage to the BST material in each column. We write Eqn. 2 in terms of R-MTS parameters by assuming that $\frac{d\phi}{dy} = \frac{R}{Np}$, where R is the tunable Rx phase range of each CID-SP unit cell in radians, N is the number of unit cells in one phase period, and p is the unit-cell spacing. For our R-MTS design, the spacing in-between columns of meta-atom unit-cells is $p = 6$ mm. The reflected radiation pattern scan angle can now be written as,

$$\theta_r = \sin^{-1}\left(\frac{\lambda_0}{2\pi}\frac{R}{Np}\right). \tag{3}$$

Using this equation, we are able to vary the tunable phase range (R) and the unit-cell phase periodicity (N) to achieve the desired scan angle of the radiation pattern. The relationship between the reflected wave's scan angle and the tunable phase range of the CID-SP is shown in Fig. 2.

3 Simulation Results and Discussion

As mentioned in the previous section, the progressive phase shift at each element in MTS decides the direction of the reflected radiation pattern. The required phase shift between each element to steer the beam in the desired direction can be calculated using the generalized law of reflection as in [8]. Figure 3 shows the reflection phase map of CID-SP element when ε_r varies from 3.5 to 5.0 in steps of 0.1. The simulated tunable phase range of the CID-SP over frequency is shown in Fig. 4a. A maximum phased tuning range of 301° degrees is achieved at 12.8 GHz (denoted by black dashed

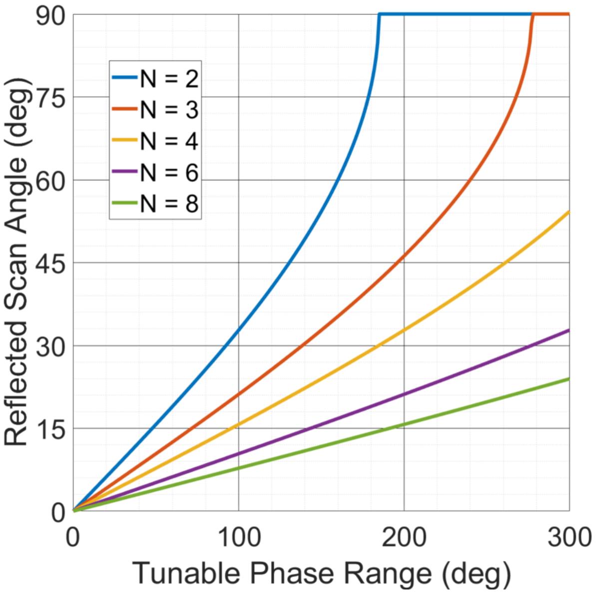

Figure 2. Analytical calculation of reflected radiation pattern scan angle over the tunable phase range of the meta-atoms at 12.8 GHz using Eqn. 3. N denotes the unit-cell phase periodicity.

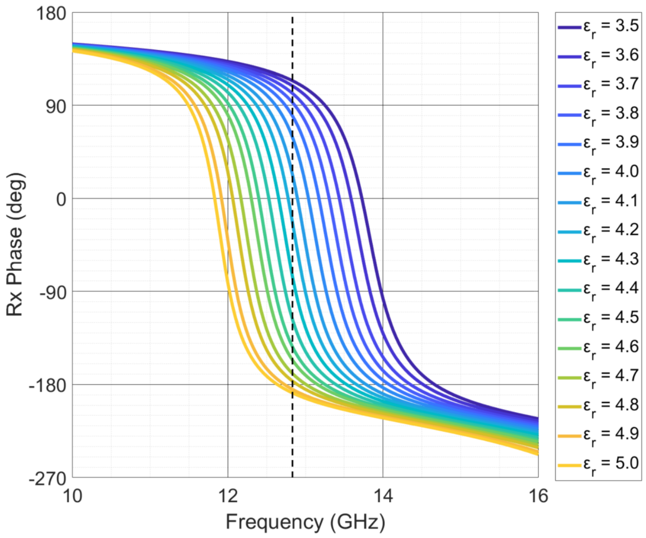

Figure 3. Simulated reflection (Rx) phase using HFSS for the CID-SP unit-cell over frequency for different ε_r values within the tunable range of the BST material substrate. The vertical dashed line denotes the operating frequency of 12.8 GHz, which provides the maximum 301° degrees of Rx phase tunability for the CID-SP.

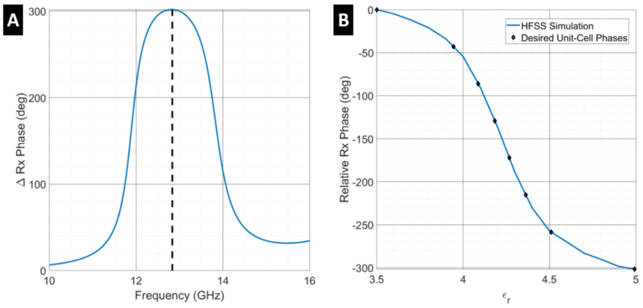

Figure 4. (a) Simulated tunable phase range of the CID-SP over frequency. A maximum phased tuning range of 301° degrees degrees is achieved at 12.8 GHz (denoted by black dashed line). (b) Simulated Rx phase over the tunable permittivity (ε_r) for the BST material. The black diamonds denote the ε_r values shown in Table 1 that realize an equally-spaced progressive phase shift for radiation pattern scanning.

line). This design achieves a phase tuning range > 180 degrees over a bandwidth (BW) of 11.9 to 13.8 GHz (16% BW). From this data, we are able to create a look-up table that maps substrate permittivity to reflection phase of the CID-SP element, shown in Fig. 4b. The design of the CID-SP can be altered to achieve the full 360 degree phase tuning range, however, at the expense of higher loss. We have traded this design factor to balance low-loss ($<$ 2dB across the phase tuning range) while still achieving a large > 300 phase tuning range [6].

To verify the design concept, we model a finite MTS array consisting of 8x8 CID-SP cells using HFSS, as depicted in Fig. 1. When the phase shift between each element is set equal zeros, most of the energy is reflected in the direction of $\theta_r = \theta_i$ as predicted in Eqn. 1. A trivial example of an incident broadside wave reflecting back at $\theta_r = \theta_i = 0$ deg is shown in Fig. 5a and Fig. 6a. To steer the beam +26 degrees with respect to the incident waves, we calculate the required phase shift of 43 degrees between each element. It is then translated to the required ε_r using phase map as depicted in Fig. 4b. As demonstrated in Fig. 5a and Fig. 6, the beam steers 26 degrees (with respect to the incident waves) as expected. According to results shown in Fig. 2, the reflected radiation pattern can be scanned from 0 to ± 90 deg by decreasing the value of N (increasing $d\phi/dy$). To demonstrates the polarization-independent response of our CID-SP meta-atom, we perform HFSS finite R-MTS array simulations to scan the reflected beam to $\theta_r = +26$ deg for incident plane waves with horizontal, vertical, and slant polarizations. Figure 5b shows the results of the finite R-MTS array simulation illuminated by each polarization. In each case, the main lobe of the beam is successfully scanned to +26 deg. We observe some variation in the side-lobes between polarization, however, these difference are likely due to numerical convergence variations in the HFSS simulations rather than the physical structure.

4 Conclusions

In this work, we present a MTS design that offers a reconfigurable reflective beam steering. By tuning the dielectric constants of constituent material used in dielectric layer, the scattering beam can be tilted ±26 deg at 12.8 GHz in 8x8 CID-SP cells structure. By changing the phase coding of the R-MTS, the reflected radiation pattern can be scanned

Table 1. Substrate permittivity values of each R-MTS column to scan the radiation pattern to various θ_r angles given a broadside incident plane wave ($\theta_r = 0$ deg) at 12.8 GHz with $N = 8$.

Scan Angle (θ_r)	**Column #**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0 deg	ε_r	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
+26 deg	ε_r	3.50	3.94	4.09	4.18	4.27	4.36	4.51	5.00
-26 deg	ε_r	5.00	4.51	4.36	4.27	4.18	4.09	3.94	3.50

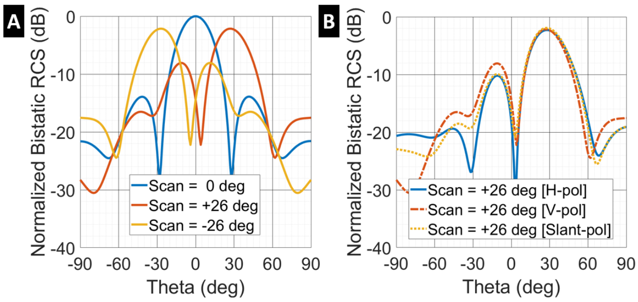

Figure 5. (a) HFSS finite R-MTS array simulation results for scanning the reflected beam to 0, +26, and -26 deg. The excitation for each of these beams is a plane wave traveling in the $\hat{k} = -\hat{z}$ direction with E-field polarized in the $\hat{x}$ direction. The ε_r values used to create the phase codings for each case are listed in Table 1. (b) HFSS finite R-MTS array simulation results for scanning +26 deg for the horizontal, vertical, and slant polarizations. The radiation patterns are normalized to the peak of the broadside in (a).

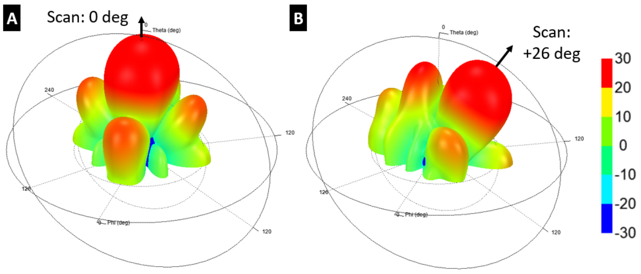

Figure 6. (a) HFSS finite R-MTS array simulation of (a) a broadside ($\theta_r = 0$ deg) reflected beam and (b) a scanned ($\theta_r = +26$ deg) reflected beam. The excitation for both of these beams is a plane wave traveling in the $\hat{k} = -\hat{z}$ direction with E-field polarized in the $\hat{x}$ direction. The ε_r values used to create the phase codings for both cases are listed in Table 1. Units are in dB.

from 0 to ±90 deg. We believe that using this design concept, adaptable MTSs become more realizable for practical wireless communication and radar applications.

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References

[1] S. Sun, K. Y. Yang, C. M. Wang, T. K. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W. T. Kung, G. Y. Guo, and L. Zhou, “High-efficiency broadband anomalous reflection by gradient metasurfaces,”. Nano letters, vol. 12, no. 12, pp.6223-6229, 2012.

[2] N. K. Grady, J. E. Heyes, D. R. Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. Dalvit, and H. T. Chen, “Terahertz metamaterials for linear polarization conversion and anomalous refraction,”. Science, vol. 340, no. 6138, pp.1304-1307, 2013.

[3] P. Nayeri, F. Yang, and A. Z. Elsherbeni. Reflectarray Antennas: Theory, Designs and Applications. John Wiley & Sons, 2018

[4] J. A. Hodge, K. V. Mishra, and A. I. Zaghloul, “Reconfigurable metasurfaces for index modulation in 5G wireless communications,” in IEEE International Applied Computational Electromagnetics Society Symposium, 2019, pp. 1–2.

[5] J. A. Hodge, K. V. Mishra, and A. I. Zaghloul, "RF metasurface array design using deep convolutional generative adversarial networks," in IEEE International Symposium on Phased Array Systems and Technology, 2019.

[6] Q. Nguyen, J. A. Hodge, and A. I. Zaghloul, “Circular Inter-Digitated Design for Self-Phased Reflective Pixel/Cell for Metasurfaces and Reflectarrays,” in Proc. of XXXIII General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS).

[7] Q. Nguyen and Amir I. Zaghloul, "Design of Beam Steering Patch Arrays Using Self-Phased Metasurface Pixels" in IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science, 2020.

[8] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, “Light propagation with phase discontinuities: Generalized laws of reflection and refraction,” Science, p. 1210713, 2011.