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A 1-Bit Coding Reconfigurable Metasurface Reflector for Circularly Polarized Wave Beam Steering from Linearly Polarized Incidence

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Abstract

A 1-bit reconfigurable metasurface reflector is designed. It can provide beam-steering of circularly polarized (CP) reflected waves when a linearly polarized (LP) plane wave is incident upon it. The unit cell of the metasurface provides 1-bit coding ('bit-0' and 'bit-1') for both v- and u-polarized reflected waves when two distinct reverse bias voltages (3 V and 20 V) are applied to the varactor diodes. Using such unit elements, a 20×20 array is constructed. During the array construction, a quadrature phase difference is maintained between the v- and u- polarized components of each element. Using both theory and full-wave simulation results, it is shown that the proposed metasurface reflectarray can steer two symmetrically deflected CP beams with two opposite handedness for a LP plane wave incidence.

1 Introduction

Circularly polarized (CP) wave is often prefered over linearly polarized (LP) wave in different wireless communications. The former exhibits lower propagation loss in Faraday rotation and multi-path fading, and better signal reception for disorientation of transmitting and receiving antennas [1]. Moreover, to improve signal to noise ratio (SNR) in many aplications, antennas with higher directivity and beam steering capability are necessary. Reconfigurable metasurface-based reflectarray can be good candidate for those application as it can provide beam-steering with high gain and directivity [2, 3]. As compared to the beam scanning phased arrays, reconfigurable reflectarrays are less expensive and consume less power as they do not require any complex feeding networks. Moreover, nowadays, they have become a key component in reconfigurable intelligent surfaces (RIS), which are being considered to be useful for future wireless communications [4, 5].

In the literature, most of the reconfigurable metasurfaces for beam-steering are realized for LP [6, 7]. Only a few reconfigurable metasurface for CP beam-steering have been reported till now [8, 9]. In those works, CP beam steering is shown using element rotation by either mechanical [8] or electronic control [9]. However, the element rotation technique requires the feed or source of illumination to be always CP. Generally, LP sources are easily available, mechanically simple and less expensive. Moreover, implementation of CP beam steering with LP feed is more of a conceptual problem than the mechanical problem in CP-fed beam-steering, thus appears more interesting. Very recently, in [10], CP beam-steering of a reconfigurable metasurface is shown using a LP feed. However, the incident wave from the feed is along skewed ($\phi = \pm 45^\circ$) planes, instead of cardinal ($\phi = 0^\circ$ or $xz-$, and $\phi = 90^\circ$ or $yz-$) planes. Moreover, it requires a dedicated feed with spherical wave-front to illuminate the metasurface, whereas many RIS-related applications require plane-wave incidence on the metasurface from distant source.

In this paper, a 1-bit reconfigurable metasurface is presented for beam steering of CP reflected wave with LP plane wave illumination. The plane wave can be either $y-$ or $x-$ polarized on the cardinal planes. It uses a simple unit cell with two-varactor diodes. The reflectarray can steer two symmetrically deflected CP beams with opposite handedness for a LP plane wave incidence. This particular attribute of beam-steering with polarization diversity can be very useful for reconfigurable intelligent surface (RIS)-assisted multi-spot communications.

2 Unit Cell Design and Analysis

The proposed unit cell is shown in Figure 1. It consists of a diagonally oriented cross-dipole on the top layer. A ground plane is sandwiched between two Rogers RO 4003C substrates ($\varepsilon_r = 3.55, \tan\delta = 0.0027$) with thickness of 60 mil and 32 mil, respectively. Two Skyworks-SMV1405-040LF varactor diodes [11] are attached to one side of each dipole. The varactor provides equivalent series capacitance (C)-resistance (R) of C_{0-bit}=0.7 pF, R_{0-bit}=0.3 Ω and C_{1-bit}=1.8 pF, R_{1-bit}=0.2 Ω for reverse bias voltages of 20 V and 3 V, respectively. On the opposite side of the dipoles, two Murata-GJM1555C1HR50WB01 capacitors [12] pF are attached. These passive capacitors provide equivalent series C and R of C_p=0.65 pF, R_p=0.3 Ω, respectively. They are included to maintain the symmetry of the ac currents on the two sides of each dipole in order to reduce the cross-polarized reflection coefficients, $|r_{uv}|$ and $|r_{vu}|$. The decomposition of a y-polarized E-field into orthogonal $v-$ and $u-$ polarized components is illustrated in Figure 1(d). Biasing control to each varactor diode is pro-

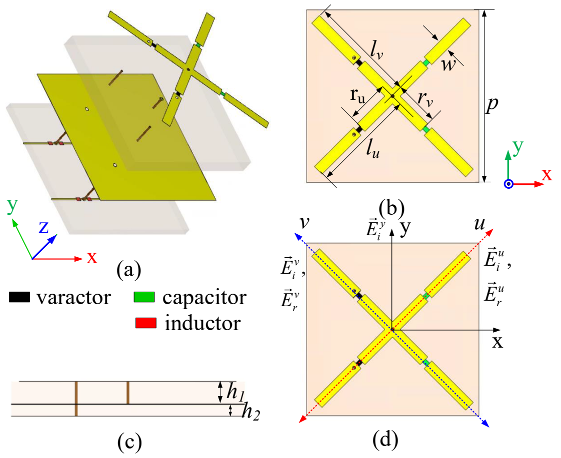

Figure 1. Unit cell of the proposed 1-bit reconfigurable metasurface. (a) Exploded view. (b) Top view. (c) Side view. (d) Illustration of decomposition of incident and reflected E-fields into orthogonal v- and u-components. Design parameters of the unit cell in mm are $h_1 = 1.524$, $h_2 = 0.8128$, $p = 16$, $w = 1$, $l_v = 10$, $l_u = 10$, $r_v = 4.1 = r_u$, $w_{bias} = 0.15$.

vided using dc bias lines on the back side of the bottom substrate and necessary vias. To block the RF on dc bias lines, inductors of 4.5 nH are connected on the bias line at the two sides of the vias.

The phase and magnitude response of the unit cell, simulated in Ansys HFSS are plotted in Figure 2. It can be observed from Figure 2 that for the *v*- polarized reflection, the phase difference between 20 V and 3 V reverse bias voltages is π at around 5.2 GHz. Thus, these two phases are denoted as 'bit-0' and 'bit-1', respectively. The phase responses remains same for *u*- polarization also due to diagonal symmetry of the unit cell geometry. The magnitude response of the unit cell is shown in Figure 2(b). It can be observed that maximum reflection loss at 5.2 GHz is below 2 dB. The reflection loss can be attributed to the inherent parasitic losses of the varactor diodes, passive capacitors as well as to the dielectric and ohmic losses of the unit cell.

For normal incidence of a LP plane wave, the desired *v*- and *u*- polarized phases at each cell of a $M \times N$ reflector to direct a collimated CP reflected beam towards θ_0 on $\phi = 0°$ plane can be calculated using generalized Snell's law as

$$\varphi_{v_m} = k_0 p(m-1)sin\theta_0 \quad \text{and} \\ \varphi_{u_m} = \varphi_{v_m} \mp \pi/2, \tag{1}$$

where k_0 is the propagation constant, $m = 1,2,...,M$, and $-$ve and $+$ve sign represent LHCP and RHCP, respectively. With plane wave incidence, there will be no phase variation along $y-$ direction for beam steering on $\phi = 0°$ plane. To use the proposed 1-bit unit cell to construct the array, φ_{v_m} can be discretized to

$$\{\varphi_v\}_{m,1-\text{ bit}} = \begin{cases} 'bit-0' & \text{for } \varphi_{v_m} \notin [90°, 270°) \\ 'bit-1' & \text{for } \varphi_{v_m} \in [90°, 270°) \end{cases} \tag{2}$$

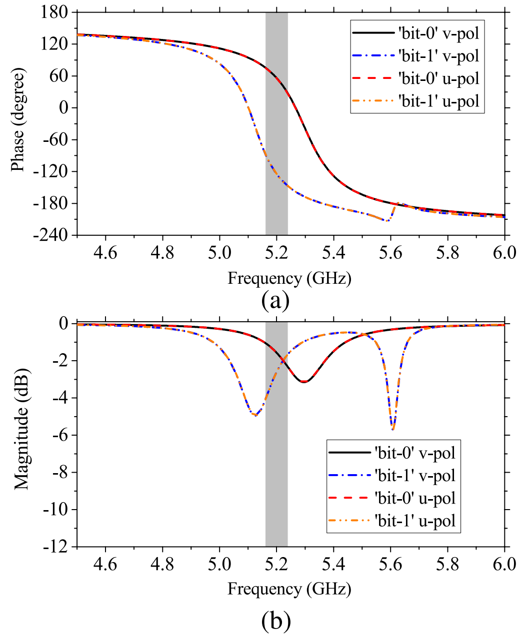

Figure 2. (a) Simulated phase response of v- and u-polarized reflected waves. (b) Simulated magnitude response of v- and u-polarized reflected wave.

Similarly, φ_{u_m} can be discretized to $\{\varphi_u\}_{m,1-\text{ bit}}$. With the above *v*- and *u*-polarized 1-bit phases, the radiation pattern for beam towards any θ_0 can be theoretically obtained using array factor approach.

3 Results and Discussion

The above 1-bit unit cell is considered to construct a 20×20 reconfigurable metasurface reflector. As for example, the desired $\{\varphi_v\}_{m,1-\text{ bit}}$ and $\{\varphi_u\}_{m,1-\text{ bit}}$ polarized phases for a beam towards $\theta_0 = 30°, \phi = 0°$ are calculated using (1)-(2). The calculated discretized phase distributions are shown in Figure 3. It can be observed from Figure 3 that the discretized *v*- and *u*-polarized phases vary only along x-direction when plane wave incidence is considered. As a result, it creates coding sequence of 0s and 1s along x-direction. As there are only two phases in the coding sequence, the reflector will produce two symmetrically deflected beams [13]. The direction of the deflected beams

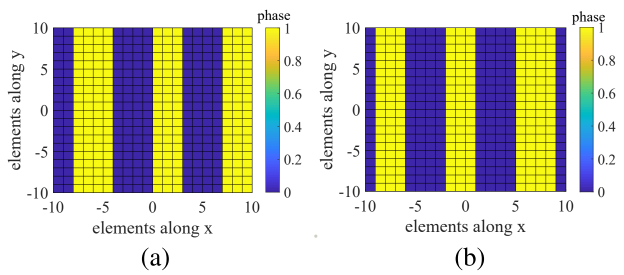

Figure 3. Desired phase distribution at 5.2 GHz on a 20×20 array for deflected symmetric beams at $\pm 30°$. (a) Desired *v*-polarized phase. (b) Desired *u*-polarized phase.

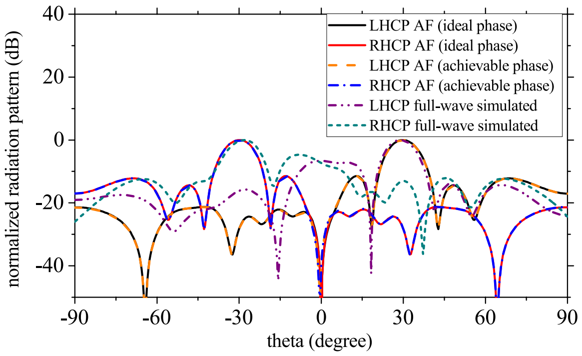

Figure 4. Radiation patterns of the reconfigurable metasurface reflectarray calculated at 5.2 GHz using the v- and u-polarized discretized phases for beam at $\theta_0 = 30°$.

can also be found out using

$$\theta_0 = \pm \sin^{-1}(\lambda/\Gamma_n) \tag{3}$$

where λ is the free-space wavelength and Γ_n is the periodicity for n^{th} order coding sequence (which is periodicity of the group of 0s and 1s that repeat in the coding sequence), respectively. The theoretically calculated and full-wave simulated radiation patterns of the reconfigurable reflector are shown in Figure 4 at 5.2 GHz. It can be observed that there are two symmetrically deflected CP beams at $\pm 30°$. Interestingly, the co-pol component of the beam at 30° is LHCP whereas it is RHCP at $-30°$. This can be attributed to the Pancharatnam-Berry (PB) phase of the reflector as the condition of $\pi/2$ phase difference between $v-$ and $u-$ polarized phases imposed by (1) is a geometric phase to its 1-bit phase gradient [14].

4 Conclusion

In this paper, a 1-bit coding reconfigurable metasurface reflector has been proposed. The unit cell uses two varactor diodes with only two reverse bias voltages to achieve 1-bit phase response for orthogonal $u-$ and $v-$components. For a linearly polarized plane wave incidence on the reflector, two symmetrically deflected steerable beams with opposite handedness are generated. The proposed reflector will be further explored with detailed analysis and measurement results in the upcoming work.

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