Re-configurable Linear-Linear Polarization Conversion Meta-surface Composed of Dual Split Ring Resonators

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Abstract

A re-configurable meta surface based linear to linear polarization converter is presented.
Re-configurable Linear-Linear Polarization Conversion Meta-surface Composed of Dual Split Ring Resonators

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Abstract—In this letter, a re-configurable meta-surface for linear-to-linear polarization conversion is proposed, fabricated, and verified. It consists of two Split Ring Resonators (SRR) with a pair of splits in each and is designed to operate in two modes of reflection— with polarization conversion and without polarization conversion. This re-configurability is realized by utilizing two PIN diodes in a unit cell. Linear-to-linear polarization conversion is realized by the OFF state of the diodes and when the PIN diodes are ON, a complete reflection is achieved. The structure of the proposed meta-surface is simple to implement with only two PIN diodes. The unit cell of the meta-surface contains two SRR with a pair of splits in each and is designed to operate in the frequency range 6.04-9.93 GHz. A 42×42 array of the unit cell is fabricated and the re-configurability is verified experimentally. It is fabricated on an FR4 substrate backed by copper ground. The polarization conversion for different incident angles is measured and compared with the simulation results. A Polarization Conversion Ratio (PCR) ≥90% is achieved up to 30° incident angle. A good agreement of simulation and experimental results is verified.

Index Terms—Meta-surface, Polarization-conversion, Re-configurable, PIN-diode

I. INTRODUCTION

The sixth generation (6G) of mobile communication is already proposed by the research community even though the 5G coverage is not fully established. This is intended to be realized with several technologies like Re-configurable Intelligent Surfaces/Intelligent Reflecting Surfaces (RIS/IRS), Visible Light Communications (VLC), Electromagnetic-orbital angular momentum, etc [1]. From this point of view, the IRS concept is an assuring technology for 6G wireless communications [2]. Recent research reported that IRS can effectively control the wavefront, e.g., the phase, amplitude, frequency, and even polarization [3]. Meta-surfaces are the core technology behind this assuring concept, which is the two-dimensional metamaterials. Metamaterials are artificially engineered materials, composed of subwavelength metallic/dielectric structures, and have attracted tremendous research interest due to their exceptional ability to manipulate the EM waves [4]. [5]. Metamaterials offer challenges like complicated structures, bulky sizes, and relatively high losses. Meta-surfaces can be an excellent substitute for metamaterials. Over the past decade, meta-surfaces have been used for waveform shaping, polarization conversion, and radiation control or energy concentration [6]. Polarization converters have many applications like polarization re-configurable antenna, Radar Cross Section (RCS) reduction, etc. [7]. Among these, Split Ring Resonators (SRR) have been popularly used for meta-surface. Since the resonance frequency of the SRR depends on its dimension, we can tune the SRR frequency from microwave to terahertz and even visible frequency [8] and the anisotropic structure of the SRR enables the polarization conversion function also.

In this letter, a reflective type SRR meta-surface for re-configurable linear to linear polarization conversion is proposed. During the simulation, PIN diodes are used as switch across each splits. It can act as a linear-to-linear polarization converter when the two PIN diodes in the outer SRR are OFF and as a reflector as well when the PIN diodes are ON. In section II, the structure and the simulation results are discussed. Section III explains the fabrication and experimental analysis. In Section IV, theoretical analysis of the proposed unit cell is presented. Finally, a conclusion is marked out in section V.

II. SIMULATIONS AND DISCUSSION

The geometry of the unit cell is shown in Fig. [1] with dimensions as L=5.1mm, M=2.5mm, g=1mm, s=0.45, and r=0.8mm. The periodic length P is chosen as 7 mm. The SRR used here have a pair of splits that are positioned on opposite sides of the SRR. The SRR structure is modeled on a 3.2 mm thick substrate (FR4) having a relative permittivity of 4.4 and a loss tangent of 0.02 backed by a metal ground. Re-configurability is achieved by using two PIN diodes loaded at the outer SRR [9]. The PIN diode HPND-4005 [10] is selected and modeled. During the simulation, the ON state and OFF states of PIN diodes are approximated to 4.7 Ω capacitor and 0.017 pF capacitor respectively.

We define the cross-polarized reflection coefficients as

$$r_{yx} = \frac{E_y^{Ref}}{E_x^{Inc}} ; ; r_{xy} = \frac{E_x^{Ref}}{E_y^{Inc}}$$ (1)

for the x-polarized and the y-polarized incident wave. Similarly, co-polarized reflection coefficients can be expressed as [11]:

$$r_{xx} = \frac{E_x^{Ref}}{E_x^{Inc}} ; ; r_{yy} = \frac{E_y^{Ref}}{E_y^{Inc}}$$ (2)

To get more insight into the polarization conversion efficiency, we can define the Polarization Conversion Ratio (PCR) as:
\begin{equation}
\text{PCR}_x = \frac{r_{yy}^2}{(r_{xx}^2 + r_{yx}^2)}; \quad \text{PCR}_y = \frac{r_{xx}^2}{(r_{yy}^2 + r_{xy}^2)} \tag{3}
\end{equation}

for the x-polarized and y-polarized incident wave respectively. Fig. 2a and Fig. 2b indicate the \(r_{xx}, r_{yx}, r_{yy}\) and \(r_{xy}\) for the normal incidence when the PIN diodes are OFF and ON for \(x\) and \(y\) polarized incident waves respectively. It can be observed that the -10 dB bandwidth of co-polarization reflection coefficients is ranging from 6.04 to 9.93 GHz and the value of \(r_{yx}\) and \(r_{xy}\) are above -3dB from 5.76 to 10.93 GHz, indicates a solid cross-polarization and a weak co-polarization in this frequency band. On the other hand, when PIN diodes are ON, co-polarization reflection coefficient is almost equal to 0dB and a very low value of cross-polarization reflection coefficients is obtained in the frequency band 4-12 GHz. This indicates a perfect reflection without any polarization conversion.

To examine the angular stability, polarization conversion for different angle of incidence is also studied which is shown in Fig. 3 and Fig. 4 for the OFF and ON conditions of PIN diodes of the x-polarized and y-polarized incident waves respectively. To get more insight into the polarization conversion efficiency of the proposed meta-surface for different incident angles, PCR values for the OFF state of PIN diodes are plotted as shown in Fig. 5. The results show a PCR \(\geq 90\%\) for the incident angles ranging from 0\(^\circ\) to 30\(^\circ\). But, with a further increase in incident angles, the PCR value will decrease. In short, the proposed meta-surface shows a good polarization conversion ability up to 30\(^\circ\) in the OFF state of PIN diodes. In the ON state, it can act as a perfect reflector.

III. EXPERIMENTAL ANALYSIS

To verify the results experimentally, an array of the proposed unit cell is fabricated, measured, and validated the results with the simulation results. The array is shown in Fig. 6. The array comprised 42×42 unit cells having 30.5 × 30.5 cm in dimension. It is fabricated by using the conventional photolithography method. It is fabricated on 3.2 mm thick FR4 material with a copper coating on its backside.

To verify the results, PIN diodes in the fabricated array are approximated to ideal open and short as shown in Fig. 6a and Fig. 6b respectively. The arch-type measurement testing system is shown in Fig. 7 which enables to change the incident angle from 0\(^\circ\) to 90\(^\circ\).
Two horn antennas of operating frequency range 2-18 GHz are used for transmission and reception. The R&S ZVB20 vector network analyzer is employed to measure the reflected coefficients. First, to calibrate the system, the reflection from the metal sheet of the same size as the proposed meta-surface is measured. The horn antennas and the meta-surface are kept at the same height and a 3° deviation from the normal is maintained to make the maximum reception and reflection possible by the meta-surface. The transmitter and receiver orientation are kept parallel and orthogonal to measure the co- and cross-polarized reflection coefficients. The measured results of co and cross-polarization reflection coefficients for the OFF state and ON state are compared with the simulation results as shown in Fig. 8a and 8b for x polarized incident wave at normal incidence. A good agreement with the simulated results can be seen in the frequency range of 6.04 to 9.8 GHz. In the OFF state also, a complete reflection is observed as in simulation results. The proposed meta-surface can act as both a 90° polarization rotator in the OFF state of PIN diodes and can act as a perfect reflector when the PIN diodes are ON. We also investigated the polarization conversion property by changing the incident angles for both the ON and OFF states experimentally. The results are shown in Fig. 9. As the results are shown in Fig. 9, as increasing with the incident angle, the polarization conversion property decreases. Some mismatches between the measured and simulated results are because of the fabrication tolerances and the disorder in the measurement set up.

IV. THEORETICAL ANALYSIS

To get a physical insight into the polarization conversion mechanism, a theoretical model is developed to interpret the simulated and the measured results. To understand the phenomenon assumes, a linearly polarized plane wave $\vec{E} = \vec{E}_0 e^{i(kz - \omega t)}$ along the x-axis is incident on the proposed meta-surface, where $\vec{E}$ is the unit vector along x-axis, $E_0$ is the amplitude of the incident electric field, $k$ is the wave vector and $\omega$ is the angular frequency. Disintegrating the incident electric field into its two orthogonal components along u and v as shown in Fig. 10a can be expressed as:

\[ E_i = \vec{u} E_{iu} e^{i\phi} + \vec{v} E_{iv} e^{i\phi} = \vec{u} E_0 \cos(\theta)e^{i\phi} - \vec{v} E_0 \sin(\theta)e^{i\phi} \quad (4) \]

where $\phi = k z - \omega t$, the subscripts i represents the incident, u and v represent u and v polarization directions respectively. The electric field upon reflection from the meta-surface can be expressed as:

\[ E_r = \vec{u} E_{ru} + \vec{v} E_{rv} = (\vec{u} r_u E_{iu} + \vec{v} r_v E_{iv} e^{i\Delta \psi})e^{i\phi} \quad (5) \]

where $r_u$ and $r_v$ are the reflected coefficients along the u and v axis respectively, $\Delta \psi$ represents the phase difference between $E_{ru}$ and $E_{rv}$ due to the anisotropy of the meta-surface. If the condition of $r_u r_v \approx 1$ and the phase difference between them, $\Delta \psi = \pm 180^\circ$ is satisfied, the vector sum of $E_{ru}$ and $E_{rv}$ will be along y direction as shown in Fig. 10b. This is verified by the simulated reflected amplitude and difference of the reflected phase for the u and v polarized incident wave for
the polarization conversion mode and the results are shown in Fig. 10b. The results show the value for the reflection coefficients, $r_u$ and $r_v$, along the $u$ and $v$ direction respectively are almost equal. In addition, the phase difference between them, $\Delta \psi$ is $\pm 180^\circ$ in the frequency range 6.04 to 9.93 GHz which implies a $90^\circ$ polarization rotation in this range.

An equivalent circuit for the proposed meta-surface in the polarization conversion mode is drawn in the $y$ direction and its simplified circuit is deduced as shown in Fig. 11a. As the equivalent circuit represents, metals are regarded as inductors, the splits in the individual SRR and the gap between the two SRRs are represented by the capacitors. Moreover, taking into account the internal resistance of capacitors, dielectrics, and inductors, four resistors are included in the equivalent circuit. The optimized value of components is shown in Table I.

![Fig. 10: (a) Inherent scheme of $x$ to $y$ polarization (b) Amplitude and phase difference of reflection coefficients, $r_u$ and $r_v$](image)

![Fig. 11: (a) Equivalent circuit and simplified circuit of the PCM (b)Impedance vs frequency graph (c) Reflection coefficient](image)

**TABLE I: OPTIMIZED VALUES**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
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<tr>
<td>$L_1'=L_1/2$</td>
<td>0.8396nH</td>
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<tr>
<td>$L_2'=L_2/2$</td>
<td>5.71nH</td>
</tr>
<tr>
<td>$L_{g1}$</td>
<td>1.14025nH</td>
</tr>
<tr>
<td>$L_{g2}$</td>
<td>1.7611nH</td>
</tr>
<tr>
<td>$C_1'=2C_1$</td>
<td>0.9752pF</td>
</tr>
<tr>
<td>$C_2'=2C_2$</td>
<td>0.1203pF</td>
</tr>
<tr>
<td>$C_{b1}=C_{b1}/2$</td>
<td>0.2392pF</td>
</tr>
<tr>
<td>$C_{b2}=C_{b2}/2$</td>
<td>0.2025pF</td>
</tr>
<tr>
<td>$C_g$</td>
<td>3.3pF</td>
</tr>
<tr>
<td>$R_2$</td>
<td>0.5Ω</td>
</tr>
<tr>
<td>$R_{b2}$</td>
<td>2.1955Ω</td>
</tr>
<tr>
<td>$R_{bg}$</td>
<td>3.3068Ω</td>
</tr>
</tbody>
</table>

The corresponding impedance and the reflection coefficient of the equivalent circuit are plotted as shown in Fig. 11b and Fig. 11c respectively. It shows an increased impedance in the polarization conversion band for the y-polarized incident wave. The change in impedance corresponds to the reflection coefficient curve shown in Fig. 11c. The reflection coefficient shown in Fig. 11c is similar to the $r_{yy}$ curve shown in Fig. 26. Therefore, a current is induced in the $x$-direction and an $x$-polarized wave is reflected from the proposed meta-surface [12].

![Fig. 11: (a) Equivalent circuit and simplified circuit of the PCM (b)Impedance vs frequency graph (c) Reflection coefficient](image)

**TABLE II: COMPARISON WITH PREVIOUS RELATED WORKS**

<table>
<thead>
<tr>
<th>Ref</th>
<th>CF(GHz)</th>
<th>Thickness(mm)</th>
<th>BW(GHz)</th>
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<tbody>
<tr>
<td>[12]</td>
<td>4.2</td>
<td>5.1</td>
<td>1.62</td>
</tr>
<tr>
<td>[13]</td>
<td>4.75</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>[14]</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>This work</td>
<td>7.985</td>
<td>3.2</td>
<td>3.89</td>
</tr>
</tbody>
</table>

CF:Center Frequency, BW:Bandwidth

It can be seen that the proposed SRR based metasurface for polarization conversion has simple structure, compact and broadband performance. More over, the proposed metasurface has a PCR value of 90% up to an incident angle of 30°.

**V. CONCLUSION**

A meta-surface based re-configurable linear-linear polarization converter dependent on PIN diodes is proposed. It can switch between polarization rotation mode and reflection mode. In the conversion mode, PCR is above 90% for the normal incidence in the frequency range 6.04-9.93 GHz. In the reflection mode, co-polarized reflection coefficients are above -1 dB in the frequency range 4-12 GHz. The simulation results are obtained by the equivalent circuit of PIN diodes and to verify the results experimentally, PIN diodes in the fabricated array are approximated to ideal short and open. A reasonable agreement between the simulated and measured results is obtained. The proposed polarization converter finds applications in Intelligent Reflecting Surfaces(IRS), communication system, RCS reduction, stealth technology, etc.
REFERENCES


