1-bit reconfigurable transmitarray with low loss and wide bandwidth

Wen Hua Gao, Mao Chen, Qiang Cheng, Rui Wen Shao, Jing Cheng Liang, Yuan Gao and Tie Jun Cui

1 Institute of Electromagnetic Space and State Key Laboratory of Millimeter Wave, Southeast University, Nanjing 210096, People’s Republic of China
2 Center of Intelligent Metamaterials, Pazhou Laboratory, Guangzhou 510330, People’s Republic of China
* Authors to whom any correspondence should be addressed.

E-mail: qiangcheng@seu.edu.cn and tjcui@seu.edu.cn

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Abstract

We present a novel X-band 1-bit reconfigurable transmitarray with excellent polarization conversion. The basic element consists of two layers of metal patterns connected by a metal through-hole and feed structures. The top layer is used to realize a 1-bit phase response by controlling the states of two PIN diodes; the bottom layer is composed of a rectangular patch with a U-slot to realize conversion from linear polarization to cross polarization. The agreement between simulation and measurement results indicates that when the diode states are switched in turn, this unit achieves the phase difference of cross-polarized transmitted waves within $180^\circ \pm 15^\circ$ and high transmittance in a broad band. The scattering patterns demonstrate that beam splitting or multi-beam generation can be achieved by controlling the different coding sequences of each column unit. The element offers low transmission loss, wide bandwidth of 1-bit phase control, and small thickness for easy integration. Thereby, it has numerous potential applications in radar and wireless communications.

1. Introduction

Transmitarrays (TAs), a kind of new artificial lenses with the powerful beamforming ability, are widely served in the radar and communication systems [1–3]. TAs are planar structures extended by a combination of traditional lenses [4] and microstrip arrays [5]. Without complicated feeding networks, they are advantageous for low profiles and light weights.

Metasurface-based transmission arrays usually utilize two methods to achieve full 360-degree phase coverage [6–10]. One is to use multiple layers to achieve phase accumulation. The other is to employ multiple electrical and magnetic resonances [11]. The common methods for achieving different phases include designing units of different sizes in different positions, loading delay lines of different lengths, and rotating units to different angles [12–16]. The traditional TAs are passive, which can not achieve dynamic beam scanning. This abuse limits their applicability to radar detection. Hence to meet the demand of future communication and radar systems, active transmitarrays are essentially needed to realize the reconfigurable functionalities in real-time.

To realize the active TAs, some device-embedded metasurfaces have been recently proposed, which are combined with solid-state controllable devices (varactor diodes, pin diodes, and micro-electromechanical system switches) [17–19]. Such TAs can achieve dynamic phase control and reduce target scattering, but they still have shortcomings of narrow band, large insertion loss, and insufficient dynamic range. Recently, Cui [18] proposed the concepts of digital coding and field programmable metasurfaces. Coding metasurfaces apply the binary codes 0 and 1 to characterize the reflected/transmitted phases of $0^\circ$ and $180^\circ$, respectively. The meta-atoms are designed to have different reflection or transmission phases for the incident electromagnetic (EM) waves. They are coded appropriately to implement low backscattering and
dynamic beamforming [20–23]. These novel metasurfaces enhance the flexibility of EM wave manipulations and expand the effective dynamic range.

However, most coding metasurfaces are based on reflective meta-atoms [24–26]; and transmissive ones are required in array applications. At present, there are two main methods for implementing the phase regulation of reconfigurable TAs: continuous-phase modulation and discrete-phase modulation. The former is typically realized by varactors; however, such modulation is accompanied by narrow bandwidth and high loss. In addition, the varactor requires high biasing voltages, and the speed of varactors to switch state is limited. For the latter, PIN diodes and MEMSs are typically used to attain 1-bit or multi-bit metasurfaces [27–32]. The multi-bit element needs a high phase resolution while it is accompanied by complex bias circuit. Nevertheless, the 1-bit element takes fewer active devices and simpler the feeding structures. It also benefits from low loss, easy integration, and reduced complexity. Therefore, it is suitable for many applications because of these profits. While in the design of some active 1-bit TAs, there are few units for achieving broadband phase control and low insertion loss [33, 34].

Here, we propose an original 1-bit reconfigurable transmissive metasurface that realize the function of low-loss, wideband cross polarization conversion at X-band. Two pin diodes with opposite working states are exploited to control the direction of the surface current, resulting in a 1-bit phase response in the frequency band of interest. The loaded interdigital structures are employed to increase the transmittance. The rest of the paper is arranged as follows. In section 2, the 1-bit reconfigurable transmission element and the simulation results are presented. Section 3 explains in detail the mechanisms of the unit for achieving the polarization conversion and the 180° phase difference. To verify the element performance, a 10 × 10 array prototype is designed, fabricated and measured. Comparison between simulation and measurement is presented in section 4. Finally, the conclusion is presented in section 5.

2. Element design and simulation

The proposed 1-bit reconfigurable transmissive element is presented in figure 1. The element consists of four copper layers with 0.018 mm thickness attached to two identical F4B substrates (εr = 3.5, tan δ = 0.001). A bonding film (Rogers 4350, εr = 3.38, tan δ = 0.004) with the thickness h2 of 0.1 mm is applied to bond the substrates. The element has a period of p = 12.6 mm (only 0.43λ, where λ is the wavelength of free space at 10.2 GHz). Although the element has a multilayer structure, its total thickness is 3.1 mm (only 0.1λ).

A rectangular patch loaded with interdigital constructions in the gap is printed on the top layer, as shown in figure 1(b). The bottom layer contains a rectangular patch with a U-slot, as illustrated in figure 1(c). Such two layers are connected by a metal through-hole at the center of the unit cell. The upper metal structure can not only receive the incident-wave energy and pass it to the bottom layer, but also receive energy from the bottom layer and transmit it into free space. The same is true for the bottom layer. Two PIN diodes (SMP1320-040LF) are loaded in the slot of the top layer along the y direction, which work in opposite states. It means that one PIN diode is on, while the other is off. The bias circuit of the two PIN diodes is presented in figure 1(a). The sectors combined with microstrip lines, which are connected to one port of the PIN diodes through two metallized columns, are designed to isolate the RF signal. The other
The feeding port is attached to the bottom layer through a metalized via hole in the middle and then linked to the ground by two metal pillars.

When the $y$-polarized incident waves are illuminated to the designed transmitarray, it can be converted into the $x$-polarized waves. The current distributions can be changed to attain the phase difference of $180^\circ$ by tuning the state of PIN diodes. The optimal elemental-structure dimensions are visible in figure 1, and the details are: $l_1 = 8.3$ mm, $l_2 = 4$ mm, $l_3 = 2.2$ mm, $l_4 = 2.2$ mm, $b_1 = 6$ mm, $b_2 = 4$ mm, $b_3 = 2.5$ mm, $b_4 = 3.2$ mm, $b_5 = 2$ mm, $d_1 = 0.2$ mm, $d_2 = 0.4$ mm, and $h_1 = 1.4$ mm.

To confirm the element characteristics, the commercial-simulation software CST Microwave Studio 2019 is used for numerical simulations. Floquet ports with periodic boundary conditions are adopted to simulate the element, mimicking an infinite periodic array and considering the coupling effect of adjacent elements. The simulation method of EM/Circuit co-simulation is adopted, and the electric and parasitic characteristics are all counted into the measured $S$ parameters of the PIN diodes provided by the manufacturer. A plane wave polarized along the $y$ direction is normally incident upon the anisotropic element. The reflection coefficients are marked as $R_{yy}$ and $R_{xy}$, where the first subscript represents the reflected polarization, and the second represents the input polarization. Similarly, the transmission coefficients are written as $T_{yy}$ and $T_{xy}$. Since the PIN diode has two states, on and off, there are two cases for discussions: case 1 occurs when diode 1# is turned on and diode 2# is turned off; while Case 2 occurs when diode 1# is switched off and diode 2# is switched on. Some specifically simulated transmission amplitudes and phases are shown in figure 2.

In Case 1, the transmissive element converts the $y$-polarized incident waves into cross-polarized output waves in the broad bandwidth from 9.54 GHz to 11.38 GHz, as illustrated in figure 2(a), where the conversion loss is less than 3 dB and the minimum conversion loss is 1.1 dB at around 10.5 GHz. In case 2, good polarization-conversion ability is maintained with low conversion loss, as shown in figure 2(a). The $−3$ dB bandwidth range nearly overlaps with it in case 1, thereby ensuring to operate in the same frequency band, despite the change in the diode-switching states. Similarly, the minimum transmission loss is 1.1 dB in this case. It is worth noting that the phase difference between the two cases is almost out of phase (see figure 2(b)), suggesting that the proposed element can serve as a good candidate for a 1-bit coding meta-element.

In these two cases, the co-polarized reflection amplitudes $R_{yy}$ are basically below $−10$ dB from 9.7 GHz to 11.4 GHz. The cross-polarized reflection amplitudes $R_{xy}$ are less than $−50$ dB in the same frequency band, and the transmitted co-polarization amplitudes are also very small. Thus, these results indicate that the metasurface has very good performance in the cross-polarization transmission.

The response of the proposed element at oblique incidence is also considered, and the simulation results are presented in figure 3. In case 1, when the incident angle $\theta$ is $15^\circ$ and $30^\circ$, the $−3$ dB bandwidth is slightly trimmed. When the incident angle is $45^\circ$, the bandwidth narrows a lot, and the decreased band is displayed in the yellow area. In case 2, the polarization–conversion amplitudes have relatively slight changes under these three angles. It can be seen from the phase difference of figure 3(b) that the bandwidth of $180^\circ \pm 37^\circ$ narrows down as the incident angle increases, and also accompanied by the problem of large phase changes. In summary, the element performs well within $30^\circ$. 

![Figure 2. Simulation results of the transmission metasurface under the normal incidence of the $y$-polarized EM wave. (a) The transmission and reflection amplitudes. (b) The transmission phase and phase difference in two PIN-diode states.](image-url)
3. Analysis of the working mechanism

In this section, we first analyze the working principle of the unit for converting linear-to-linear-polarization. The Jones vector describes the polarization of light in the free space or in another uniform isotropic non-attenuating medium, in which light can be properly described as transverse waves [35]. The plane waves irradiated on the element are also transverse. The metasurface is illuminated by an incident plane wave in the $z$ direction, and the relationship between the incident and transmitted electric fields is represented by the Jones matrix $T$ as:

$$\begin{pmatrix} E^1_t \\ E^2_t \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} E^1_i \\ E^2_i \end{pmatrix}. \tag{1}$$

Here, $E_i$ and $E_t$ are the complex amplitudes of the transmitted electric field and the incident electric field. The superscripts ($x$, $y$) represent the electric field’s polarization direction. $T_{ij}$ are the matrix of transmission coefficients, where subscripts $i$ and $j$ represent the polarization of the transmitted and incident
EM waves, respectively. The incident electric field only has a component in the $y$ direction, such that $E_{xi}^i = 0$ and $E_{yi}^i = E_0 \hat{y}$. The relationship between the incident and transmitted electric fields becomes:

$$
\begin{pmatrix}
E_{xi}^t \\
E_{yi}^t
\end{pmatrix} =
\begin{pmatrix} T_{xx} & T_{xy} \\
T_{yx} & T_{yy}
\end{pmatrix}
\begin{pmatrix} 0 \\
E_0
\end{pmatrix}.
$$

(2)
Figure 9. (a) Simulated and measured cross-polarization transmission amplitudes in the two cases. The blue and green areas are where the simulated transmission amplitudes are above $-3$ dB; the green and yellow areas are where the measured transmission amplitudes are above $-3$ dB; and the green area is where both conditions are satisfied. (b) Simulated and measured transmission-phase differences in the two cases.

To convert the $y$-polarized waves into $x$-polarized waves, the transmission coefficients should satisfy $|T_{xy}| > |T_{yx}|$. The simulation results of the amplitude illustrated in figure 2(a) demonstrate that the co-polarization amplitudes are lower than $-40$ dB, which is much lower than the cross-polarization amplitudes. It indicates that the metasurface achieves superior performance of polarization conversion.

To further illustrate the polarization-conversion mechanism, the power flow density along the surface of the meta-atom is displayed in figure 4(a). The energy is received by the top metal structure, transmitted to the bottom through the central metal pillar, and radiated into the free space. The U-shaped slot patch on the bottom layer is equivalent to a radiating antenna. The intersection between the metal column and patch is the feed point. According to the related theory of antennas, the antenna polarization interrelates to the direction of the excited current. If the current is excited in a single direction, then a linearly polarized wave will be radiated in that direction.

Now, the principle of polarization conversion is analyzed from the perspective of current. Let us consider the case where diode 1 is on and diode 2 is off as example. In figure 4(b), the excited currents of the bottom structure are mainly concentrated in the $x$ direction at 10.2 GHz. However, the current excited on the $y$ axis exists in both the $+y$ and $-y$ directions so that the radiated electric field will cancel out in the far field. Thus, the $x$-axis current accounts for a large part of the far-field radiations. Thus in brief, the element can convert the $y$-polarized incident waves into $x$-polarized ones.

Next, the mechanism of broadband 1-bit phase response is illustrated. The structural symmetry of the unit is primarily responsible for the broadband and stable phase difference for the two cases. It can be obtained from figures 4(b) and (c) that, when the diode is switched on, the mode current near the diode is along $y$ direction. On the contrary, when it is switched off, the current flows along $-y$ direction. Furthermore, the current directions along the surface of the bottom layer are also reversed in the two cases.
Moreover, the interdigital structure in our meta-atom is a broadband structure allowing the excitation of multiple resonances at different frequencies. Thereby, opposite phase response can be invoked in a large bandwidth.

Finally, the reason for the high transmittance is carefully explained. The interdigital structures are the major factor of wave transmission; they form multiple capacitors for better energy coupling. As shown in figure 5, more energy is localized around the interdigital structure because of the larger effective receiving area. Due to this divergence, more energy is transmitted to the bottom to improve the transmittance of the element. It can be clearly seen that the interdigital structure effectively improves the transmittance in figure 6.

4. Experimental verification

To validate the element’s performance, a TA composed of 10 × 10 elements is designed and manufactured based on the printed-circuit-board technology. The practical top and bottom layers of the meta-atom are displayed in figure 7. During experiments, the sample is placed in an absorbing screen with an open window of the same size, as illustrated in figure 8, to eliminate unwanted reflections from the environment and to improve the measurement accuracy. The whole measurements are performed in a microwave anechoic chamber.

Two horn antennas with different polarizations located on two sides of the wave-absorbing screen are employed to transmit and receive the EM waves, respectively. They are connected to the vector network analyzer through phase-stable coaxial lines. The distance from the transmitting antenna to the absorbing screen is carefully selected, such that it satisfies the far-field condition. The direct-current source provides +0.9 V and -0.9 V voltages to feed the PIN diodes, corresponding to cases 1 and 2 mentioned earlier, respectively.

For calibration, the transmission results of the open window in the absorbing screen shown in figure 8 are measured prior to testing the sample. Then, the sample is mounted on the window to measure its amplitude and phase. The polarization direction of the linearly polarized incident wave is consistent with the placement direction of the PIN diodes, whereas the received wave polarization is perpendicular to it. Finally, the measured results are normalized to those of air, and thus the actual sample-measurement results are obtained.
The actual experimental-amplitude results are displayed in from 10 GHz to 11.54 GHz, with the maximum transmission amplitude of $-1.69$ dB. In case 2, the metasurface achieves the transmissive cross-polarization loss within 3 dB in the frequency band from 10.25 GHz to 11.4 GHz, where the minimum insertion loss is 2.2 dB. The difference between the magnitudes in the two cases is very small. The measured phase difference between the two cases is within $180^\circ \pm 15^\circ$ in the X-band, as illustrated in figure 9(b), in which the maximum difference is $195^\circ$ and the minimum difference is $175.5^\circ$.

The comparison of the simulation and measurement results indicates that the differences of the cross-polarized amplitudes and phases are basically consistent. Nevertheless, there is a slight frequency shift between the experimental and simulated amplitudes. The measured phase difference has a larger fluctuation range than the simulated one. The difference between the measurements and simulations can be attributed to the errors in the PIN diodes’ model parameters during the simulations, the deviation of the substrate’s dielectric constant, fabrication errors, and the offset in the diodes’ positions.

The coding strategy is changed to further illustrate the ability of wavefront manipulation. For example, the digits ‘0’ and ‘1’ are used to represent the transmission phases in cases 1 and 2 respectively. Then we consider four coding sequences as 00 000 000, 0001 110 001, 0110 011 001, and 0010 010 010, where each column of the metasurface shares the same code simultaneously. The measured scattering patterns are presented in figures 10(a)–(d). It can be seen that the beam splitting or multi-beam generation can easily be realized by changing the coding strategies as expected.

5. Conclusion

A novel type of transmitarray with high transmittance and broad bandwidth is designed and fabricated. It achieves the 1-bit phase response and linear-to linear-polarization conversion by controlling the PIN diodes. Different from coupling energy transmission, we adopt a method of connecting the upper and lower structures with a metal through-hole to transmit the energy, which is proved to be more effective. To expand bandwidth and increase the transmittance of the element, the interdigital structures are used. Furthermore, the metasurface with the polarization—conversion function expand its application potential.

Measurements are implemented to verify the performance of the transmitarray. When PIN diode 1# is on and diode 2# is off, the proposed TA achieves a cross-polarization transmission amplitude above $-3$ dB with the bandwidth of 1.54 GHz; the maximum transmission amplitude is $-1.69$ dB. When the states of the PIN diodes are opposite to the previous ones, the proposed TA can obtain the transmission amplitude with the loss below 3 dB in the bandwidth of 1.15 GHz; and the minimum loss is 2.2 dB. Moreover, the element attains a 1-bit phase regulation in the ultra-wide band. The measured scattering patterns show that beam splitting or multi-beam generation can be achieved for different phase coding. The excellent performance of the metasurface indicates its great potentials in the radar and communications systems.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Wen Hua Gao https://orcid.org/0000-0003-2035-7536
Tie Jun Cui https://orcid.org/0000-0002-5862-1497

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