



Design of a Wide-Angle and Polarization-Free 1-Bit Programmable Metasurface

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Programmable metasurfaces have the powerful capability of controlling electromagnetic (EM) waves by coding the digital state of each meta-atom. However, conventional programmable metasurface units are difficult to maintain stable controllability under wide-angle incidence conditions, which limits the application of 1-bit programmable metasurfaces in single-beam scanning. A 1-bit dual-polarized programmable metasurface that allows oblique incidence at large angles is presented in this article. Inspired by the principle of reciprocity in the antenna theory, a wide-angle patch antenna which operates in the receiving mode and is loaded by a PIN-diode-based load circuit is designed as the basic structure of the meta-atom. Numerical simulations show that the 1-bit coding state maintains good angular stability within ± 70 degrees of the incident angle for both orthogonally polarized EM waves, and single-beam scanning can be achieved at large oblique incident angles for any polarization.

Keywords: wide-angle, polarization-free, programmable metasurface, receiving antenna, 1-bit

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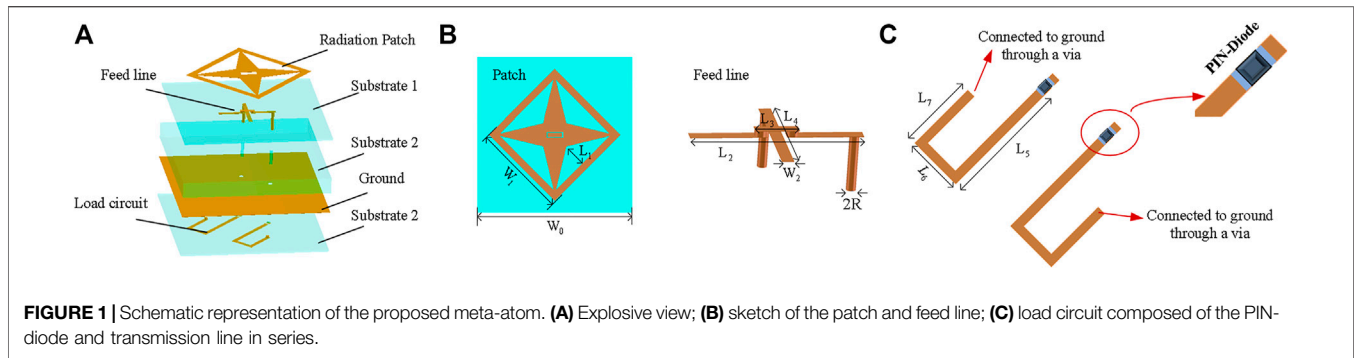
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INTRODUCTION

Metasurfaces have received extensive attention from researchers due to their powerful electromagnetic (EM) wavefront control capabilities (Cui et al., 2016; Li et al., 2017; He and Eleftheriades, 2019). Different from the basic modulate strategies of traditional metasurfaces, programmable metasurfaces construct a digital space on the physical space of metamaterials, which allows the real-time and dynamic modulation of EM waves by controlling digital codes, providing new architecture for wireless communication (Liu et al., 2016; Wan et al., 2016; Cui et al., 2019). Therefore, programmable metamaterials have developed rapidly since the concept was proposed by Cui et al. (2014).

Generally, traditional phased array antennas can achieve beam steering by changing the excitation amplitude and phase of the array elements; however, this usually relies on a complex and expensive phase-shifting network (Liu et al., 2019). Compared with traditional phased arrays, the new antenna system based on programmable metasurfaces can miniaturize the complex phase-shifting modules, reduce the manufacturing cost, and, in addition, have the advantage of flexible control (Wan et al., 2016; Zhang et al., 2020).

For an $N \times N$ programmable metasurface with n -bit, the degree of freedom for this metasurface to control the EM waves is a function of the element number N and bit number n . The larger the value of n is, the higher the degree of freedom of EM wave controllability is. Programmable metasurfaces are usually periodically integrated by active devices (such as the PIN-diode, varactor, and MEMS chips) and subwavelength meta-atoms, and a field-programmable gate array (FPGA) can be used to



generate the coding sequence to control the electrical characteristics of each active devices so as to achieve in-time and precise control of the amplitude and phase of the EM wavefront (Liu and Cui, 2017; Zhang et al., 2020). Metasurfaces with a high bit number usually have higher requirements on the cell structure design. In comparison, 1-bit metasurfaces are easier to design.

However, due to the phase symmetry and structural symmetry, 1-bit metasurfaces will generate multiple symmetrical beams under the normal incidence excitation, which is undesirable for scanning arrays and difficult to eliminate by changing the coding mode. To achieve single-beam scanning, a large angle of oblique incidence is required. However, conventional metasurface units are difficult to maintain stable coding characteristics under wide-angle incidence conditions. The wide-angle stability of programmable metasurface has been studied by Zhang and Cui (2019) and Liang et al. (2021). The meta-atoms proposed in these literature reports can maintain stable coding performance in the range of $0^\circ \sim 60^\circ$, but it is sensitive to polarization.

Based on the principle of reciprocity and inspired by the design method of antennas, a meta-atom with wide-angle characteristics and polarization-free properties is designed in this article, providing a low-cost approach for single-beam scanning. A wide-angle and dual-polarized patch antenna operating in the receiving mode and loaded by a PIN-diode-based load circuit is designed as the basic structure of the meta-atom. The phase interval required for 1-bit coding can be achieved by switching the on-off state of the PIN-diode and remains stable over a wide-angle incidence range for any polarization.

UNIT DESIGN AND SIMULATION

Unit Design

The principle of antenna reciprocity indicates that the basic characteristic parameters of the antenna when it is used as a receiver are the same as those when it is used for transmission, which means that a transmit antenna with wide-beam can also have wide-angle characteristics when it is used for receiving. Furthermore, the scattering field of the receiving antenna is composed of modal scattering and structural scattering based on the antenna scattering theory, where the modal term is related to the load condition

(Andersen and Frandsen, 2005; Best and Kaanta, 2009). Therefore, when the receiving antenna is used as a meta-atom, the required reflection coefficient phase interval can be realized by appropriately controlling the load condition of the antenna.

In order to realize the wide-angle and polarization-free properties of the meta-atom, a microstrip patch antenna with wide-beam, high-isolation, and dual-polarization characteristics, as proposed by Huang et al. (2019), has been chosen as the basic structure of the meta-atom, as shown in **Figure 1**. The radiating patch of this antenna is a four-pointed star fed by two orthogonal striplines. The element size W_0 is set to be 36.8mm, which is a sub-wavelength structure under 3GHz, to ensure good field modulation characteristics after forming an array. As shown in **Figure 1A**, the meta-atom contains three substrates, of which are F4BM300 dielectric slabs ($\epsilon_r = 3.0$ and $\tan \delta \leq 7 \times 10^{-4}$) with thicknesses of 0.5, 4, and 0.5 mm, respectively. The remaining parameters for patch and feed lines in **Figure 1B** are $W_1 = 22\text{mm}$, $W_2 = 1\text{mm}$, $L_1 = 5.5\text{mm}$, $L_2 = 14\text{mm}$, $L_3 = 3.6\text{mm}$, $L_4 = 11\text{mm}$, and $2R = 0.8\text{mm}$.

The two feeding ports of the antenna are, respectively, connected to a load circuit formed by a certain length of microstrip line and a PIN-diode (MA4AGP907 from MACOM) connected in series at the bottom of substrate 3, as shown in **Figure 1C**. The lengths of the microstrip line are $L_5 = 14\text{mm}$, $L_6 = 6\text{mm}$, and $L_7 = 7.8\text{mm}$, and the terminal of the microstrip line is connected to the ground plane through a hole. By switching the state of the PIN-diode through the DC bias voltage, the load condition of the antenna can be changed so that the 180° phase interval for the 1-bit performance of the meta-atom can be realized.

Simulated Results of the Unit Cell

The full-wave numerical simulation software CST Microwave studio was used to analyze the electromagnetic properties of the proposed meta-atom under different coding states and incident angles. The code “0” represents the “on” state of the PIN-diode; on the contrary, the code “1” represents the “off” state of the PIN-diode. **Figure 2A** shows the reflection coefficient phase characteristics of the meta-atom under the TE wave illumination at the incident angles of 0° , 20° , 40° , and 70° . The reflection phases of state “1” and state “0” are represented by the solid line and dash line, respectively. A phase interval of about 180° can be achieved around 3 GHz for both the normal illumination and oblique incidence over the range of $0^\circ \sim 70^\circ$.

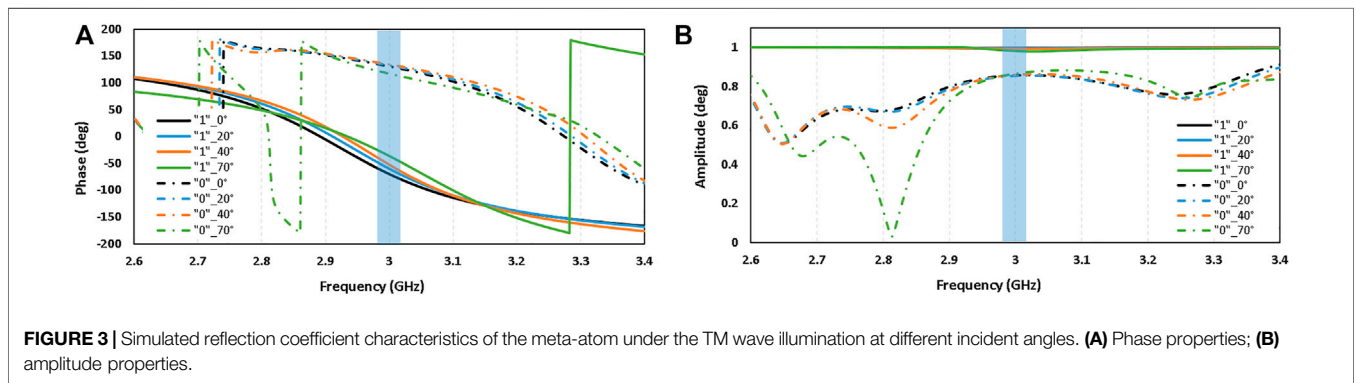
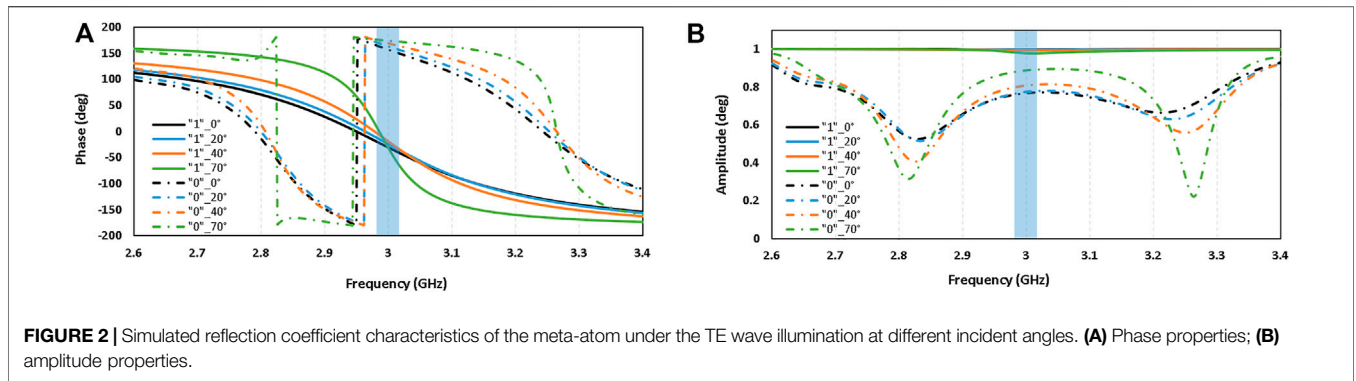
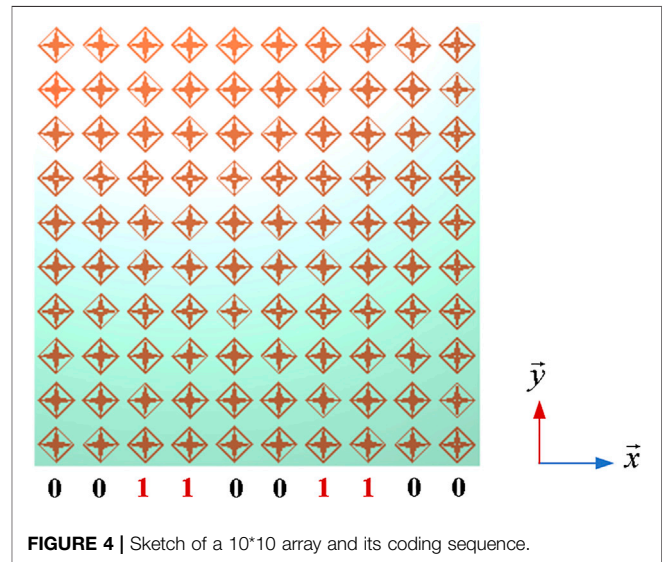


TABLE 1 | Comparison with recently reported relevant works.

Reference	Bit-number	Range of incident angles	Polarization modes
Proposed	1-bit	0° ~ 70°	Dual-polarized
Zhang et al., 2020	1-bit	—	Dual-polarized
Zhang et al., 2019	2-bit	0° ~ 60°	TM-polarized
Liang et al., 2021	3-bit	0° ~ 60°	TM-polarized

Figure 2B is the corresponding amplitude characteristics. The amplitude of the reflection coefficient is close to 1 when the PIN-diode is turned off at the working frequency, which means the energy is almost totally reflected. When the PIN-diode is turned on, the reflection amplitude decreases due to the loss and mutual-coupling caused by the circuit, but it is all greater than 0.7. Based on the antenna array theory, the beam properties of a large array depend more on the phase characteristics than the amplitude of each unit. Therefore, the beam steering capability of the metasurface formed by this unit can still be guaranteed.

The phase and amplitude characteristics of the PIN-diode in two states under TM wave illumination from 0° to 70° are shown in **Figures 3A and B**, respectively. A phase interval of about 180° can also be achieved around 3 GHz for TM polarization, and the 1-bit coding properties remain stable over the 0° ~ 70° incident range. The reflection amplitude of each coding state is greater than 0.8, which enables efficient TM wave modulation.



To sum up, the proposed meta-atom exhibits stable angular insensitivity in the reflection amplitude and phase responses over a wide range of incident angles for both TE and TM polarization properties of its radiation mode. The performance comparison of the proposed programmable metasurface with recently reported relevant works is presented in **Table 1**. It can be seen that the proposed metasurface not only provides a wider incident range

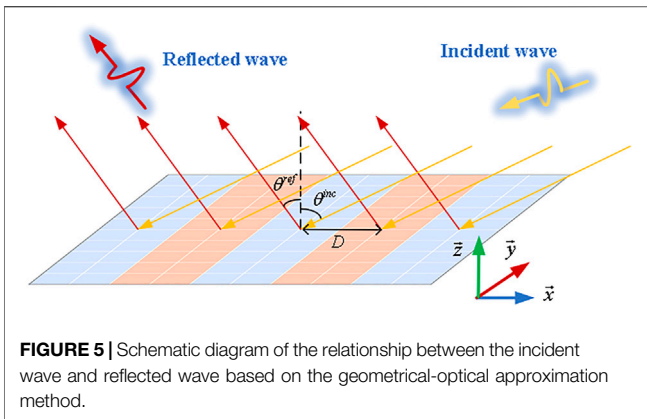


FIGURE 5 | Schematic diagram of the relationship between the incident wave and reflected wave based on the geometrical-optical approximation method.

but also removes the restriction on the polarization mode of the incident wave. It should be pointed out that the problem that this article attempts to solve is the limitation that the 1-bit metasurface is difficult to achieve single-beam scanning under normal incidence excitation, and thus, high bit number is not our goal.

METASURFACE AND ITS APPLICATIONS

To verify the modulation capability of the programmable metasurface constructed by the proposed meta-atom. A 10*10

array, as shown in **Figure 4**, has been simulated. The coding sequence in the *x* direction is 0011001100.

Performance of Wide-Angle Incidence

The reflected beam pointing angle of the programmable metasurface with different coding sequences and different incident angles can be estimated by the geometrical-optical approximation method, as shown in **Figure 5**. The main lobe usually points in the direction where the electric fields are superimposed in phase. Assuming that the amplitude of the reflection coefficient for each unit is uniform and the phase difference between the two coding states is 180° and taking the keyboard coding mode as an example, the in-phase superposition should satisfy the following formula:

$$\frac{2\pi D}{\lambda_0} (\sin \theta^{inc} + \sin \theta^{ref}) + \Delta\Phi = \pm 2\pi n, \tag{1}$$

which is related to the phase delay caused by the path difference of oblique incidence, the phase difference of metasurface modulation, and the phase delay caused by the reflection. Here, $n = \pm 0, 1, 2, \dots$, λ_0 is the wavelength in free space. D represents the spacing between adjacent coding lattices. θ^{inc} and θ^{ref} are the incident angle and reflected angle (the maximum beam pointing angle), respectively. $\Delta\Phi$ represents the phase difference between adjacent codes, and $\Delta\Phi = \pi$ stands for 1-bit.

The electric field pattern under the normal incident condition of the TE polarization wave is shown in **Figure 6A**. Two symmetrical beams pointing at $\pm 39^\circ$ can be observed in the upper half-space,

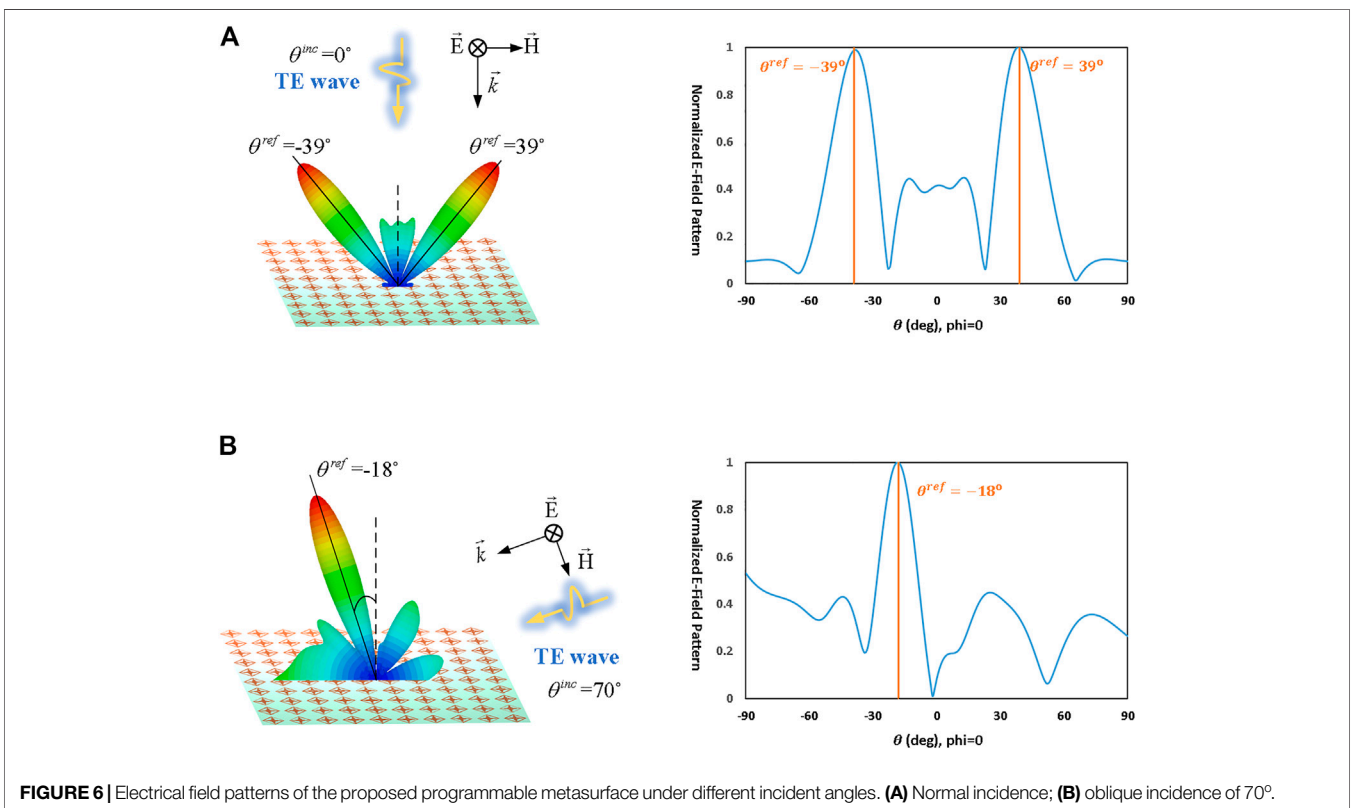


FIGURE 6 | Electrical field patterns of the proposed programmable metasurface under different incident angles. **(A)** Normal incidence; **(B)** oblique incidence of 70°.

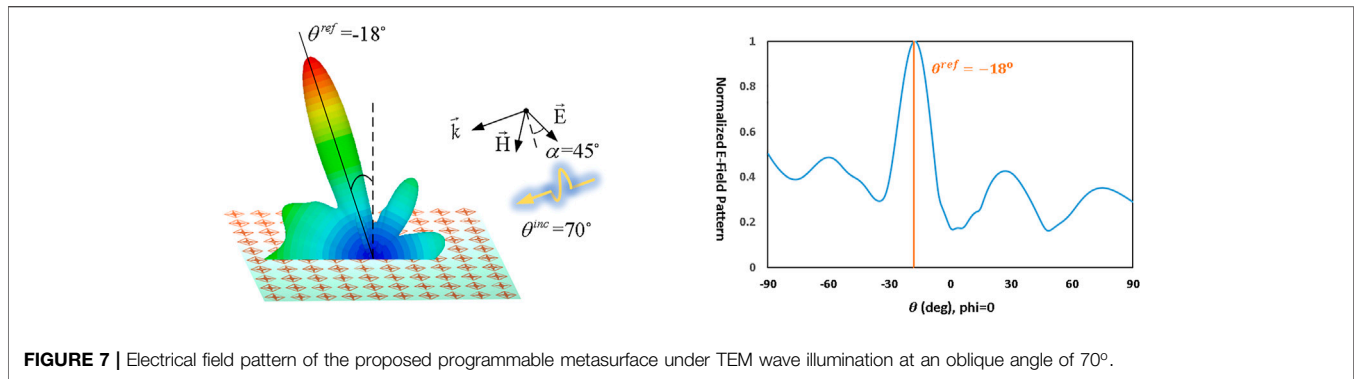


FIGURE 7 | Electrical field pattern of the proposed programmable metasurface under TEM wave illumination at an oblique angle of 70°.

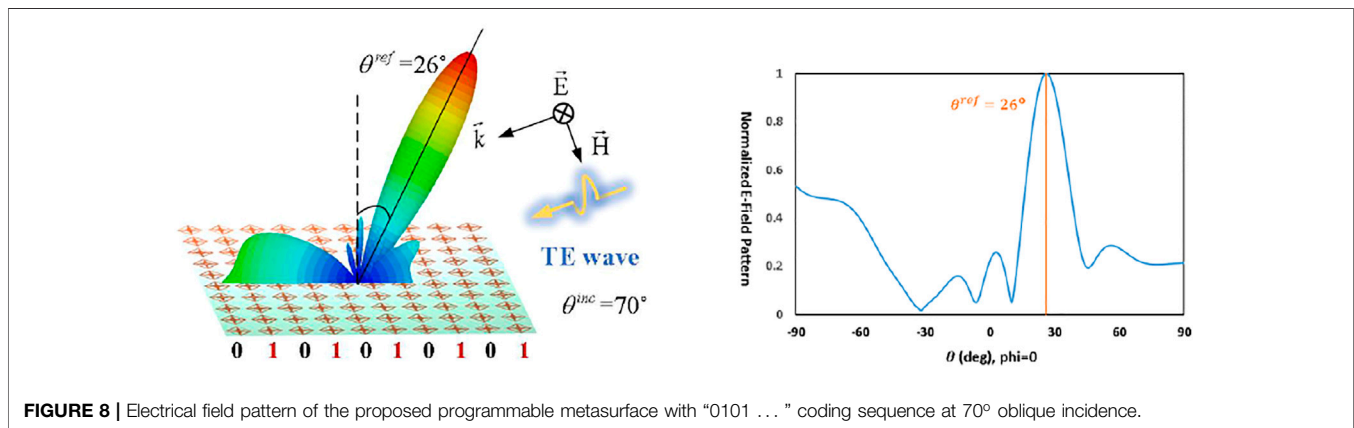


FIGURE 8 | Electrical field pattern of the proposed programmable metasurface with "0101 ..." coding sequence at 70° oblique incidence.

which is close to the theoretical predictions $\pm 42^\circ$ calculated by **formula (1)** for the 0011001100 coding sequence.

It can be seen that the 1-bit metasurface will inevitably generate two symmetrical beams in the upper half-space under normal illumination, which means that the 1-bit metasurface cannot achieve single-beam scanning under normal incident conditions or small incidence angles. When the energy needs to be concentrated into a single beam of radiation, a large angle of oblique incidence is required. **Figure 6B** shows the electric field pattern at an oblique incidence of 70°. A single beam pointing at -18° can be obtained, which is close to the results -15° predicted by **formula (1)**. There are two main reasons for the 3-degree error between theoretical predictions and simulation results. First, the theoretical prediction **formula (1)** is derived based on the geometrical optics approximation without considering the mutual coupling between adjacent elements. Second, there is a small error between the reflection coefficient magnitude and phase of the proposed meta-atom and the assumptions of the prediction formula.

Performance of Different Polarization Components

To verify its polarization-free characteristics, a TEM plane wave consisting of both TE and TM polarization is used as the incident condition. The angle between the electric field polarization direction of the TEM plane wave and the incident plane is 45° , so there are both the x polarization component and y polarization component of

this plane wave. **Figure 7** gives the electric field pattern of the TEM wave illuminated at an oblique angle of 70°. A single beam pointing at -18° is observed, which is consistent with the result of TE wave illumination, as shown in **Figure 6B**. Therefore, the proposed programmable metasurface exhibits a stable modulation capability for any polarization form.

Performance of Different Coding Sequences

According to **formula (1)**, the beam direction is related to D , determined by the coding scheme and incident angle θ^{inc} . Therefore, when the incident angle is determined, different beam directions can be achieved by controlling the coding sequence, thereby realizing beam scanning. **Figure 8** shows the electric field pattern for the 0101010101 coding sequence under the TE wave oblique incident at 70°. A single beam pointing at 26° , which is close to the theoretical result 25° estimated by **formula (1)**, is observed. Therefore, different beam pointing angles can be realized by controlling the coding sequences, which can reduce the cost and the complexity of the feeding network compared with the traditional antenna array.

CONCLUSION

In this article, a wide-angle and polarization-free programmable metasurface has been proposed. For arbitrarily polarized TEM

waves, it maintains a stable 180° phase interval for 1-bit coding over the range of the 0° ~ 70° incident angle by switching the on-off state of the PIN-diode to change the load conditions. The proposed metasurface enables single-beam scanning for any polarized wave under oblique incidence at a large angle, providing an efficient and low-cost option for beam scanning, and may find further potential applications in radar cross-section reduction and future-oriented wireless communications.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

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AUTHOR CONTRIBUTIONS

HCZ put forward the initial idea and supervised the project. LL performed the model design and drafted the manuscript. YFH helped with the simulation analysis. All authors fully contributed to the research.

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