Dynamic Manipulation of Electromagnetic Waves Based on 1-bit Reconfigurable Metasurface

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Abstract

A 1-bit reconfigurable reflective metasurface for dynamic manipulation of electromagnetic (EM) waves is proposed in this paper. Through dynamically controlling the bias voltage to switch the ON/OFF state of the PIN diodes on the metasurface, the EM response of the metasurface can be reconfigured at 10.4 GHz. As a proof of concept, dynamic beam steering and near-field focusing are realized to demonstrate the feasibility of the proposed reconfigurable metasurface, which provides a new platform for dynamically manipulating electromagnetic waves.

Introduction

Recently, metasurfaces have been developed for controlling electromagnetic (EM) responses such as amplitude, phase, polarization, and frequency resulting in a large number of applications [1-4]. However, most passive metasurfaces have fixed structures and without any reconfigurable factor, thus, their function is performed stationary. To dynamically tailor the EM response of the metasurface, scientists have proposed that by integrating some active tunable devices (such as varactor diodes and PIN diodes) on the metasurface, the reflection phases on the metasurface can be tuned by changing the external excitation signal, as a result, it's feasible to dynamically manipulate the EM wavefront. Particularly, 1-bit reconfigurable metasurface can be tuned simply and accurate and is enough to achieve lots of functions, therefore, it's popular in its research field. In this paper, a 1-bit reconfigurable reflective metasurface is composed of sub-wavelength meta-atoms with PIN diodes (MACOM MADP-000907-14020W). The reflection phase of the meta-atom can be tuned binarily between 0 and π at 10.4 GHz by switching the bias voltage of the PIN diode, able to reconfigure the functions dynamically. As a proof of concept, dynamic beam steering and near-field focusing are realized, validating the high performance of the metasurface. In summary, the proposed 1-bit reconfigurable metasurface provides a new practical solution for building a dynamic metasurface system.

Meta-atom Design

The structure of the proposed meta-atom is illustrated in Fig.1. The meta-atom is a single layer structure, including a bow tie shape metallic patch containing a PIN diode, a dielectric substrate, 4 metallic vias and the ground metallic feedlines. The dielectric substrate is made of F4B (εr = 4.4, tanδ = 2.5 × 10-3), with a thickness of 1.5 mm. The PIN diode is loaded on the gap in the middle of the bow tie shape metal patch to form an electrical connection with the patch, as shown in Fig. 1(a), the reflection phase of the y polarization incident wave can be controlled between 0 and π at 10.4 GHz as the PIN diode switch between ON and OFF, but invalid for that of x polarization. The ground plane is divided into two pieces with a narrow slot, it not only acts as a reflection ground to keep high reflection but also behaves as a bias control line for controlling the voltage to change the state of the PIN diodes.

Subsequently, the operation mechanism of the proposed meta-atom is studied. The equivalent serial circuits of the PIN diode on ON and OFF states are shown in Fig. 1(c), where Re, Le and Ce are the equivalent serial resistance, inductance and capacitance of the PIN diode. When the state is OFF, Re = 0 , Le = 0.09 nH, Ce = 0.02 pF, and when the state is ON, Re = 7.8 Ω, Le = 0.09 nH, Ce = 0 pF. Because the lumped parameters of the PIN diode change significantly as the state of the PIN switch, the EM response of the meta-atom can change sharply. Through optimizing the structure parameters of the meta-atom, the reflection phase can be manipulated binarily between 0 and π corresponding to the ON and OFF state respectively. In Fig. 2, in the two different states, the phase of the simulated reflection coefficient under y polarization incidence performs sharply different, the phase in the OFF state decreases as frequency much faster than that in the ON state, as a result, the phase difference between the two states can be set as π. Meanwhile, the amplitude keeps over 0.93, ensuring the high efficiency of the metasurface. In sharp contrast, the EM response under x polarization is also studied. The EM response shown in Fig. 3 is almost the same in the two different states. Thus, the design meta-atom works under y polarization, whose phase can be dynamically manipulated in 1-bit between 0 and π to tailor different kinds of wavefronts.

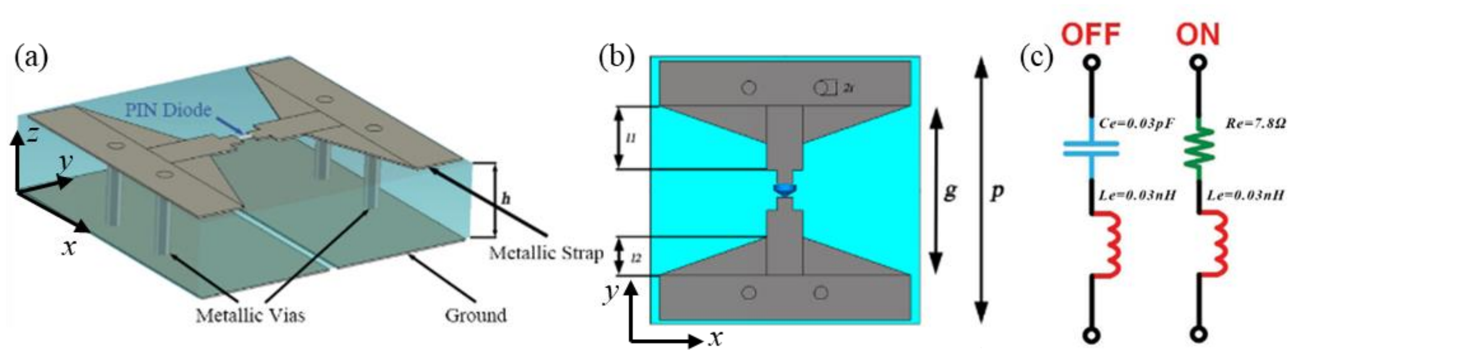

Fig. 1. The schematic of the proposed meta-atom structure. (a) 3D view and (b) front view of meta-atom. (c) The ON and OFF equivalent serial circuits of the PIN diode. The geometric parameters are h = 1.5, p = 6, g = 3.8, l1 = 1.45, l2 = 1.05, r = 0.15 (unit: mm).

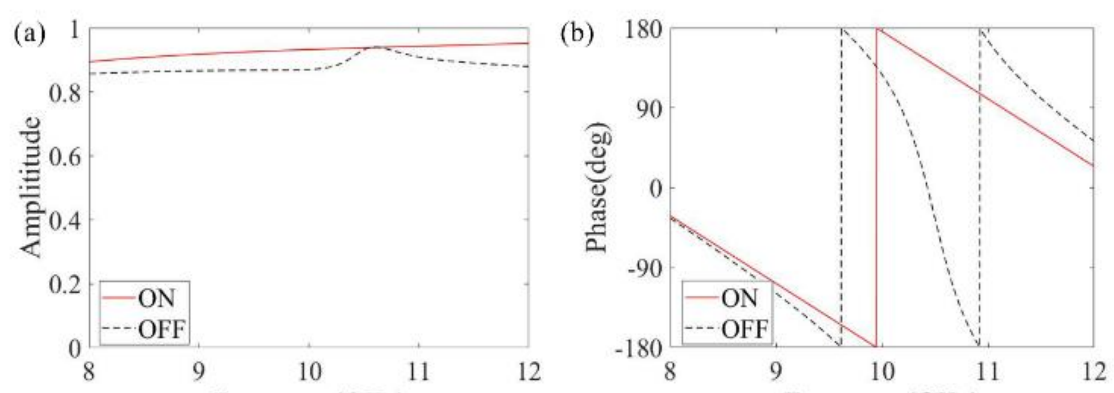

Fig. 2. Simulated (a) amplitude and (b) phase of the reflection coefficient of the meta-atom under y polarization incidence

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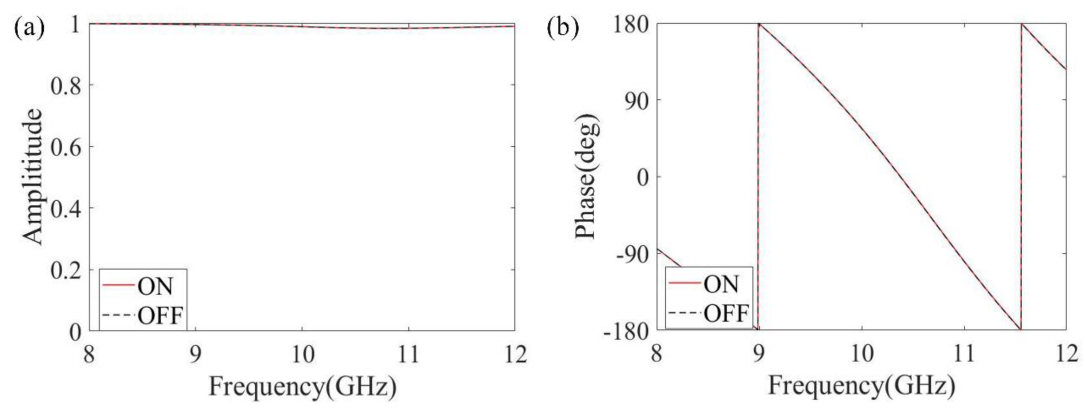

Fig. 3. The surface current of the meta-atom in (a) ON and (b) OFF states under x-polarization wave illumination

Simulation and Measurement Results

The phase difference dΦ between adjacent meta-atom can only be 0 or π, and the beam steering angle can be adjusted by changing dx. First, set the four adjacent meta-atoms to the same state, that is dx = 24 mm. The deflection angle of the reflected wave is ±41.7° based on Generalized Snell's Law, due to the symmetry phase profile, which is shown in Fig. 4(a). Its corresponding normalized far-field pattern is obtained by full-wave simulation software CST, which is shown in Fig. 4(b). It's clear that the reflected wave deflects to 41° and -41°, in good agreement with the theoretical value, which proves that the 1-bit reconfigurable metasurface can perform beam steering. To further demonstrate the proposed reconfigurable metasurface practically, we implement the experiment in the setting of dx = 24 mm. The fabricated prototype of the proposed 1-bit reconfigurable metasurface is shown in Fig. 5(a), and its measured normalized far-field pattern is shown in Fig. 5(b), the main beam steering angle is ±40°, close to the theory of ±41°. Compared to the theory, discrepancies like some sidelobes, and nonuniform main lobes appear in measurement, which results from many reasons, such as the fabrication error of the metasurface, the real performance of the meta-atom deviating from the ideal one, and the imperfect measurement environment and devices. But in general, the simulated and measured results are in good agreement.

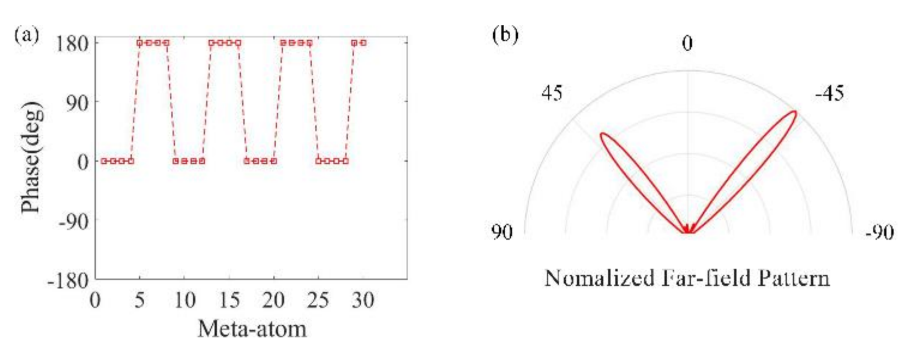

Fig. 4.(a) Ideal phase profile and (b) the simulated normalized far-field pattern when dx = 24 mm, at 10.4 GHz.

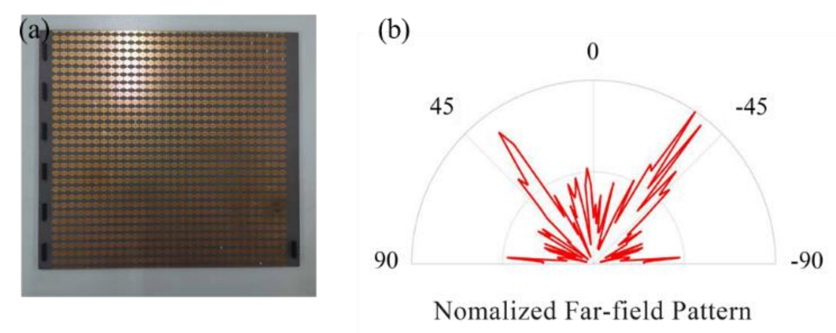

Fig. 5.(a) The fabricated prototype of the proposed metasurface and (b) the measured normalized far-field pattern when dx = 24 mm, at 10.4 GHz.

We select the focal coordinates (xF, yF, zF) = (0, 25mm, 75mm) and verify the performance of the metasurface. The theoretical phase distribution calculated by (2) is shown in Fig.6. Conduct full-wave simulation, the distribution of the reflected electric field in the yoz plane at the operating frequency is displayed in Fig. 7(a). Obviously, the EM wave is highly concentrated in the region near (0, 25mm, 75mm). And observe the focal plane at z = 75 mm, can be seen more intuitively that the focus has shifted about 25mm along the y-axis, and the reflected field distribution is close to the preset value of 25 mm. At the same time, the energy distribution of xoy section is less except for the focus, which proves that the proposed 1-bit reconfigurable metasurface can well realize the near-field focusing of the focus shifting along the y-axis.

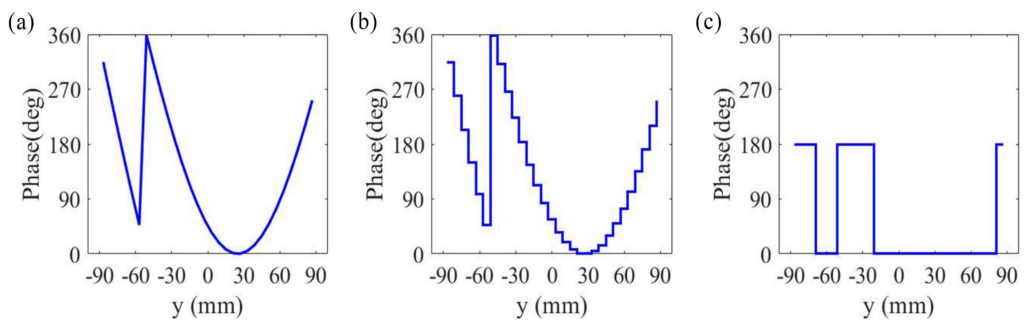

Fig. 6 The focusing phase profile when (xF, yF, zF) = (0, 25mm, 75mm). (a) continuous phase, (b) discrete phase and (c) binary phase.

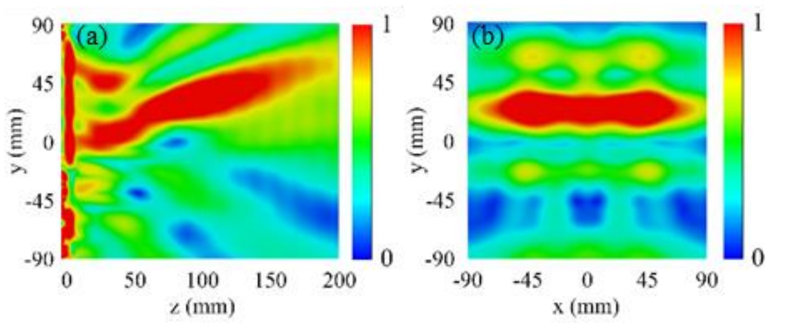

Fig. 7 The near-field results when (xF, yF, zF) = (0, 25mm, 75mm). (a) yoz plane (b) xy plane at z = 75 mm.

Conclusion

In summary, a 1-bit reconfigurable metasurface is proposed to dynamically manipulate the EM wavefront by changing the voltage of control bias to switch the ON and OFF states of the PIN diodes loaded on the metasurface. It works at 10.4 GHz and y polarization incident, providing a binary phase of 0 and π for the reflected y polarization wave under the two different states. For dynamic beam steering, the goal beam steering angle is set as ±41.7° and the result calculated by full-wave simulation is consistent with the goals, besides, the case that beam steering angle equals ±41.7° is measured, the corresponding measured result in good agreement with theory. For Dynamic near-field focusing, the focal spot is shifted from (yF, zF) = (25mm, 75mm), and their near-field results are close to the pre-setting goals, proving the capability of dynamic focusing. The proposed 1-bit reconfigurable metasurface is able to dynamicaclly manipulate of EM wavefront, which is favor in praitcal wireless communication system.

References

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