Reconfigurable 2-bit Digital Coding Metasurfaces in a non-contact way

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***Abstract*—In this paper, we propose and design an optically reconfigurable 2-bit digital coding metasurface in microwave band. The embedded two varactors in the digital element are controlled by a photodiode module, and hence the states of the designed digital element can be remotely tuned by the intensity of illuminating light. Using such elements to compose reflective digital coding metasurfaces, dynamically reconfigurable radiation beams are obtained in a non-contact tuning way. Simulation results verify that the proposed digital coding metasurface is capable of generating the desired wave controlling, beam deflection and beam splitting.**

Keywords—reconfigurable coding metasurface; 2-bit coding; beam deflection; beam splitting

I. Introduction

Metasurfaces, a kind of artificial structures with thin thickness, are composed of periodically or nonperiodically arranged subwavelength units. In recent years, metasurfaces have attracted extensive attention due to their functional properties that can be designed for flexibly tailoring light[1]. Many electromagnetic (EM) metasuface-based devices have been realized for achieving different EM functions[2-4]. However, most of the currently demonstrated metasurfaces only have one specific EM response, that is to say, the function of the meta-device is fixed once the meta-device is fabricated completely. The poor tunability restrains the development of the dynamically tunable or multi-functional EM metasurface-based device. Hence, it is important to develop reconfigurable EM metasurfaces for controlling the waves in real time. One effective method to realize reconfigurable metasurfaces is to load tunable active components in the metasurface, such as PIN diodes and varactors, to switch or tune the states[5-7]. In 2014, the metasurfaces characterized by digital bit have been proposed and verified[8]. The digital metasurfaces provide a powerful tool to control the EM waves in real time with a low cost approach.

In this paper, we propose and design a 2-bit microwave digital coding metasurface that can be controlled by remote light. We first design a light-tunable digital element, and then study its phase responses under the different states. Finally, as a proof of the concept, a light-dependent reflective digital coding metasurface consisting of 48×48 such digital elements is designed and numerically verified.

II. Coding Metasurface Design and Smiulations

A. Design of 2-bit Light-tunable Digital Element

We propose and design a 2-bit light-tunable digital element, the detailed structure is shown in Fig. 1. Two varactors are loaded in the digital element for achieving the tunability of reflection phase of EM wave. To tune the capacitances (C_{T1}, C_{T2}) of the two embedded varactors by illuminating light, we use the photodiode module consisting of silicon PIN photodiodes series array to provide direct-current (DC) bias. Hence, the reflection phase of the designed digital element can be controlled by illuminating the photodiodes array with intensity-varying light in a non-contact way. The designed metallic pattern and the ground are printed onto the top and bottom faces of the substrate F4B with a dielectric constant of 2.65 and loss tangent of 0.001, and the thickness h of the substrate is 3.0 mm. The top metallic pattern contains a larger metallic rectangular patch and two small symmetric metallic rectangular patches on the sides of larger patch, and the gap between the patches is w = 1.2 mm. The side-length of the digital element is a = 12.0 mm and the thickness of metallic patches and ground is set as 0.018 mm. In our simulation, we use RLC series circuits with R = 0.8 Ω, L = 0.7 nH and the adjustable capacitance C_{T1} and C_{T2} to mimic two varactors, respectively. The parameters b, L_1, L_2 and two capacitances of C_{T1} and C_{T2} are optimized for realizing the desired binary element, and the optimized values of b, L_1 and L_2 are 5.0 mm, 2.0 mm and 10.0 mm, respectively.

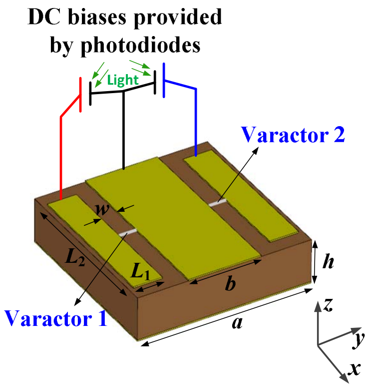

Fig. 1. The proposed 2-bit digital element tuned by illuminating light.

B. *Simulations and Reasult Analysis*

For different values of the varactor capacitance, the simulated reflection phases are shown in Fig. 2. From the simulation results, we observe that the phase differences among four distinct combination states of two capacitances are approximately 90° at 4.0 GHz. Hence, we use the digital element with different capacitances of $C_{T1} = C_{T2} = 2.67$ pF, $C_{T1} = 2.67$ pF, $C_{T2} = 0.70$ pF, $C_{T1} = C_{T2} = 1.03$ pF and $C_{T1} = C_{T2} = 0.63$ pF to mimic “00” unit, “01” unit, “10” unit and “11” unit, respectively.

Next, we make numerical simulations to verify the beam-modulating performance of the designed 2-bit digital coding metasurface. The 2-bit digital coding metasurface contains 48×48 digital elements, which can be divided into 8×8 super unit cells and hence each super unit cell is composed of 6×6 sub-elements. In one super unit cell, the state of each sub-element is identical. Hence, each super unit cell has four states “00”, “01”, “10” and “11”, which are indicated by four different color blocks, respectively, as shown in Fig. 3.

The simulated radiation beams of the 2-bit digital coding metasurfaces with four different coding patterns at 4.0 GHz are shown in Fig. 3. It is observed that under the coding Pattern One, the metasurface has one main beam that is directed to the *z*-axis. Under the coding Pattern Two, the main beam splitting into two main beams along the *y* direction (1-bit coding). We observe that the main beam has a deviation angle under the coding Pattern Three, because the digital elements have a gradient phase change along the *y* direction. In the case of coding Pattern Four, the main beam splits into two main beams along the *x* direction and these two beams are both reflected at oblique angles. The simulation results show that the designed 2-bit digital coding metasurface is capable of generating different radiation patterns for different spatial coding patterns.

In summary, we have proposed and designed an optically reconfigurable 2-bit digital coding metasurface, which is verified and analyzed through full-wave simulation. The designed 2-bit light-tunable digital element is able to realize four distinct phase responses to mimic “00” unit, “01” unit,

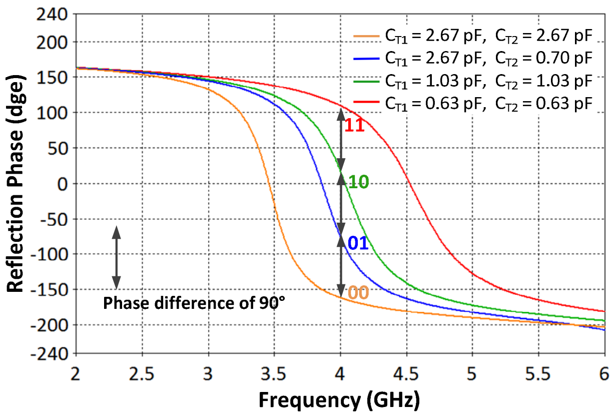

Fig. 2. Simulated reflection phases of the designed digital element under different values of varactor capacitance.

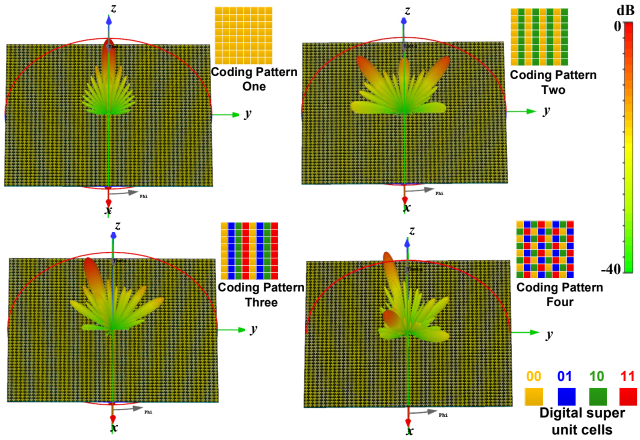

Fig. 3. Simulated far-field radiation patterns of the 2-bit digital coding metasurface with different coding patterns at 4.0 GHz.

“10” unit and “11” unit, respectively. The simulated far-field radiation patterns of the reflection-type digital coding metasurface further validate the feasibility of the light-controlled microwave digital coding metasurface.

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