

Article

Multifunctional Reflective Digital Metasurfaces of Arbitrary Base Based on Liquid Crystal Technology

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Abstract: This paper presents a multifunctional reflective digital metasurface of arbitrary base based on voltage tunable liquid crystal (LC). The reflective digital metamaterial can be multiplexed for different desirable functions by properly biasing the LC for different code patterns. Simulation results of three significant functions, beam steering with a steering elevation angle 27° at 75GHz, RCS reduction of at least 15dB along the incident direction, and beam shaping with different beam shapes have been presented to prove the concept.

Keywords: digital metamaterial; liquid crystal (LC); coding particle; beam steering; RCS reduction; beam shaping.

1. Introduction

Metamaterials [1] are a new artificial material with special electromagnetic properties which are inexistent in natural materials. The concept of metamaterials can be traced back to left-handed materials [2], or double-negative materials [3,4], which were first discovered by Veselago in 1968 [5]. In recent years, metamaterials have experienced a rapid development and been applied to realize tons of amazing functions such as cloaking [6], negative refraction [7] and perfect lens [8].

As a 2D metamaterial consisting of arrays of subwavelength microstructure elements, metasurface provides exhilarating capabilities for manipulating electromagnetic properties such as phase [9–11], amplitude [12] and polarization [13,14]. Compared with 3D bulk metamaterials, metasurfaces can significantly reduce losses [15,16] due to their ultra-thin thickness. It is well known that the electromagnetic properties of a device vary with its electrical size. As such, engineering unit cells with different electrical sizes properly and tailoring the required phase/amplitude distributions can make metasurfaces achieve versatile functionalities.

Recently, digital metamaterials [17,18], or in more particular, coding metasurfaces (CMS) [19], have been proposed for these purposes. CMS only consist of two types of unit cells, namely 0 and 1 elements. The phase difference between 0 and 1 elements is approximately 180° . By coding 0 and 1 elements, CMS allow for the realization of flat and efficient beam-shapers [20,21], beam deflectors [22], and holograms [23], to name just a few. In the pioneering research [18], “a subwavelength square metallic patch printed on a dielectric substrate” is exploited to realize the binary elements. Consequently, although CMS encoded with different patterns might correspond to different functions, instant switching of coding patterns for different functions is a very tough challenge.

In a variety of dynamically adjustable electromagnetic devices, tunable structure plays a crucial role for realizing dynamic performance. In particular, numerous tuning methods have been demonstrated for dynamic manipulation. One of the common methods uses switches to change the

electrical size of patches on the surface of unit cells. Applicable switches include PIN diode, varactor diode [24,25], microelectromechanical system (MEMS) device. Unfortunately, the binary characteristics of switches seriously limits the coding freedom of CMS. CMS might be very complicated and bulky. In addition, tuning switches usually cause parasitic resistances, electrostatic forces [26], losses [27], cost, etc., especially at higher frequencies.

Liquid crystal (LC), consisting of rod-like molecules, is a potential tunable dielectric due to its continuously tunable effective permittivity by applying a bias voltage to orient LC molecules [28-30]. It has become a promising research topic in electromagnetic community due to its experimentally confirmed liquid state, low loss, low profile and low cost, especially at higher frequencies. Material characterization of LC has been widely carried out in microwave and millimeter-wave frequencies. LC has been incorporated into a great deal of electromagnetic devices including phase shifter [31,32], reconfigurable antennas [33,34], and metasurface [35,36] to date.

In this article, we propose a tunable multifunctional reflective digital metasurface of arbitrary base based on voltage tunable LC. General coding elements or codes of specific base are designed by carefully designing geometrical configuration and selecting appropriate LC. Switching between custom applications corresponding to different coding patterns is made simple. As a proof of concept, we numerically demonstrate our CMS can be instantly tuned for beam deflection, RCS reduction and beam-shaping.

2. Materials and Methods

In this section, we will start by a brief description of the tunable multifunctional reflective digital metasurface of arbitrary base based on voltage tunable LC in terms of its concept, working mechanism, and design strategy.

2.1. Digital Metasurface

Different from the mechanism of general metasurfaces, the far pattern of a digital metasurface as shown in Fig. 1 is

$$f(\theta, \varphi) = \sum_{m=1}^M \sum_{n=1}^N \exp \left\{ j \left\{ \phi(m, n) + kD \sin \theta [m \cos \varphi + n \sin \varphi] \right\} \right\} \quad (1)$$

where θ and φ are the elevation and azimuth angles, $\phi(m, n)$ is the phase difference between reflected and incident waves arising from the digital coding particle, D is the periodicity in x and y .

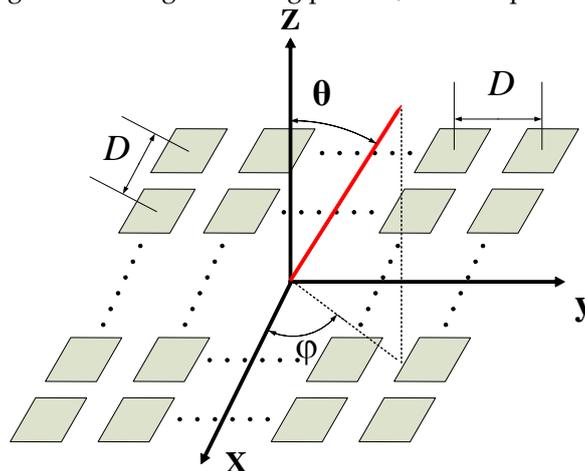


Figure 1. The far pattern of an digital metamaterial.

Obviously, in digital metasurface, the digital state $\phi(m, n)$ of particle (m, n) plays a crucial role. The digital metasurface can be multiplexed for different functions by properly changing $\phi(m, n)$ to achieve different far patterns.

Ideally, for a digital particle of base B ,

$$\phi(m, n) \in \left\{ \phi_i \mid \phi_i = \frac{i}{B} 360^\circ, 0 \leq i \leq B-1 \right\} \quad (2)$$

In recent researches, different digital states correspond to different geometries of passive coding particles or ON/OFF states of PIN diodes of active coding particles [17-19]. Obviously, PIN diode-based active binary particles can only achieve 1-bit CMS. On the other hand, although multi-bit CMS can be realized by applying passive multi-bit coding particles, each passive coding particle corresponding to a specific digital state has to be independently designed. The design process is therefore much more tedious. What's worse, it is impossible to multiplex a passive CMS once finalized.

2.2. LC-based Digital Particle of Base B

In this work, LC is introduced to develop active digital particles of base B and accordingly multifunctional reflective base- B digital metasurface for different applications. The LC exhibits different dielectric characteristics depending on different bias voltages. LC molecules are aligned parallel by utilizing a polyimide layer with no bias voltage applied, the LC shows the minimum permittivity $\varepsilon_{r,\perp}$, accordingly. At maximum bias voltage V_{max} , the effective permittivity of LC is $\varepsilon_{r,\parallel}$. Increasing the bias voltage would rotate the LC molecules and change the effective permittivity of LC continuously from $\varepsilon_{r,\perp}$ to $\varepsilon_{r,\parallel}$. In accordance, ϕ or equivalently the digital state of the active digital particle depends on the applied bias voltage.

By properly selecting LC and tuning the geometrical parameters of the digital particle, the digital particle will achieve maximum phase difference $\Delta\phi$ and B digital states if

$$\Delta\phi \geq \frac{B-1}{B} 360^\circ$$

2.3. LC-based Digital Metasurface Design

We propose an innovative reflective LC-based digital metasurface design based on a square unit cell, which comprises a top layer of quartz (relative permittivity of $\varepsilon_r=3.75$ and loss tangent of 0.0004), an arrow-type metallic patch, a bottom layer of LC, and a metal ground. The digital particle is supported by another layer of quartz below the metal ground. The geometry of the metasurface is illustrated in Figure 2.

The electromagnetic responses of coding particles are numerically simulated with unit cell boundary condition in commercially available software CST Microwave Studio. GT3-23001 manufactured by Merck Lab. [37] has been chosen in this study for its excellent tunability and low loss at higher frequencies ($\varepsilon_{r,\parallel}=3.2$, $\varepsilon_{r,\perp}=2.4$, $\tan\delta_{\parallel}=0.002$, and $\tan\delta_{\perp}=0.006$, $V_{max} = 14V$). There are 4 geometrical parameters for us to determine: periodicity P , patch angle θ , patch length L and patch width W . A series of parametric studies has been carried out to determine their values numerically.

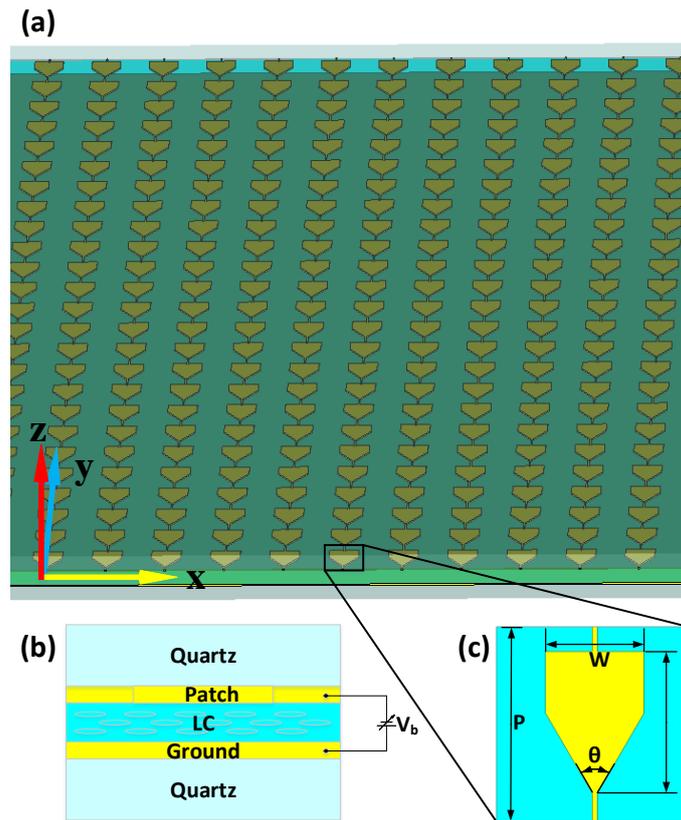


Figure 2. a) Schematic view of a reflective LC-based digital metasurface. The thicknesses of quartz and LC layers are 500 and 50 μm . b) Cross section of LC-based coding particles. c) Sketch of an arrow-type unit cell, $L = 1.5$ mm, $W = 1$ mm, $P = 2$ mm, and $\theta = 60^\circ$.

3. Results

The optimized values are $P = 2$ mm, $\theta = 60^\circ$, $L = 1.5$ mm, $W = 1$ mm. The corresponding simulated reflection phase and amplitude of an arrow-type unit cell for various effective dielectric constant values of the liquid crystal by applying bias voltage at normal incidence ($\theta=0^\circ$, $\varphi=0^\circ$) are shown in Fig. 3a & b.

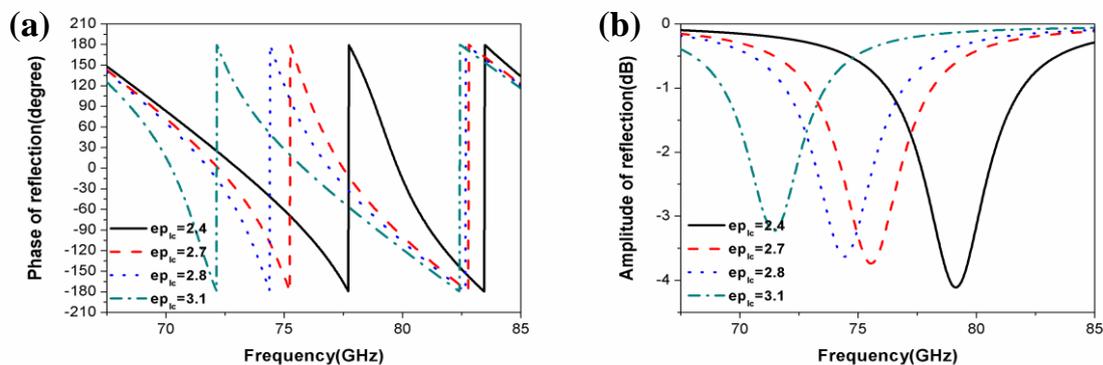


Figure 3. Broadband performance of the a) phases and b) amplitudes of reflections for the four coding particles from 67.5 to 85 GHz.

For demonstrating the concept, a full model of the reflective LC-based digital metasurface has been simulated.

3.1. Beam steering

Beam steering is one of the most common and significant applications for radio communication. The basic mechanism utilized in beam steering is phase gradient distribution:

In our study, the beaming direction

$$\theta \propto \arcsin\left(-\frac{1}{B}360^\circ / \beta d\right)$$

where B is the base for the digital particle, d is the distance between adjacent digital particles and β is the wavenumber. Therefore, θ can be tuned by changing B . Coding base $B=3$ or larger is absolutely necessary for phase gradient in digital metasurfaces.

In our design, the coding base $B=4$ is chosen for multiplexing our reflective LC-based digital metasurface. The four digital states 0, 1, 2, and 3 corresponding to phase difference 0° , 90° , 180° and 270° can be obtained by biasing the digital coding particles with different voltages. Under encoding with the "0123" coding sequence, the outgoing beam at 75 GHz is re-directed to 27° by our reflective LC-based digital metasurface as shown in Fig. 4.

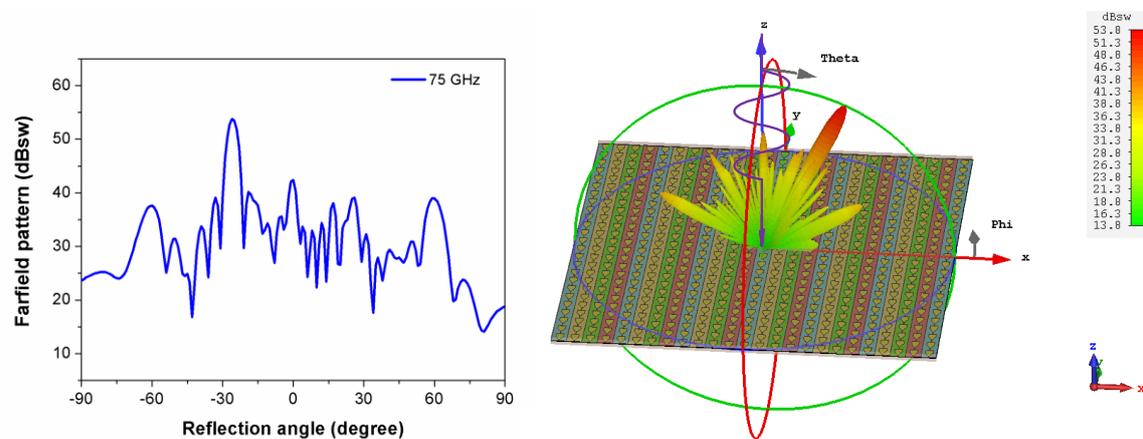


Figure 4. Simulated scattering patterns of the reflective LC-based digital metasurface encoded with the "0123" coding sequence at 75 GHz.

3.2. RCS reduction

RCS reduction is another valuable application for radio communication. By diversifying the incoming beam to as many outgoing beams as possible, the RCS at a specific direction can be significantly reduced, even if there is no loss in the digital metasurfaces.

Figure 5a, b illustrates the basic functionalities of coding metasurfaces with two interesting alternating coding patterns: "00110011/00110011..." and grid "00110011.../11001100...". The two digital states 0 and 1 corresponding to phase difference 0° and 180° . It can be clearly observed that the normally incident plane wave is diverted to two symmetrical directions by the first coding pattern (Figure 5a) and four symmetrical directions by the second coding pattern (Figure 5b), the RCS at the incident direction can be significantly reduced at least 15dB.

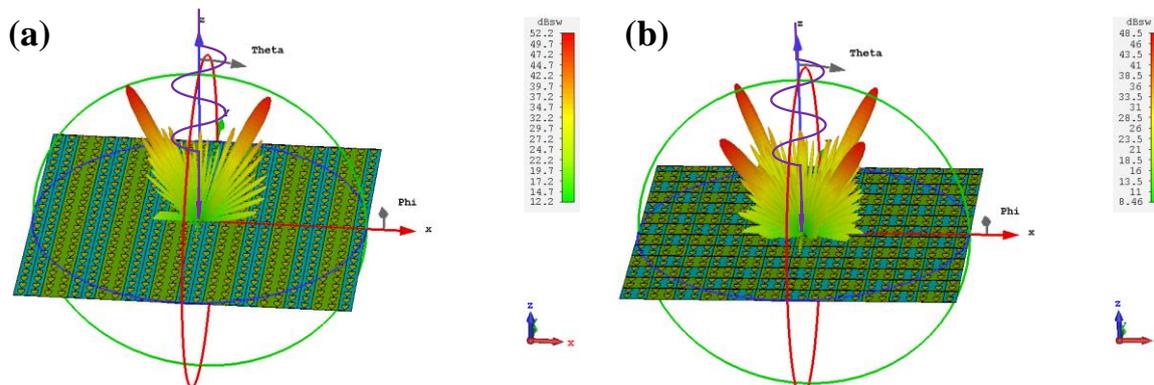


Figure 5. Schematic illustration of two classical functionalities of LC-based digital metasurface under the normal illumination, which are a) dual-beam and b) quad-beam generations, respectively.

3.3. Beam shaping

Beam shaping is also a significant application for radio communication. Figure 6 shows the theoretically calculated radiation pattern, in which some ring-shaped radiation patterns are clearly observed.

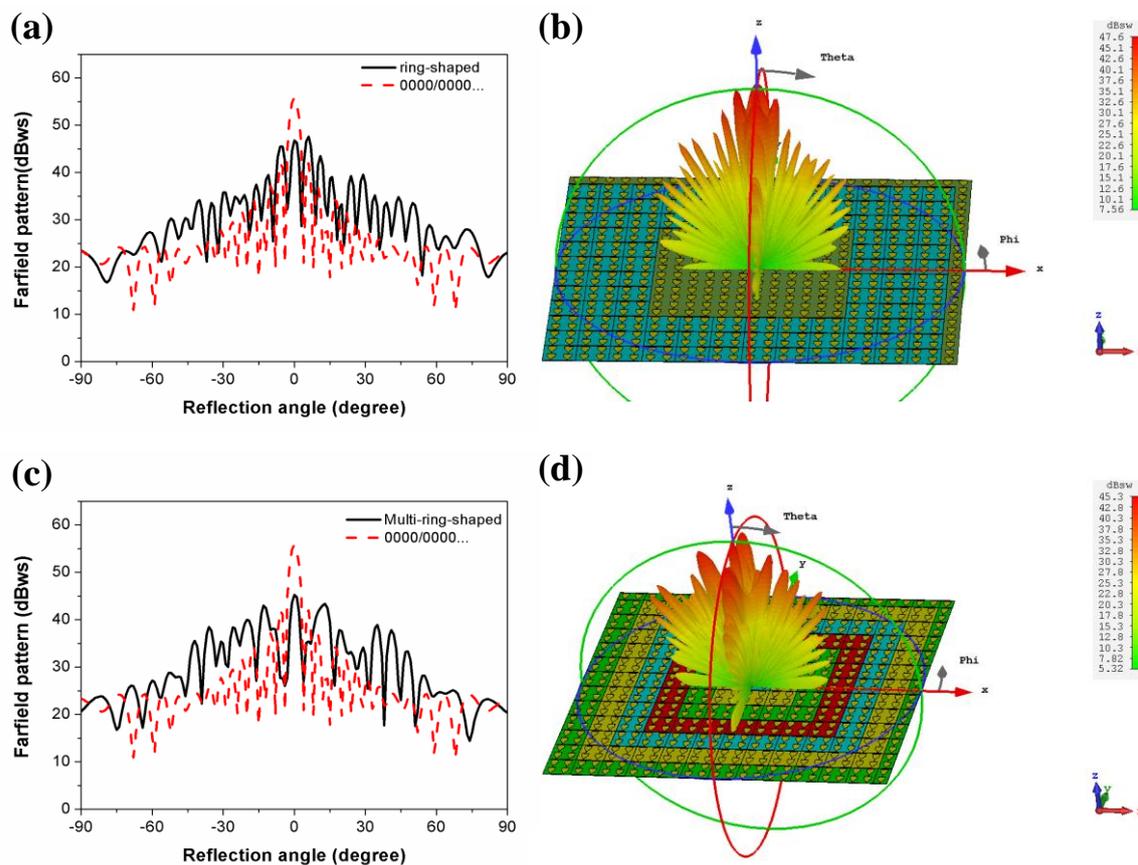


Figure 6. Simulated scattering patterns of the reflective LC-based digital metasurface encoded with the ring-shaped coding sequences at 75 GHz.

Simulation results of Figure 6a, c show that the beam width and beam direction of the reflective LC-based digital metasurface encoded with the ring-shaped coding sequences are different compared with that with “0000/0000...” coding sequence due to the distribution of different unit responders based on the special ring-shaped coding sequences.

4. Conclusions

In this paper, a multifunctional reflective digital metasurface of arbitrary base based on voltage tunable LC is proposed. It is composed of a superstrate of quartz, an array of metallic patches, a substrate of LC, and a ground. Encoding is realized by biasing LC to shift phase of incoming waves. The novel coding mechanism has been proven by numerical simulation.

Three representative applications of digital metasurfaces, namely beam steering, RCS reduction and beam shaping, have been presented to justify the novel digital metasurface. The coding freedom of the reflective LC-based digital metasurface is demonstrated very clearly.

It is regretful to point out that the desirable LC, GT3-23001 manufactured by Merck, is yet not available to the authors by the time this paper is submitted. Purchase has been in progress. Progress will be timely updated in following publications.

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