Microwave Vortex Beam Generation Using Holographic Artificial Impedance Surface

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***Abstract*—In this letter, a method has been proposed to convert the surface wave into an orbital angular momentum (OAM) vortex wave at a desired angle using sinusoidally-modulated holographic artificial impedance surface. A metallic patch with a grounded plane spaced by a dielectric substrate is selected as the unit cell of impedance surface, whose effective impedance can be characterized by changing the size of the metallic patch. As an example, a holographic impedance surface, which can generate a vortex beam with +1 order OAM mode deflecting to the direction of 30º from broadside at 17 GHz, has been designed and simulated.**

Keywords—vortex beam; orbital angular momentum (OAM); impedance surface; surface wave

I. INTRODUCTION

The orbital angular momentum (OAM) beam has a spiral phase wavefront, whose center is phase odd point with the strength of zero, so it is also called the vortex beam or the hollow beam. In the early works, the researches of OAM are mainly focused on the optical region. In 2004, Glasson et al. first proposed the applications of OAM to the optical communication, which have been confirmed by different OAM modes to realize multi-channel independent modulation in the same frequency transmission [1]. In 2013, Jia et al. reported a free-space communication scheme based on sidelobe-modulated OAM coding [2]. In 2015, Du Jing and Wang Jian experimentally proved that the obstruction-free encoding and decoding by using Bessel beam with OAM [3]. Generally, a plate with spiral phase is the most commonly used to achieve vortex beam at optics.

It has been proved that the OAM beams in different modes are orthogonal to each other without interference, which also provides a multiplexing technology for wireless communication technologies at low frequencies. In 2012, the first experiment of the wireless radio transmission applying the vortex beam has been reported, which verified that the OAM-carried electromagnetic (EM) waves can make a contribution to the increase of communication capacity without increasing the bandwidth [4]. The spiral phase plates [5-6] and the antenna arrays [7-8] are the common method used for generating vortex beam at microwave and millimeter wave band.

In this letter, we propose a method to generate an OAM vortex beam using a sinusoidally-modulated holographic impedance surface. According to the holographic technology, the surface impedance distribution is firstly achieved by the interference of the reference wave and the object wave. Then, an artificial impedance surface is designed to realize the required distribution of the surface impedance by changing the size of the unit cell, which is a subwavelength square metallic patch with a grounded plane spaced by a dielectric substrate. Hence, once the designed holographic impedance surface is excited by the same reference wave again, then the radiated wave will be the corresponding object wave. In our design, the reference wave is a cylindrical surface wave generated by a point source, and the object wave is a vortex beam with +1 order OAM deflecting to the direction of 30º from broadside at 17 GHz. In simulation, a dipole antenna is used as a feeding source to generate reference wave, so the radiated wave should be a desired vortex beam (object wave). The final simulated results verified that the cylindrical surface wave generated by the dipole antenna (reference wave) is efficiently converted to a vortex beam (object wave) with a good performance as expected.

II. THEORY DESIGN AND SIMULATION

According to the holographic theory, the holographic pattern is first achieved by calculating the hologram between the reference wave and the object wave, whose surface impedance distribution can be written as [9]

$$Zs=j[X+M\times \mathrm{Re}(\Psi^{*}_{ref}\Psi_{obj})] \qquad (1)$$

in which X is the average surface impedance, M is the modulation depth, Ψ_{ref} and Ψ_{obj} represent the reference wave and the object wave, respectively.

In our designing, we choose the cylindrical surface wave radiated from the origin (0, 0) as a reference wave, whose currents distribution is as follows:

$$\Psi_{ref}=\exp(-jk_0 n\rho) \qquad (2)$$

where k_0 is the free-space wavenumber, n is the effective surface refractive index, and ρ is the coordinate with respect to the center position.

The object wave is an OAM vortex wave deflecting from the broadside along the x-axis, whose fields distribution on the surface can be written as:

$$\Psi_{obj}=\exp(jk_0 x\sin(\theta)+jm\varphi) \qquad (3)$$

where θ is the deflecting angle, φ is angular coordinate, and m can be any integer value (positive or negative) that represents the helical mode of the OAM vortex beam.

In order to construct above impedance surface, a metallic patch printed over a grounded dielectric substrate is chosen as the unit cell to represent the distribution of the required holographic surface impedance as shown in Fig. 1(a), in which g varies from 0.2 mm to 1 mm, p=3 mm, t=1.57 mm. The dielectric substrate is the printed circuit board (PCB) of F4B, whose effective permittivity is 2.2 with loss tangent of 0.001. The simulated dispersion curves with respect to the size of the unit cell are demonstrated in Fig. 1(b), and then the surface impedance of the unit cell can be calculated according to the phase constant Φ shown in Fig. 1(b):

$$Zs = Z_0\sqrt{1-c^2\Phi^2/p^2w^2} \tag{4}$$

where c and Z_0 represent the speed of light and wave impedance in free space, respectively, and $w=2\pi f$ is the angular frequency. Once the above designed holographic impedance surface is again excited by the same reference wave, then the radiations generated by the holographic impedance surface will be the expected object wave [9].

As an example, we designed an impedance surface to convert the cylindrical surface wave into a vortex beam with +1 order OAM deflecting to the direction of 30º from broadside at 17 GHz. The finial designed holographic impedance surface is demonstrated in Fig. 2, whose dimension is $l*l$=243 mm*243 mm. A monopole antenna has been used as the feeding source located at the center of the impedance surface. The simulated S_{11} parameter is shown in Fig. 3 with low reflectivity, which means the high radiation efficiency. Figure 4(a) demonstrates a three-dimensional (3D) far-field radiation pattern at 17 GHz, which clearly shows that the strength of the radiation is zero at center of the beam. Figure 4(b) illustrates a two-dimensional (2D) radiation pattern in E plane (xoz plane) at 17 GHz, which shows that the beam deflects to the θ=30º as expected.

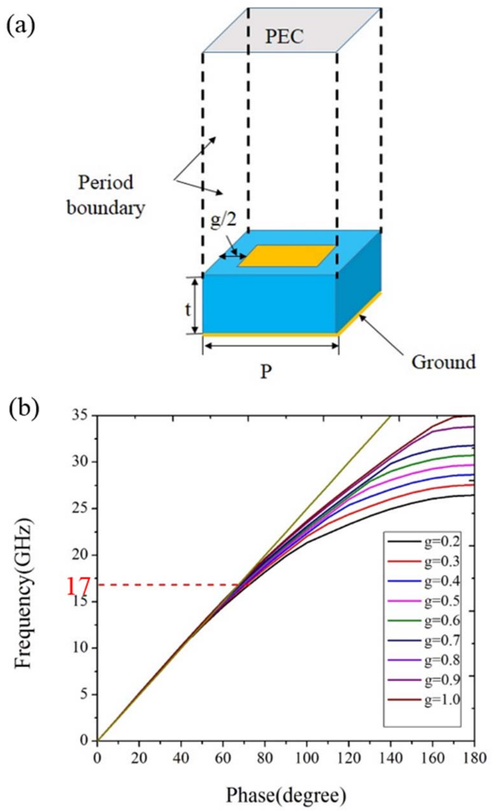

Fig. 1. (a) The unit cell of the impedance surface. (b) The dispersion curves with respect to the dimension of the metal patch.

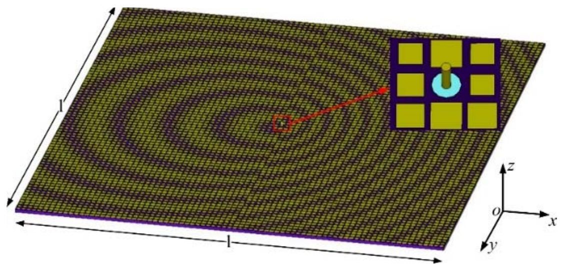

Fig. 2. The schematic of the proposed impedance surface.

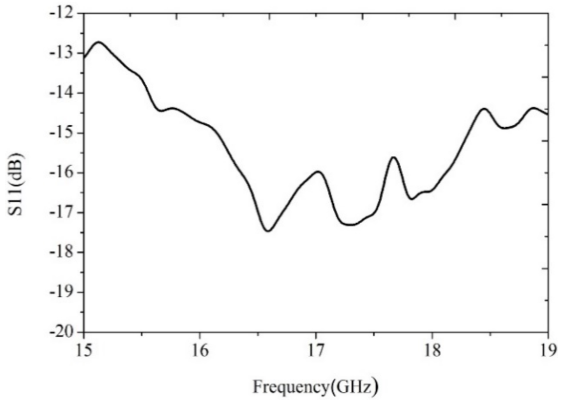

Fig. 3. The simulated S-parameters of the proposed impedance surface.

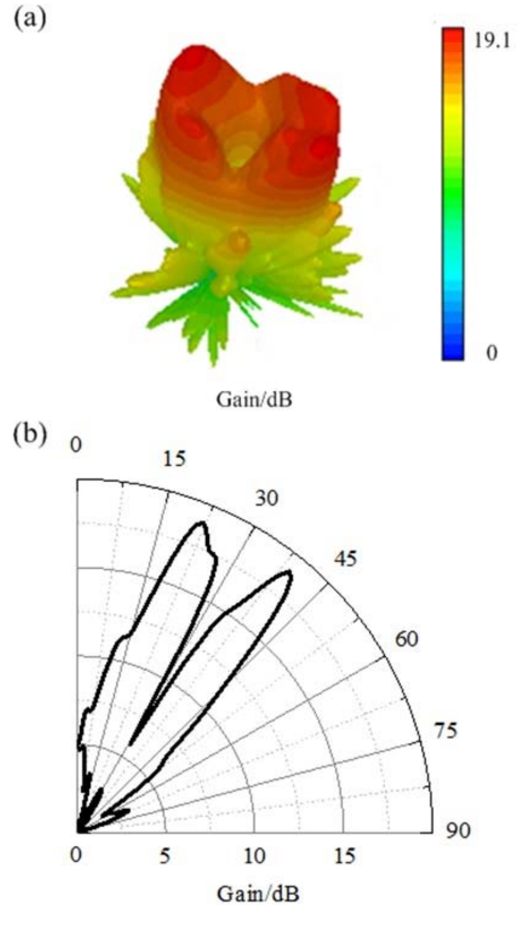

Fig. 4. The simulated far field radiation patterns (a) 3D, (b) 2D.

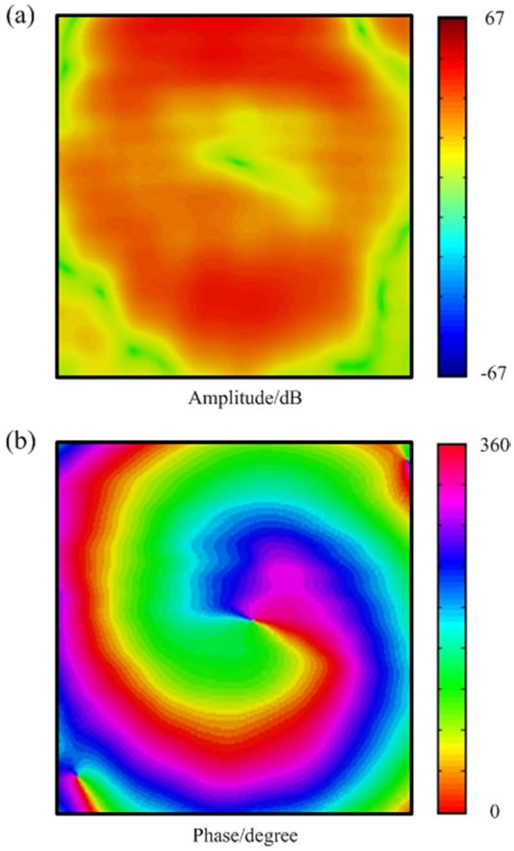

Fig. 5. The simulated near electric-field distribution (a) amplitude, (b) phase.

In order to further make sure that if the radiation beam is a OAM, we investigate the distributions of the near electric-field amplitude and phase of the radiations as shown in Fig. 5, which demonstrate an obvious characteristic of the +1 order OAM vortex beam with a middle-hollow amplitude and a spiral-pattern phase.

III. CONCLUSION

In this paper, we presented a method to generate a +1 order OAM vortex beam using holographic impedance surface. The holographic surface impedance pattern was first achieved by the interference of a cylindrical surface wave (reference wave) and an OAM vortex beam (object wave), and then the artificial holographic impedance surface was designed to construct the distribution of the surface impedance. When the designed impedance surface is excited by the cylindrical surface wave (reference wave) again, the radiation generated by the surface will be the desired vortex beam (object wave), which have been verified by the simulations. The proposed method provides a new solution to convert a surface wave to an OAM vortex beam.

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