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Low-profile microwave lens antenna based on isotropic Huygens' metasurfaces

Wang Zhengbin[1,2] (✉), Wang Haofang[1], Dong Zhuangli[1], Wu Zhihang[1], Zhang Yerong[1], Zhou Zhipeng[3]

1. School of Electronic Science and Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210023, China
2. State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China
3. China Electronic Technology Group Corporation Fourteenth Research Institute, Nanjing 210039, China

Abstract

An isotropic electromagnetic (EM) lens based on Huygens' metasurface is proposed for 28.0 GHz lens antenna design. The lens consists of a series of non-resonant and subwavelength metallic patterns etched on both sides of an ultrathin dielectric substrate. Both electric and magnetic responses are introduced to realize desired abrupt phase change and high-efficiency transmission for the secondary wavelets in the incident wavefront. Then, a substrate-integrated waveguide (SIW) fed patch antenna is combined with the lens as the primary feed to form a low-profile lens antenna system. The simulated and measured results coincide with each other, and demonstrate that the prototype realizes 8.8 dB~12.6 dB gain increment and low side-lobe levels over the bandwidth of 26.7 GHz~30.0 GHz. The novel design leads to a low-profile, light weight, and low-cost antenna solution in a wireless communication system.

Keywords microwave lens antenna, Huygens' principle, metasurface, low-profile

1 Introduction

Lenses are the key devices that known to steer EM energy to prevent it from spreading in undesired directions. Traditional lenses realize beam collimation by modulating optical path difference, which can be realized through engineering the dielectric lens' curvature, or designing the refractive index of the lens' spatial profile [1–4]. Generally, lenses with curve surfaces are bulky, heavy, and difficult to integrate with other components at microwave frequencies. As for the planar lenses fabricated with metamaterials through transformation optics skills, although they have continuously changing refractive index, the total height cannot be very thin. In recent years, two-dimensional (2D) lenses based on abrupt phase change became the research hotspot due to their much thinner thickness and lighter weight [3–10]. Such lenses consist of microscopically structured layers, and can be interpreted with Huygens' secondary wavelets principle. Because the total thickness of the lens is much smaller than operating wavelength, it is also called metasurface lens. Great efforts have been devoted to the design of subwavelength unit cells that are able to modulate the phases and/or amplitudes of the Huygens' secondary sources, such as V-shaped antennas [5], H-shaped antennas [6], dipoles [7], and Pancharatnam-Berry phase elements [8]. Recently, Li et al. [9] further designed an ultrathin planar lens antenna using cross and double cross rings, which can achieve pencil-shaped far-field radiation pattern with a simulation peak gain of 16.7 dB at 10.0 GHz. Hou et al. [10] fabricated a broadband (15 GHz~22 GHz) planar antenna composed of orthogonally I-shaped structures. Both of them have made meaningful exploration to the application of metasurface lenses. However, the above design methodology is based on the physical mechanism of EM resonance and polarization rotation, which restricts their operating bandwidth and transmission efficiency. In microwave engineering field, there is another approach to realize phase compensation for an in-phase far-field

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Corresponding author: Wang Zhengbin, E-mail: wangzb@njupt.edu.cn
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radiation, which is based on bandpass frequency selective surface (FSS) technology [11]. Nevertheless, in order to acquire large phase coverage, stacked parallel FSSs are needed, which make the fabrication processes complicated.

In this paper, firstly, we introduce an ultrathin metasurface lens operated at 28.0 GHz band, which is proposed for the fifth generation (5G) communications [12]. The *F*/*D* (*F* is the focal length and *D* is the diameter) of the lens is designed to be 0.34. The lens is composed of a set of isotropic, subwavelength structures with metallic patterns etched on both sides of a single-layer dielectric substrate. These construction elements can realize large phase coverage while maintaining high transmission efficiency. Full-wave analysis is performed with commercial software CST Microwave Studio (http://www.cst.com). Then, a SIW fed patch antenna is placed at the focal point of the metasurface lens as the primary feed to form a low-profile lens antenna system. The simulated and measured results of the proposed lens-antenna solution represents an innovative alternative to the existing antenna configurations for its thinner thickness, lighter weight and easier fabrication process.

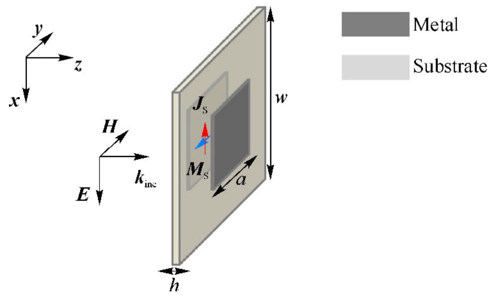
2 Lens design and simulation results

In order to obtain a broadband, highly efficient lens, each subwavelength element of the Huygens' metasurface should exhibits large phase coverage and high transmittance, and the phase difference between them should also be kept almost constant. Now consider an isotropic (polarization insensitivity), electrically thin sheet composed of a number of closely spaced metallic patterns etched on both sides of a single-layer dielectric substrate, as is shown in Fig. 1(a). Assuming that the metasurface is located at $|z| = 0$, and illuminated by a normally incident plane wave propagating along z direction, the transmitted wave can be considered as the EM field excited by the equivalent electric and magnetic currents ($\boldsymbol{J}_\mathrm{S}$ and $\boldsymbol{M}_\mathrm{S}$) in these elements. Therefore, the total EM field can be expressed as [13–14],

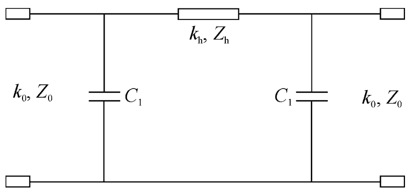
$$\left.\begin{aligned} \boldsymbol{E} &= Z_\mathrm{e}\boldsymbol{J}_\mathrm{S} \\ \boldsymbol{H} &= \frac{\boldsymbol{M}_\mathrm{S}}{Z_\mathrm{m}} \end{aligned}\right\} \tag{1}$$

where Z_e and Z_m are the penetrable surface electric impedance and magnetic impedance, respectively. If the electric and magnetic currents are well collocated, each element of the metasurface radiates a unidirectional field, and becomes a reflectionless Huygens' source, which will lead to very high transmittance.

From the viewpoint of transmission line (TL) theory, the periodically tiled microstructures can be modeled in a local sense as a homogeneous effective impedance sheet sandwiched between two semi-infinite TLs with characteristic impedance Z_0=377 Ω (normal incidence is assumed), as is shown in Fig. 1(b), where k_h and z_h are the wave number and the impedance of the metasurface, respecitivly. As known, the real part of the metasurface impedance represents the loss, while the imaginary part determines the phase shift. Both of them can be modulated through changing the metallic pattern on the metasurface. Therefore, through the accurate modeling of each unit cell, we can obtain the phase shift of the transmitted field by solving the relevant TL model.



(a) Three dimensional topology of a spatial-phase-shift unit cell



(b) Equivalent TL circuit model

Fig. 1 Prototype and the equivalent TL circuit model of a spatial-phase-shift unit cell

In order to acquire large phase coverage and high transmittance at the 28.0 GHz band, we designed a set of subwavelength unit cells with different metal patterns etched on both surfaces of an ultrathin dielectric substrate. Fig. 2(a) shows the detailed geometries of the six unit cells that are designed to realize abrupt phase changes from 0 to 200° in a wide frequency band. For cell 1: w=6.000 mm, h=0.813 mm, a_1=5.800 mm, b_1=2.000 mm, c_1=1.200 mm, d_1=1.600 mm. Cell 2: a_2=5.800 mm, b_2= 2.200 mm, c_2=1.600 mm. d_2=1.600 mm. Cell 3: e= 5.600 mm, f=3.200 mm, g=1.600 mm. Cell 4: r_1= 2.700 mm, l_1=0.400 mm. Cell 5: r_2=2.700 mm, l_2= 0.500 mm. Cell 6: r_3=2.800 mm, l_3=0.500 mm. In order to