A Simple High-resolution Imaging System Made of Metamaterials

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Abstract— High resolution imaging or super resolution imaging is always a hot topic in the field of artificial metamaterials. Since the conventional optical imaging lenses suffer from the so-called diffraction limit, the resolution is limited to half a wavelength. In order to break this restriction, many metamaterial-based superlenses and hyperlenses have been proposed and investigated. In this work, we present a simple high-resolution imaging system, which is composed of a magnifying lens and a planar focusing lens. The all-dielectric metamaterial magnifying lens is a modified hemispherical solid immersion lens (SIL) with impedance-matching layer, which is made of gradient-index materials. The high permittivity materials in the core of the magnifying lens can magnify evanescent waves that carry subwavelength imaging information. The magnified waves will propagate smoothly to the free space by the matching layer outside the core region. The planar focusing lens will gather the imaging information and produce the image. Therefore, the image formed by the focusing lens contains the magnified subwavelength-imaging information. The planar focusing lens is designed by geometry optics and cylindrically symmetrical. In the simulation, two point sources with a distance of less than half a wavelength are embedded in the core of the magnifying lens. Thus, the two point sources are imaged at the focus of the planar focusing lens with enlarged distance. Both of the magnifying lens and planar focusing lens are made of isotropic dielectric metamaterials, hence, such a simple high-resolution imaging system works efficiently in a broad band.

1. INTRODUCTION

To break Abbe's "diffraction limit" [1], a lot of theoretical and experimental works have been reported in recent decade [2–8]. In 2000, J. B. Pendry proposed a theory about "perfect lens" composed of negative permittivity and negative permeability, which can amplify the evanescent waves and realize the perfect imaging [2]. After that, metamaterial-based superlens [3, 4] and hyperlens [5–8] have been proposed and investigated to achieve the subwavelength imaging. Recently a dielectric metamaterial magnifier was proposed, it is capable of creating a virtual color image with far-field subwavelength information [9]. The magnifier is a gradient refractive index lens that can magnify the imaging target and enhance the resolution. The corresponding device was verified experimentally soon after that, which is also a modified immersion lens [10].

In this work, we propose and design a planar focusing lens, together with the modified immersion lens to form a simple imaging system in microwave band. The simple imaging system can magnify electromagnetic information of the object, and focus the image in the focusing plane. Both the magnifying lens and planar focusing lens are made of inhomogeneous isotropic dielectrics which is easier to implement. The simulation result shows that these two lenses can produce a magnified image in front of the planar focusing lens. It was verified that the simple high-resolution imaging system have excellent super-resolution performance in simulation from 12 to 16 GHz.

2. THEORETICAL ANALYSIS

The main component of our high-resolution imaging system is the magnifying lens. Because of the symmetry of lens structure, we construct a half spherical magnifying lens. The design of magnifying lens follows the coordinate transformation shown in Figures 1(a) and 1(b). The real and virtual spaces are denoted with (x, y, z) and (x', y', z') respectively. In order to construct the magnifying lens a two-fold transformation needs to be implemented. First, the region I' in the virtual space is compressed into region I in real space. Second, the annular region II' in the virtual space is stretched into region II in the real space.

When compressing region I' into region I, the transformation formula is

$$r = \frac{L}{R-t} r', \quad \phi = \phi' \tag{1}$$

To stretch the annular region II' into region II, the following transformation can be used

$$r = \frac{R-L}{t} \left(r' - R\right) + R, \quad \phi = \phi' \tag{2}$$

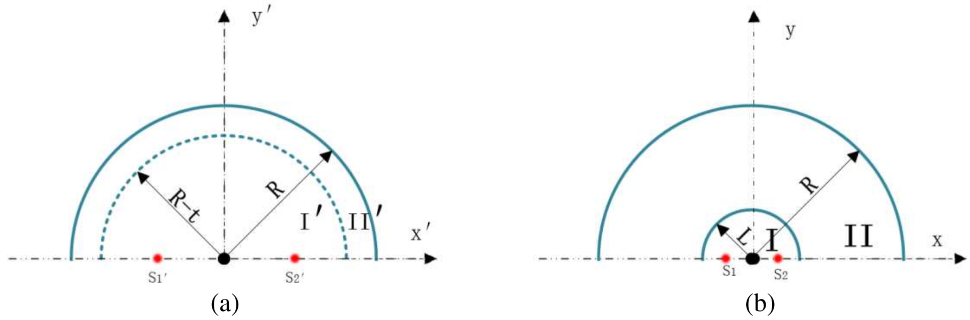


Figure 1: The schematic illustration of coordinate transformation for the design of magnifying lens. (b) The far-field patterns of two sources (s1 and s2) in the real space (a) is equivalent to two sources (s1' and s2') in the virtual space.

After some approximate treatment, the simplified refractive index of magnifying lens is

$$n(r) = \begin{cases} \frac{R}{L} & r \le L \\ \frac{R}{r} & L < r \le R \end{cases} \tag{3}$$

The planar focusing lens is composed of two parts, the core (Part A in Figure 2) and the matching layer (Part B in Figure 2). Two pieces of thin layer can achieve the impedance matching between the core and the free space. Both of the refractive index distributions of two parts are illustrated in Figure 2. The refractive index distribution of the magnifying lens is also shown in Figure 2, which is governed by Equation (3). The core of the magnifying lens is composed of high permittivity materials. The refractive index of the annular region outside the core decrease gradually from the center to the periphery. The distance between two point sources S_1 and S_2 are magnified by the magnifying lens, then the planar focusing lens will focus the imaging information and produce the magnified image. The magnification factor of our simple high-resolution imaging system can be adjusted according to specific case. In this work, we set the magnification factor as four to demonstrate the amplification characteristic of high-resolution imaging system.

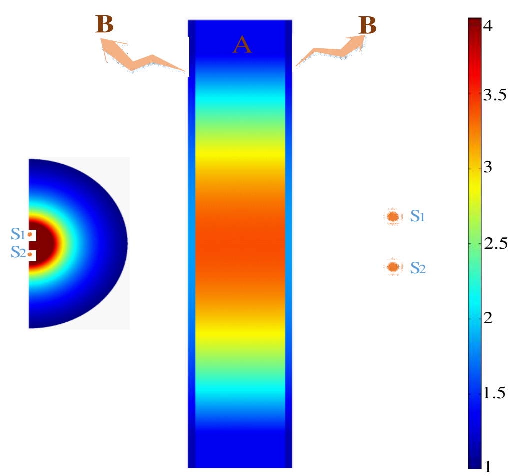
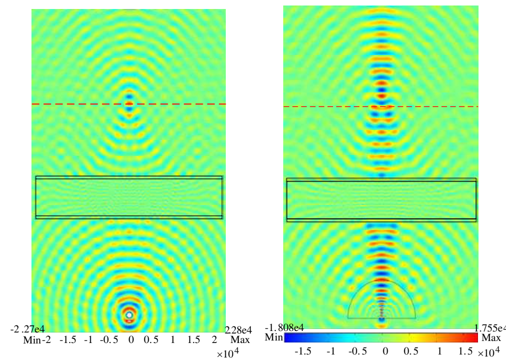


Figure 2: The refractive index distribution of magnifying lens and planar focusing lens. The distance of two point source S_1 and S_2 will be magnified in the imaging plane.

3. NUMERICAL DEMONSTRATION OF HIGH RESOLUTION IMAGING

To verify the performance of the designed high-resolution imaging system, numerical simulations are made by using commercial package, COMSOL Multiphysics. The simulation results are illustrated in Figure 3. We set the distance of the sources as 7 mm and free space wavelength $\lambda_0 = 21.4$ mm. It can be seen from the date that the distance of sources is smaller than the half-wavelength. It is obvious that two sources cannot be separated in the far-field image plane. Figure 3(a) shows the simulation result without the solid immersion lens. The size of Part A in the planar focusing lens is 78 mm ∗ 450 mm, Part B is set to be 6 mm ∗ 450 mm. The planar focusing lens is designed using the theory of geometry optics [1]. By phase compensation the lens can gather the information and then reproduce them in the imaging plane, which is represented by the red dotted line in Figure 3(a).

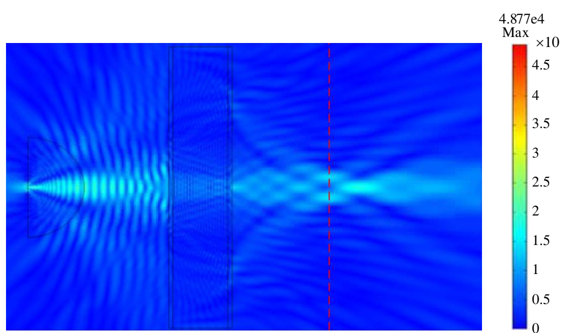


(a) (b)

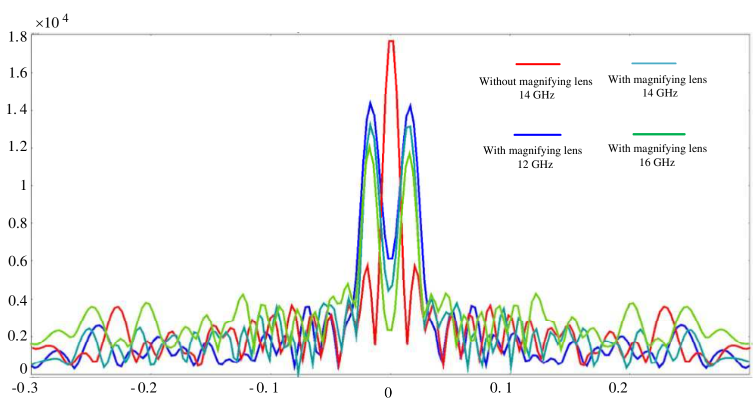
Figure 3: The electric field distribution (a) without and (b) with magnifying lens.

In Figure 3(b), the electric-field distribution of two sources with the magnifying lens is illustrated. We set $R = 80\,\text{mm}$, $L = 20\,\text{mm}$ and the free space wavelength $\lambda_0 = 21.4\,\text{mm}$. The parameters of the planar focusing lens are the same as the above. By observing the electric field distribution, two sources are clearly separated comparing with Figure 3(a).

In order to further illustrate the effect of our simple high-resolution imaging system, we analyze the magnitude distributions of the electric fields. In Figure 4(a), two sources are clearly focused on the red dotted line. To validate the broadband feature of our system, we make the similar simulations at the wavelength of 25 mm, 21.4 mm and 18.75 mm. Then the magnitudes of electric



(a)



(b)

Figure 4: (a) Distribution of the magnitude of electric field; (b) The magnitude of electric fields along the red dotted line under four different cases.

field on the red dotted line are shown in Figure 4(b). The red line in Figure 4(b) is the simulation result without the magnifying lens. Only one peak represents that two sources cannot be separated. The lines of other three colors are the simulation results at the wavelength of 25 mm, 21.4 mm and 18.75 mm with the magnifying lens, respectively. All of them have two peaks and the distance between them is about four times long of the real distance between the two sources. It means that our simple high-resolution imaging system has excellent super-resolution performance from 12 to 16 GHz.

4. CONCLUSION

In this paper, we propose a high-resolution imaging system in two dimensions. The simulation result demonstrates that imaging system can work well in a broadband. We will investigate the high-resolution imaging system in three dimensions in near future.

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