

Design of transmissive lens with nearly 100% efficiency by using Huygens metasurface

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Abstract. We proposed a high-efficiency meta-surface with a parabolic phase distribution that can focus a plane wave to a point image in transmission geometry. For realizing the predicted effects, we use the meta-atoms with 100% transmission to make it. Then we operate the simulation in the CST Microwave Studio to perform the focusing characteristic. The results show that the maximum efficiency is up to 90.6% at 10GHz and the half-power bandwidth is 31.8%, which is better than other previous works.

1. Introduction

Until now, Meta-surfaces (MS) have been a research spot for their electromagnetic (EM) control, EM integration, low cost and easy fabrication [1-5]. Typically, one of the most important applications for meta-surfaces is to realize the super lens which could transform the plane wavefronts into a focusing spherical wavefronts, inspired by Pendry's work [2]. Besides, what utilize the phenomenon of reversible transmission of light or EM wave to design the lens antenna with high gain has been successful in many researches [6-10]. Consequently, there has been more expectation for designing a lens with high performance.

Therefore, many scientists and engineers are endeavored for improving the performance of lens [11-21]. For instance, ultrathin flat MS without impedance mismatch problems in reflection geometry, working in the microwave regime, have been engineered, which makes the lens can focus efficiently [11]. What's more, it is designed and experimented that a lens in reflection geometry with 91% efficiency [12]. However, a lens with very high efficiency in transmission geometry is more useful in practice. Unfortunately, there have been minority of designs to achieve the goal in recent years, for others' focusing efficiency used to be less than 70% [16-20].

In this paper, we use Huygens meta-surface (HMS) to improve the focusing efficiency of transmissive lens. Huygens meta-surface can exhibit both electric and magnetic responses, and it was succeeded in obtaining anomalous refraction with high-efficiency in a recently paper, nevertheless, it did not apply to improve the performance of lens in previous works [21, 22]. Thus, for application to lens, we rigorously prove that achieving the 100% transmission coefficient with arbitrary phase should satisfy the certain criterions, and the theoretical result coincide well with the result by using finite-difference time-domain (FDTD) simulation in Section II. Then the transmissive lens is engineered by such meta-atoms with 100% transmission. Obviously, these meta-atoms must meet the parabolic-phase profile in Section III. Finally section IV concludes the whole paper.



2. The 100% transmission mechanisms of the proposed meta-atom

It can be easy to achieve 100% transmission when using Huygens metamaterial which can exhibit both electric and magnetic responses [21]. In this paper, we utilize three types of meta-atoms to achieve the phase coverage up to 360. For demonstrating the 100% transmission, we select two types of meta-atoms to illustrate shown in figure 1 (a) and figure 1 (b). The substrate is F4B with $\epsilon_r=2.65+0.001i$, 1.5mm thickness. We can see from figure 1 (c) and figure 1 (d) that the transmission amplitude of two selected meta-atoms are 100% and the phase is 21.8 deg. and -143.8 deg. (or 216.2 deg.), respectively, which satisfy the parabolic transmission-phase distribution. The serial number of the meta-atoms in figure 1 can be seen in figure 2 (d).

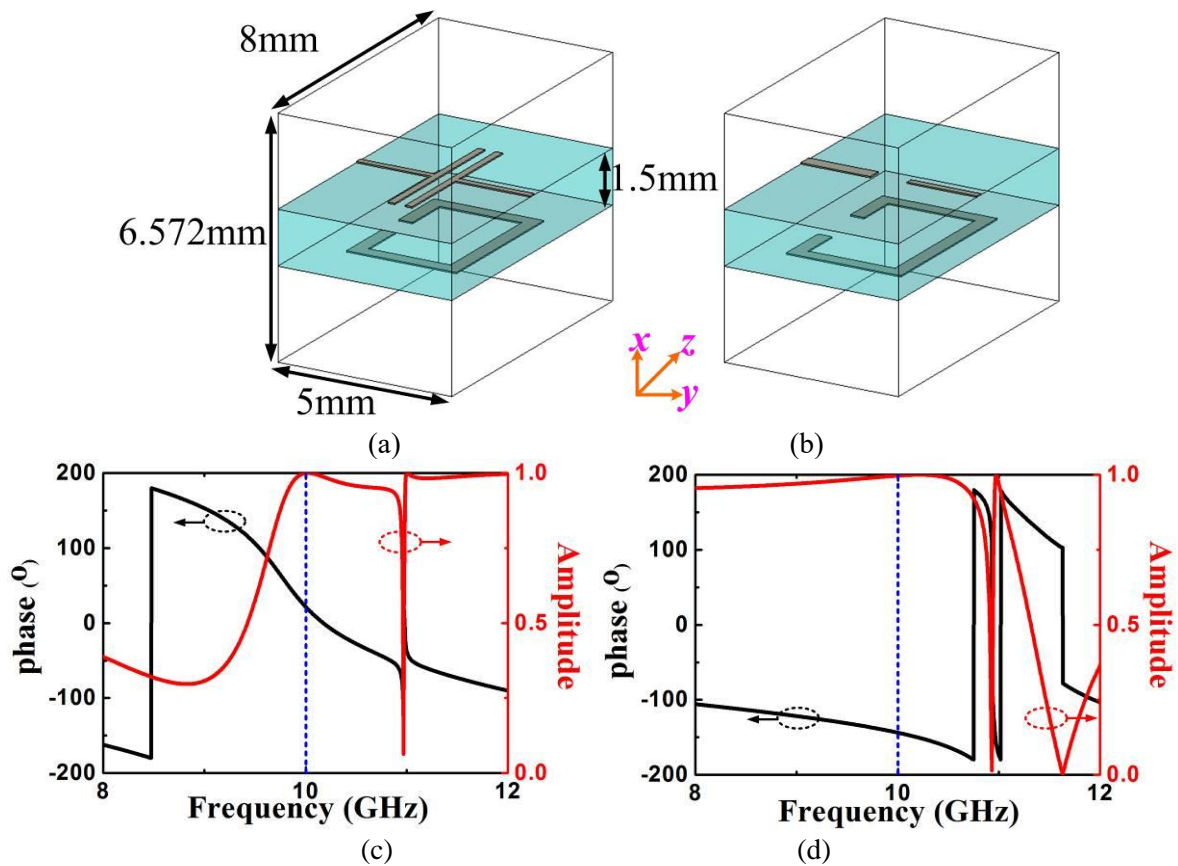


Figure 1. (a) Schematics of meta-atom 19, (b) schematics of meta-atom 26, (c) transmission amplitude and phase distribution of meta-atom 19, (d) transmission amplitude and phase distribution of meta-atom 26.

3. Design and Analysis of the nearly 100% efficiency lens

In this part, we use the 100% transmission coefficient meta-atoms for designing the nearly 100% efficiency lens. Thus, the HMS should satisfy the following parabolic refraction-phase profile for the incident electric and magnetic (EM) wave with propagation along z-direction and E field parallel to y-direction.

$$\varphi(x, y) = k_0 \left(\sqrt{x^2 + f^2} - f \right) + \varphi_0 \quad (1)$$

Where $k_0=2\pi/\lambda_0$ is the propagation constant in free space, f is the focal distance, φ_0 is reference phase, λ_0 is the wavelength at the 10GHz. It is known that the focusing point can be arbitrary, thus, the focal distance $f=2\lambda_0=60\text{mm}$ is selected for generality.

Figure 2 (d) shows the transmission amplitude of each meta-atom and the transmitting phase distribution of the proposed HMS. Besides, the simulated one is calculated by FDTD and the theoretical one is obtained by MATLAB and we can see that all transmission amplitudes are more than 0.9, even to 1, which coincide well with the theoretical one. The refracted-phase distribution also agrees very well.

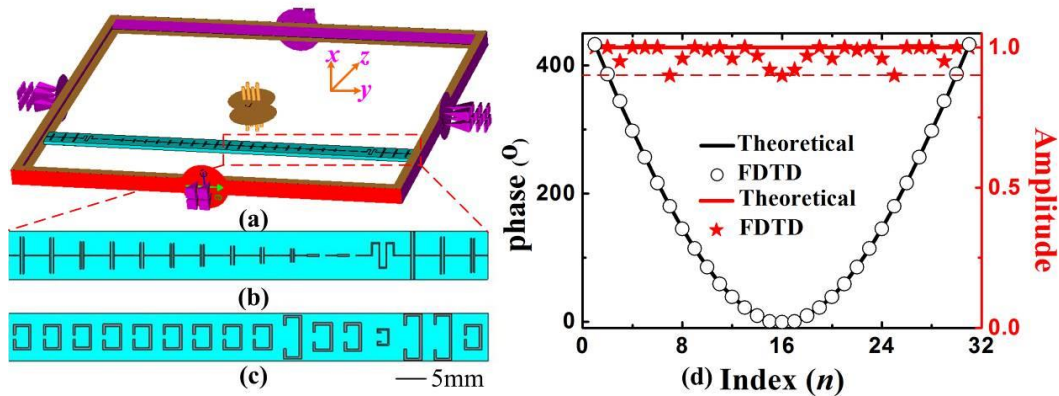


Figure 2. (a) Schematics of simulated environment in CST Microwave Studio, the orange represents periodic boundary, the violet represents open (add space) boundary, the red represents plane wave port (y-polarized electric field and z-direction propagation) (b) Top view and (c) bottom view of the half structures. “—— 5mm” in the lower right is the dimension scale, (d) transmission amplitude including theoretical results (red line) and FDTD results (red star structures), as well as refracted phase distribution including theoretical results (black line) and FDTD results (black circle structures), the red dash line present the amplitude is 0.9.

Then, we can complete our 100% efficiency HMS. figure 2 (a) depicts the simulated environment of the proposed meta-surface in CST Microwave Studio by using periodic boundary. Here, we intercept the half of the structures to describe the detailed size of each meta-atom, just showed as the figure 2 (b) (top view) and figure 2 (c) (bottom view).

For exhibiting the focal characteristic, we have been completing the simulation. Figure 3 depicts the simulated electric field amplitude $\text{Re}(E_y)$ patterns at 10 GHz in yoz -plane. Most importantly, EM wave in front of the HMS is very flat, which means almost no reflection. Figure 4(a) shows power distribution along the intersection line of yoz -plane at 10GHz which is good supplement for figure 3. For making sure the location of focal point, we retrieve the power distribution along line $y=0$ just shown in figure 4 (b), which show the simulated maximal power converge to the focal line located at $z=63\text{mm}$, which can be explained by the finite-size effect.

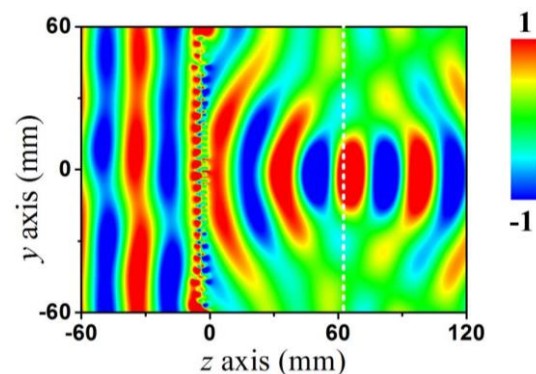


Figure 3. Simulated normalized electric field amplitude $\text{Re}(E_y)$ patterns at 10 GHz in yoz -plane, the white dash line present the focal line.

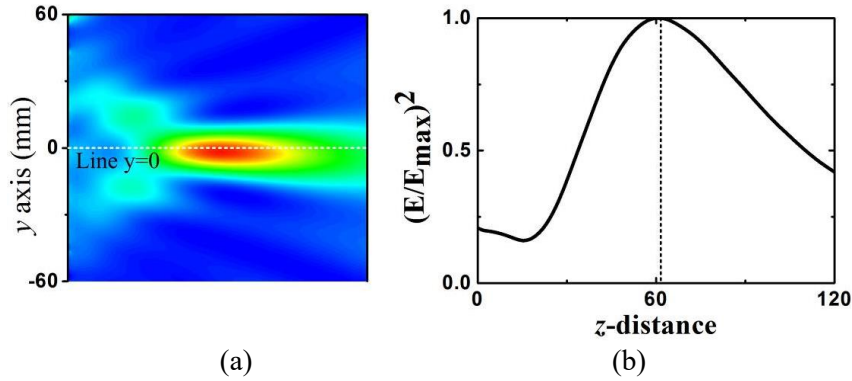


Figure 4. (a) Simulated power distribution at 10GHz, the white dash line present line $y=0$, (b) Normalized power distribution along line $y=0$.

For calculating the focusing efficiency, we define that P is the total power, P_f is the focusing power, P_s is the scatter power, P_r is the reflection power, P_t is the transmission power, t_i represent the transmission coefficient of meta-atom (i is the serial numbers can be seen in figure 2 (d)). Thus, we can obtain their relationships as following.

$$P = P_f + P_s + P_r \quad (2)$$

$$P_t = P_f + P_s \quad (3)$$

$$\eta_1 = \frac{P_f}{P_t} \quad (4)$$

$$\eta_2 = \frac{P_t}{P} = \frac{\sum_{i=1}^n t_i}{n} \quad (5)$$

Where the η_1 is the focusing efficiency of transmission part, η_2 is the transmission efficiency which is equal to the average of all meta-atoms' transmission coefficient. We can know that the reflection power P_r is negligibly small for the proposed HMS has almost no reflection. So power P_r can ignore. Here we define that η is the total focusing efficiency. So we can immediately calculate η by

$$\eta = \frac{P_f}{P} = \frac{P_f}{P_t} \times \frac{P_t}{P} = \eta_1 \times \eta_2 \quad (6)$$

Equation (6) tells us that we can divide into two parts to get the efficiency η . One part is calculating η_1 , which we can retrieve the power distribution of the focal line to obtain, just shown in figure 6 (b). Another part is calculating η_2 , which we can immediately get from figure 2, and the numerical value is 0.97 according to Eq. (5).

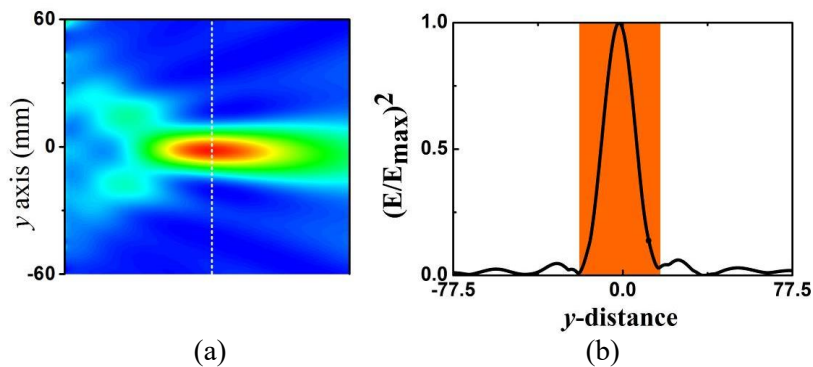


Figure 5. (a) Simulated power distribution at 10GHz, the white dash line present focal line, (b) normalized power distribution along corresponding focal line.

The orange part in figure5 (b) presents the focusing power in the transmission part, others present the scattering power. Thus we can get the η_1 is 93.4% by Eq. (4). Therefore, the total simulated focusing efficiency η is 90.6% at 10GHz by Eq. (6), which is higher than others [16-20]. The total focusing efficiency over the operating frequencies is shown in figure 6. We can see that the half-powered bandwidth is 31.8%.

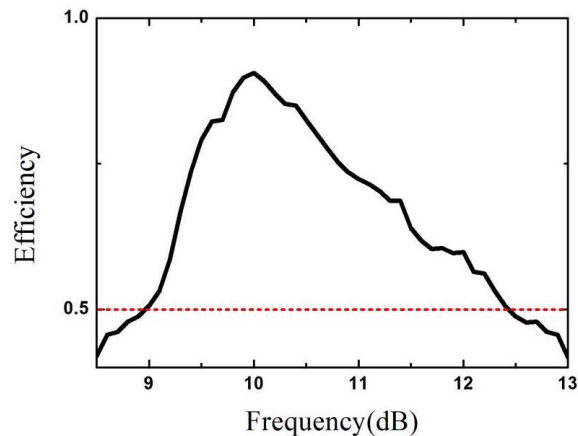


Figure 6. (a) Simulated efficiency of the focal HMS against the frequency. The red dash line presents that the efficiency is 0.5.

4. Conclusion

In summary, we show that the microwave lens with nearly 100% efficiency can be realized by using Huygens meta-materials with 100% transmission characteristic. The results show that the maximal focusing efficiency reaches 90.6% at 10GHz higher than other previous work, and half-power bandwidth reaches 31.8%. In general, this strategy to achieve the high efficiency of lens is proposed and demonstrated.

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