The Analysis of E-plane Metal Lens in Beam Forming

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Abstract. In communication system, for the different application, it's need antenna provide different pattern, such as cosecant squared pattern, The antenna with cosecant square pattern can rapidly find object, and cover the larger effective region, so the antenna which have cosecant squared pattern is widely used in the radar system. This article will analyze how to use E-plane metal lens to realize beam forming, and designed a kind of E-plane metal lens which can realized cosecant squared beam forming in 9.5GHz.

Introduction

Metal-plate lens is consists of a series of metal plates, Metal-plate lens can be divided into E-plane metal lens and H-plane metal lens, and the E-plane metal lens is a kind of accelerating lens, the H-plane metal lens is a kind of delayed lens, That is to say when the electromagnetic wave propagates in the E-plane metal lens, the phase velocity v_g is greater than v_0 which is the phase velocity in the free space, and when the electromagnetic wave propagates in the H-plane metal lens, the phase velocity v_g is less than v_0 which is the phase velocity in the free space. So the phase distribution of the electromagnetic wave can be changed by using the characteristic that the metal-plate lens can change the phase velocity. In antenna applications, this feature can be used to obtain the desired phase distribution. Reference [3] using metal-plate lens realized beam forming for the horn antenna's elevation plane, Reference [4] using metal-plate lens realized beam forming for the horn antenna's horizontal plane. This article will put aside all the specific applications, analysis and explain why the E-plane metal lens can realize beam forming, and designed a kind of E-plane metal lens which can realized cosecant squared beam forming in 9.5GHz.

1. The Analysis of Beam Forming

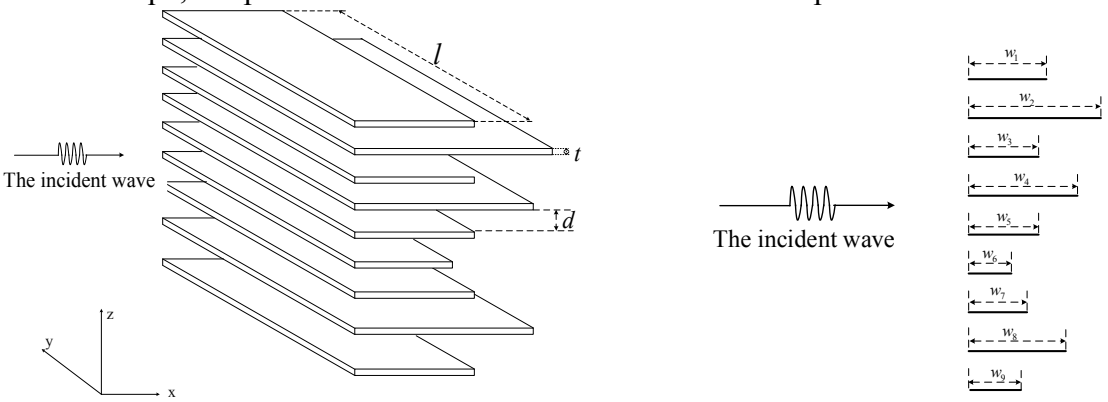
As shown in Figure. 1, the linearly polarized plane electromagnetic wave is illuminated on the E -plane metal lens, the polarization direction of electromagnetic wave is y, and the propagation direction of electromagnetic is x, it can be expressed as Eq. 1. The E-plane metal lens is composed of 9 metal plates, the 9 metal plates have the same size in the y and z direction, the size of the 9 metal plates is not the same in the x direction, and the distance between the two metal plates is the same. In order to make the electromagnetic wave through the E-plane metal lens, the distance between the two metal plates must be greater than $\frac{\lambda_0}{2}$, λ_0 represents the wavelength of electromagnetic waves in free space.

$$\vec{E}_i(x) = \vec{e_y} E_m e^{-j\beta x} . \tag{1}$$

When the electromagnetic wave propagates in the E-plane metal lens, the phase velocity v_g is greater than v_0 which is the phase velocity in the free space, and v_g can be expressed as Eq. 2.

$$v_g = \frac{v_0}{\sqrt{1-(\frac{\lambda_0}{2\cdot d})^2}}. \tag{2}$$

In the Eq.2, d represents the distance between the two metal plates.



(a). (b).

Fig. 1 (a). Three dimensional graph the structure of E-plane metal lens;
(b). two dimensional graph the structure of E-plane metal lens.

The E-plane metal lens which is shown in Fig.1 can be viewed as a radiation structure. The amplitude of the electromagnetic wave that between the n and the n+1 metal plate can be recorded as A_n, and the phase can be recorded as φ_n, so the E-plane metal lens which shown in Fig. 1 can be viewed as an antenna array composed of 8 antenna elements, as shown in Fig. 2. So it can realize beam forming in the x-z plane.

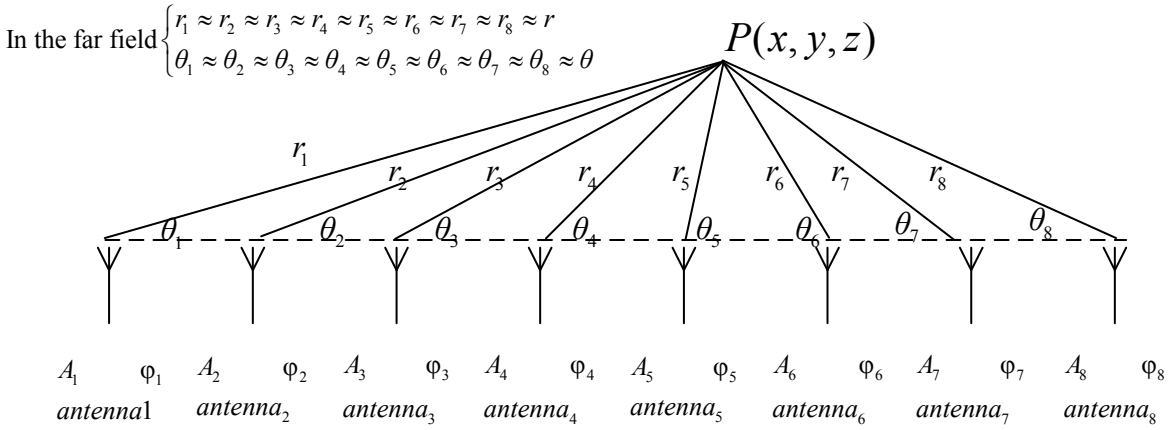


Fig. 2 The antenna array

For the antenna array shown in the figure, the far-field distribution can be expressed as Eq. 3.

$$\begin{aligned} E(r) &= j\frac{\omega\mu A_1}{4\pi r}e^{-j\varphi_1} + j\frac{\omega\mu A_2}{4\pi r}e^{-j(\varphi_2+kd\cdot\cos\theta)} + \ldots + j\frac{\omega\mu A_8}{4\pi r}e^{-j(\varphi_8+7\cdot k\cdot d\cdot\cos\theta)} \\ &= j\frac{\omega\mu}{4\pi r}\sum_{i=1}^{8} A_i e^{-j[\varphi_i+(i-1)k\cdot d\cdot\cos\theta]} \end{aligned}. \tag{3}$$

When the electromagnetic wave passed through the E-plane metal lens, the phase distribution of the electromagnetic wave was changed, for the electromagnetic wave between the n and the n+1 metal plates, the changed phase can be expressed as Eq. 3.

$$\Delta p = (v_g - v_0).\min(w_n, w_{n+1}) = \frac{v_0}{\sqrt{1-(\frac{\lambda_0}{2\cdot d})^2}}. \tag{4}$$

From Eq. 4 can be seen that when the electromagnetic wave passed through the E-plane metal

lens, the changed phase amount related with the distance between the two metal plates and the width of the metal plate, so the desired phase distribution can be obtained by adjusting the distance between the two metal plates and the width of the metal plate. For the electromagnetic wave which the amplitude distribution is known, in order to get the desired far-field pattern distribution, we can obtain the required phase distribution from Eq. 3, and then we can obtain the size of the E-plane metal lens from Eq. 4. But unfortunately, when the number of metal plates along the z direction is not infinite and the size of the metal plate along the x direction is not infinite, there is a strong coupling effect between metal plates, Therefore, the amplitude distribution of electromagnetic wave will be influenced by the size of the metal plates and the required phase distribution is difficult to calculation.

2. The Design of E-plane Metal Lens

Because of the strong coupling effect between the metal plates, the design difficulty of the E-plane metal lens is increased, In order to design the required E-plane metal lens quickly, This article will no longer pay attention to the amplitude phase distribution of the near field, and set the far field distribution as optimization goal, and using high frequency electromagnetic simulation software HFSS to optimize the E-plane metal lens. The specific design method is as follows: 1. Build the model; 2. Set the optimization goal; 3. Adjust the width of each metal plate until the simulation results meet the requirements. The design process is shown in Fig. 3.

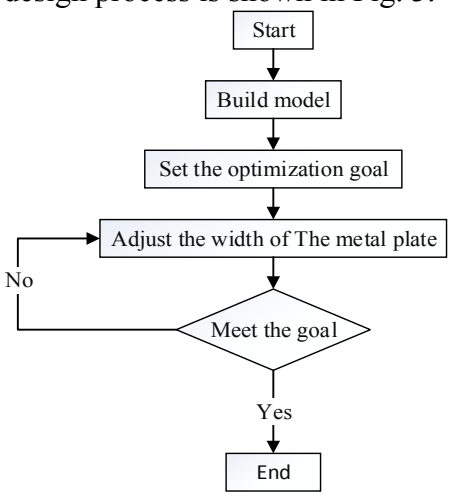


Fig. 3 the E-plane metal lens design process

Using the above mentioned method, we can get the size of E-plane metal lens which can realize cosecant squared beam forming, the working frequency of the designed E-plane metal lens is 5GHz. The size of E-plane metal lens is shown in table. 1.

Table. 1 The size of E-plane metal lens

variable	Value/mm	variable	Value/mm
t	0.5	w_4	45
d	19.5	w_5	45
l	100	w_6	45
w_1	20	w_7	45
w_2	35	w_8	60
w_3	40	w_9	45

Fig. 4 is the far field distribution of the designed E-plane metal lens which the operating frequency is 5 GHz. From Fig. 4 we can see the simulated results are in good agreement with the goal (The cosecant squared distribution), compared with the goal curve, from 0° to 36° the fluctuation is less than 3dB, from 0° to -40 °, the sidelobe is less than -10dB.

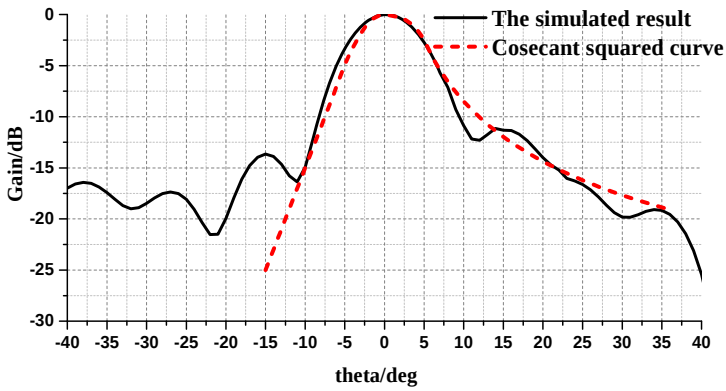


Fig. 4 The far field distribution and the Cosecant squared distribution

3. Conclusion

Using E-plane metal lens to realize cosecant squared beam forming was studied, and a method for quickly design the required E-plane metal lens was proposed in this paper. The other pattern's beam forming can also be realized by using E-plane metal lens. In the practical application, we can design the suitable E-plane metal lens according to the specific application.

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