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Very Thin Artificial Dielectric Lens Antenna Made of Printed Circuit Board

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Abstract A flat lens antenna is fabricated from artificial dielectrics, which is a collection of thin metal disks aligned in a lattice structure. The effective permittivity increases toward the center of the lens by increasing the diameter of the disks. The feasibility is shown by the fact that the gain is improved by 2 to 3 dB around the designed signal frequency when the lens is added in front of the primary radiator.

1. Introduction

Lens antennas have a long history of study. Considering optical lens, it is self-evident that a convex profile of dielectrics should converge the electromagnetic waves. It is also clear that the dielectric lens is too heavy as it is to compete with a reflector antenna. Hence, there have been many inventions to reduce its size and weight, such as a Fresnel lens antenna and artificial dielectric lens antenna.

The present study is along the line with the artificial dielectric antenna. But the distinct difference is its shape. It is not convex but flat. The permittivity, instead of the thickness, increases toward the center of a disk-shaped lens. Thus it should be quite convenient to fit it in the TX system.

The spacial variation of permittivity is attained by controlling the size of unit particles (artificial molecules). Since we fabricate the lens by stacking the printed circuit boards with photo-etched metal pattern, the size control is easily carried out.

We will simply show the feasibility of a flat lens antenna, by comparing the received signal intensity with and without the lens between the transmitting and receiving antennas. More comprehensive characteristics will be elucidated in the near future.

2. Effective permittivity

Effective permittivity is calculated by comparing the numerical input impedance of artificial dielectric with the theoretical counterpart of continuous dielectric medium as shown in Fig.1 [1]. The upper and lower walls are assumed to be perfect electric conductors, whereas the right and left walls are perfect magnetic conductors, resulting in the transversely periodic structure. The calculation is carried out in the following steps.

1) The input impedances of Fig.1(b) are given for the short and open terminations, respectively,

$$Z_{bs} = \mathrm{j}Z_w \tan \beta l \,, \tag{1.a}$$

$$Z_{bo} = -\mathrm{j}Z_w \cot \beta l \,, \tag{1.b}$$

where

$$Z_w = \sqrt{\frac{\mu_y}{\varepsilon_x}}\,, \qquad \beta = \omega\sqrt{\varepsilon_x \mu_y}\,. \tag{2}$$

2) One equates Eq.(1) to the numerically calculated input impedance of Fig.1 (a) for the short and open conditions, respectively,

$$Z_{bs} = Z_{as}\,, \tag{3.a}$$

$$Z_{bo} = Z_{ao}\,. \tag{3.b}$$

3) Substituting Eq. (2) into (1), and using Eq.(3), the effective permittivity and permeability are

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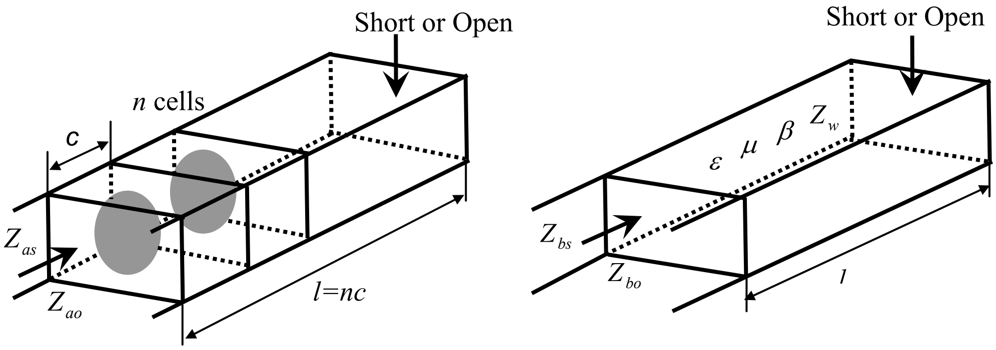
derived,

$$\varepsilon_{rx} = \frac{c_0}{\omega l \sqrt{Z_{as} Z_{ao} / Z_0^2}} \tan^{-1} \sqrt{-\frac{Z_{as}}{Z_{ao}}}, \tag{4.a}$$

$$\mu_{ry} = \frac{Z_{as} Z_{ao}}{Z_0^2} \varepsilon_{rx}, \tag{4.b}$$

where Z_0 is the characteristic impedance of the free space, and c_0 is the light velocity in the free space.



(a) Artificial medium (b) Continuous medium

Fig. 1 Calculation of effective permittivity and permeability

When we align the unit particles in the simple orthorhombic lattice structure, we obtain the effective permittivity as a function of their radius as shown in Fig.2. It naturally increases with the radius and more rapidly when adjacent particles are about to touch each other. The polarization increases proportionate to r^3 at first because the numbers of electrons increases as r^2 and the length of particle as r. When r is larger, the interaction between the particles augments the increasing rate further. By drawing the calculated result for the susceptibility in log-log scale, Fig.3 clarifies the above mentioned feature well.

The longitudinal number of cells reduces the effective permittivity as shown in Fig.4, since the shielding effect of the metal particles may obstacle the EM field's penetration, which does not occur in the natural dielectric medium. It complicates the practical use of artificial dielectrics.

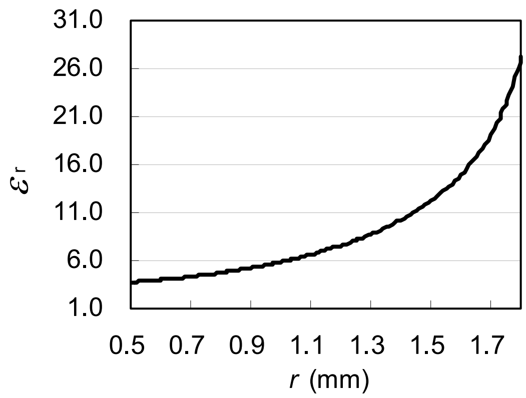


Fig.2 Effective permittivity versus radius of disk unit element (a=b=3.8mm, c=0.127mm, d=18μm, ε_r=3.27, n=2, f=1GHz)

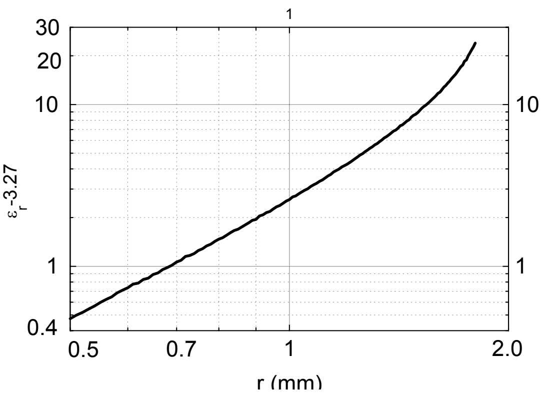


Fig.3 Effective susceptibility versus radius of disk unit element in log-log scale(a=b=3.8mm, c=0.127mm, d=18μm, ε_r=3.27, n=2, f=1GHz)

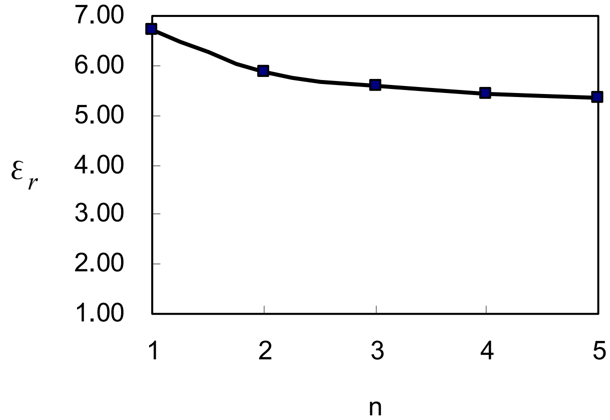


Fig.4 Effective permittivity versus number of cells in longitudinal direction
(a=b=3.8mm, c=0.127mm, d=18μm, r= mm, ε_r=3.27, f=1GHz)

3. Design of lens antenna

Referring to Fig.5, the design is carried out by keeping the phase lags of rays from the focal point to the output surface of the lens. Thus, the distribution of dielectric constant is determined by the relation

$$\sqrt{r^2+f^2}+\sqrt{\varepsilon_r(r)}d = f+\sqrt{\varepsilon_r(0)}d\ , \tag{5}$$

where r is the distance from the center, f is the focal length, $\varepsilon_r(r)$ is the radial distribution of relative permittivity and d is the thickness of the lens. Considering that the permittivity is equal to that of the host material at the periphery, a similar equation relates the thickness and the maximum relative permittivity at the center when the focal length and radius of lens are given.

$$f+\sqrt{\varepsilon_r(0)}d = \sqrt{f^2+R^2}+\sqrt{\varepsilon_h}d \tag{6}$$

After we know the distribution of the permittivity versus the distance from the lens center r, we use Fig.2 to determine the radius of disk unit cell. Figure 6 shows a designed example of metal pattern on the printed circuit board.

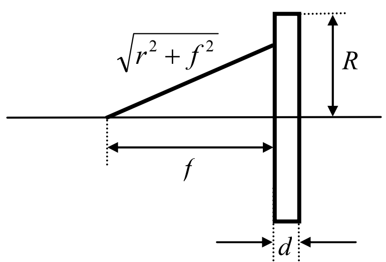


Fig.5 Design method of permittivity distribution

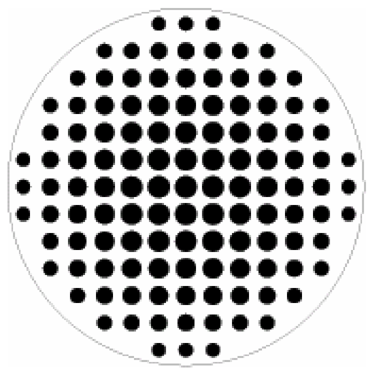


Fig.6 An example of designed metal pattern.

4. Experiments

A preliminary experiment to verify focusing effect of the lens was prepared in a radio anechoic room with 4.0 × 5.0 × 2.4 m^3 dimension. The experimental set-up is shown in Fig.7. The primary radiator is a square patch antenna with 3.5 × 3.5 × 0.2 cm^3. The specification of the fabricated lens is shown in Table1. The maximum permittivity is 58 at the center and the minimum is 3.27 around the periphery which is the value of the substrate itself. The large permittivity causes reflection due to the mismatch to the free space [2]. The design of matching layers is under way.

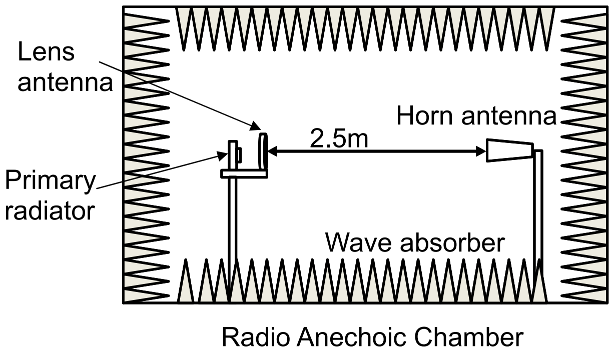


Fig.7 Experimental setup

Table1. Specification of fabricated lens

Frequency	10 GHz
Diameter	5 cm
Focal length	10 cm
Substrate thickness	0.13 mm
Number of substrate	4

The diameter is rather too small compared with the wave length of the signal. Hence the diffraction loss should be significant. It was because of the size limit of the etching equipment.

The experimental result is shown in Fig.8 with and without the lens. The difference is 2 to 3 dB around 10GHz. The result is only preliminary, but it exhibits the lens works. The bandwidth should be infinite according to Eqs.(5) and (6). But there are several reasons to reduce it, such as frequency dependence of impedance matching to the free space and the resonance of the lens due to too small transverse dimensions.

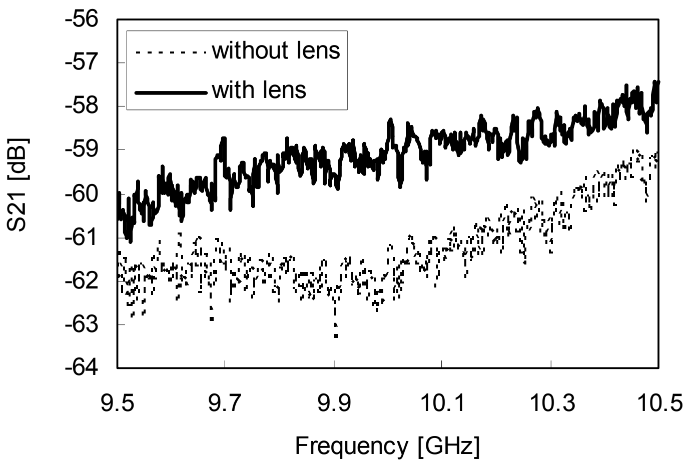


Fig.8 Experimental result for lens antenna of Table.1.

5. Conclusion

We have fabricated a flat lens antenna with artificial dielectrics, which is essentially a group of metal patches etched on the layered printed circuit boards. Though the gain increases only 2 to 3 dB by putting it in front of a patch antenna, it will be improved if we suppress the reflection at the lens surface introducing matching layers. The proposed structure is easy to fabricate and convenient to handle in a T/R system.

Acknowledgement

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