Integrated lens antenna with a conic extension at 220 GHz

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Abstract: A simple and impactful solution to reduce the size and improve the gain of extended hemispherical lens antennas is proposed. A conic extension is used for optimizing the spherical aberration of lenses. The principle is explained by ray-tracing theory, and its model is simulated, optimized and fabricated by nylon. An imaging unit is assembled by patch and the new lens. The radiation patterns are measured at 220 GHz, where close performance of the simulated and measured results is obtained. Imaging experiments have been carried out and good results were achieved.

Keywords: THz imaging, detector, lens antenna, 3D printing

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Integrated lens antennas are wildly used at terahertz imaging field for various applications, including communication [1], imaging [2], and radars [3]. Nevertheless, the volume of conventional extended hemispherical lens is limited by the permittivity of material, which makes against the integration of imaging units. This motivates the research on shortening the extension length of hemispherical lenses without depressing gain. Thus far, four techniques have been proposed to shorten the size. The simplest one is using the materials with high permittivity such as ceramics and silicon [4]. However, they are expensive, lossy and difficult to machine. The second way consists in synthesizing multi-material dielectric lenses and optimizing the lens shape [5, 6]. The third way is using biconvex lenses, which is rare and not very effective in THz imaging [7, 8]. The latest technique relies on a cylindrical air cave above the primary feed [9]. This technique is very effective in reducing the size and weight of extended hemispherical lens, yet the extended length still employ a lot of space and the gain is pulled down. Inspired by the third method, we give up the cylindrical extension and study hemispherical lenses. By the above ideas, we find another way, which is using a conic extension, to improve the spherical aberration and reduce the size.

2 The lens design

Fig. 1 shows ray-tracing analysis of four types of lenses. For the conventional extended hemispherical lens in Fig. 1a, there exists a long extension defined by the lens material permittivity and the hemisphere radius [10]:

\[ L = R \left( \frac{\sqrt{\varepsilon_r} + 1}{\sqrt{\varepsilon_r} - 1} - 1 \right) \]  

Where \( L \) is the extension length of conventional extended hemispherical lens, \( R \) is the radius of the hemisphere, \( \varepsilon_r \) is the material permittivity. Eq. (1) not only give guidance on lenses design, but also limits the size of lens. Consider the limit of
conventional extended hemispherical lens, we abandon the extension of the lens in Fig. 1b. Hemispherical lens effectively reduces the volume compared with conventional extended hemispherical lens, but its spherical aberration become deteriorative. Therefore, another structure is need for optimizing the spherical aberration. By ray-tracing analysis, the rays near the optical axis require a larger range of adjustment, which is on the contrary with biconvex lenses shown in Fig. 1c. So a conic extension is added in hemispherical lens to optimize spherical aberration and improve the lens antenna gain. Fig. 1d shows the structure of conic extension hemispherical lens.

The gains on optical axis were simulated for the sake of verifying the above analysis. Fig. 2 shows the simulation results of four types of lenses.

In Fig. 2, the coordinate origin indicates the intersection point of the optical axis and the lower half plane of the hemisphere. The highest point of gain represents the focal point of the lens. As we can see, hemispherical lenses and biconvex lenses shorten the focal length, but reduce the gain due to the spherical aberration. The designed lens shortens the focal length and improves the spherical aberration, which means greater gain under smaller size.

On the basis of above analysis, we choose nylon (\(\varepsilon_r = 2.64\)) as the material to machine the lens by 3-D printer. The final model of the lens is shown in Fig. 3.

The parameters of the conic extension lens (Fig. 3a) are denoted as follows: \(R\) is the radius of the hemisphere, \(r\) and \(h\) are the radius and height of conic extension, \(H\) and \(D\) are the height and radius of air cave, \(d\) is the thickness of the brace.

In order to determine the optimal size, simulation for \(h\) and \(r\) has been done. In Fig. 4, the line named ‘without’ is the simulation data of lens without conic extension, \(r\) and \(h\) are defined the same as Fig. 3a. As we can see, once the radius of conic extension (\(r\)) is close to the half of the radius of hemisphere (\(R\)), it plays a small part in lens gain. But the height of conic extension is important, which influences the gain and the focal distance obviously. The final details values are \(R = 6.5\) mm, \(r = 3\) mm, \(h = 0.9\) mm, \(H = 3.4\) mm, \(D = 10\) mm, \(d = 1.5\) mm. The electric field snapshot shown in Fig. 3b indicates that the incident wave is focused by the optimal lens.

![Fig. 2. The gains of four types of lenses on optical axis](image-url)
Above analysis is based on independent lenses, which is different from the practical application. A patch antenna placed on the focus of the lens is simulated together, and its results are showed in Fig. 5. We can get that the new conic extended lens antenna successfully hold the gain and reduce the size compared with traditional extended hemispherical lens antenna.

Fig. 3. Final model of the lens. (a) Model of the lens. (b) The snapshot of the electromagnetic wave propagation inside the lens.

Fig. 4. Simulation and optimization for conic extension lens.

Fig. 5. Simulated radiation patterns of traditional lens antenna and new lens antenna. (a) E-plane. (b) H-plane

3 Measurements and discussions

Patch antenna and the lens are assembled in a metal box to form an imaging unit (Fig. 6). The patch antenna designed at 220 GHz is fabricated using SMIC 130-nm RF CMOS process. A schottky barrier diode is integrated after the antenna to mix frequency to midfrequency.
The radiation pattern of the patch antenna and integrated lens antenna are measured as shown in Fig. 7. Both antennas demonstrate a very close performance, except a slight difference in the sidelobe of the integrated lens antenna. It can be easily proved that the difference is caused by the metal box.

As shown in Eq. (1), the extended length of conventional extended hemispherical lens is controlled and reduced hardly. The new lens replaces the long extension with a small conic. If we consider the reduced size of the new lens ignoring the conic, we obtain

$$\Delta = \frac{V_{\text{NEW}}}{V_0} = \frac{1}{1 + \frac{3}{2} \left( \frac{\sqrt{\varepsilon_r} + 1}{\sqrt{\varepsilon_r} - 1} - 1 \right)}$$  \hspace{1cm} (2)

The $\Delta$ indicated the volume ratio of new lens and conventional lens. In this paper, we choose the nylon ($\varepsilon_r = 2.64$) as the material, which meaning $\Delta \approx 0.39$. The volume of new lens is reduced by more than half without influencing the gain.
4 Imaging

Based on the above results, Fig. 8 shows the principle of imaging experimental. The imaging object is a 15 cm * 15 cm metal square with T shape hole, which moves with the 2D guide screw to achieve scanning. The detector is separated from the object by 5 cm, which means the resolution is 0.5 * 0.5 cm². The imaging result is shown in Fig. 9.

5 Conclusion

A new type of lens is designed and fabricated based on ray-tracing theory. The patterns comparison of the new lens antenna and the traditional lens antenna proves that the new lens is applied. The volume reduction is defined by equation, which can reach 61 percent in this paper. An imaging unit is assembled and measured. The testing results indicate that the new extended lens antenna has good performance at 220 GHz, which is helpful to achieve high levels of integration in imaging applications.

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