Design of a High-Gain Planar Lens Antenna Based on Metamaterial with Fan Beam

Zeyi Xu¹, Youyun Xu¹ and Haiming Li²

¹National Engineering Research Center of Communications & Networking, Nanjing University of Posts and Telecommunications, China
²College of Telecommunications & Information Engineering, Nanjing University of Posts and Telecommunications, China

Abstract. This paper presents the design and results of a planar lens fed by a fan beam H-plane horn antenna. Compared with traditional dielectric lens antenna, planar lens based on metamaterials is composed of several unit cells designed for changing the phase of incident wave. The presented lens is center-fed by a horn antenna located at 100mm from the lens, and the thickness of it is 5mm. The simulation results exhibits a high gain of 30dB at 76.5GHz and a fan-shaped main beam with half-power beam-widths of 1.7° and 4.1° on E-plane and H-plane respectively.

1 Introduction

With the popularization and development of wireless communication technology in the transportation, medical science and security check, more and more scholars have begun to focus on researching high-performance fan beam antennas suitable for different scenarios. Millimeter-wave fan beam antennas can radiate fan beams and have the characteristics of wide coverage and strong anti-interference ability. They have unique advantages in scan positioning, medical imaging, and anti-collision radar. A new dual-energy bone densitometer using a narrow-angle fan beam (4.5°) source was assessed, which improve the performance of medical imaging equipment [1]. For detecting close obstacles and blockages, modified four-port millimeter-wave Vivaldi antennas were set on four corners of the car’s bumper which provide a full 360 degree view around the car [2]. These demands of applications for antennas with fan beam have accelerated its development.

On the other hand, lenses have become an important way to improve the gain of antennas. A dielectric lens antenna working in 71-86GHz was reported in [3], which provided a 20dB enhancement of gain. But the dielectric unit cells of lens are difficult to manufacture, and the performance of the dielectric lens antenna is sensitive to the dimensional errors which lead to the poor stability. The lens antenna in [4] was composed of unit cells built by metamaterials. Compared with dielectric lens antenna, the planar lens antenna based on metamaterials has less cost and thickness which effectively reduced the weight and size, so that the lens is easier to integrate in the microwave circuits.

However, lens antennas face a serious problem that it is hard to achieve scanning. To solve this problem, the most usual program is to move the source horizontally or vertically [5]. Some scholars designed mechanically steering lens antenna in [6], and another good
solution was multiport wave source providing required angle of scanning [7]-[10]. Of course, lens antenna radiating fan beam is also a good substitute for mechanically steering ones. Two dielectric fan beam lens antennas were shown in [11] and [12], both of which were cylindrical shaped and parallel to their source respectively. In [13], the author proposed a fan beam lens antenna based on gradient-index metamaterials and gave an analysis of the influence on the performance of the lens due to different dielectric thickness, and the final selected thickness of dielectric unit cells determined that they can only work in a limited working environment. In summary, most of the lens antennas utilized for radiating fan beam are three-dimensional structures which cannot be easily integrated. The designs of two-dimensional Luneberg lens and dielectric lens have smaller physical size, while the lens parallel to the feed can only be utilized for specific scenarios, so they cannot replace the planar lens antenna for wide angle beam scanning. In this paper, we propose a new kind of fan beam planar lens fed by an H-plane horn antenna with high performance.

2 Design of the lens antenna

The principle of the planar lens is illustrated in figure 1, in which unit cells provide different phase shift for incident wave according to their locations. Passing through the lens, incident plane wave is converted into spherical wave and focused on a point behind the lens. Similarly, when the spherical wave is emitted from the focus point, it will be converted to plane wave which has better directionality.

![Figure 1. The principle of the planar lens based on metamaterials.](image)

Compared with conventional lens, planar lens fed by fan beam has different index of phase-shift along x-direction and y-direction which is represented by an empirical formula:

\[
\phi(x_i, y_i) = \frac{2\pi}{\lambda} \left( \frac{x_i^2}{r^2} + y_i^2 + F^2 \right)^{1/2} - F
\]

It is necessary to point out that, this formula derives from the Fermat’s principle and is simplified for fast obtaining the value of phase shift of unit cells. In this formula, we assume that the centre of the lens is the origin of the coordinate, \((x_i, y_i)\) is the distance between the No. i cell and the centre of lens, \(F\) is the distance from the phase centre point of the feed source to the centre point of the lens, and \(\lambda\) is the free-space wavelength at the design frequency. Parameter \(r\) is introduced as a ratio that indicates the different index of phase shift along x-direction and y-direction. According to formula, the phase shift of every unit cell is calculated. However, designing every corresponding phase-shift unit cell is so complex and is less helpful for the performance of the antenna, so it is wise to design several discrete values taking the place of phase range from 0 to 360. The distribution of the phase-shift unit cells is shown in figure 2.
Figure 2. The distribution of the phase-shift unit cells.

Figure 3. Structure of the phase-shift unit cells, the black parts of which are copper patches. The top layer has the same size as the bottom layer.

Table 1. Parameters of 8 kinds of phase-shift unit cells.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>0°</th>
<th>45°</th>
<th>90°</th>
<th>135°</th>
<th>180°</th>
<th>225°</th>
<th>270°</th>
<th>315°</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.9</td>
<td>1.9</td>
<td>1.2</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>b1</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.7</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>a2</td>
<td>1</td>
<td>0.6</td>
<td>1.3</td>
<td>1.9</td>
<td>1.4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

All the parameters are expressed in mm.

Each unit cell whose thickness is 0.5mm has two layers of TSM-DS3 ($\varepsilon_r = 3, \tan \delta = 0.0011$) material from Taconic, and three layers of metal patch as shown in figure 3. The top metal layer has a shape of cross same as the bottom layer, and the middle metal layer is a rectangular patch. By means of adjusting the length of a1, b1, a2 and b2, 8 phase-shift values are implemented for decreasing the cost and simplifying the process of designing. The corresponding sizes of 8 kinds of unit cells are reported in table 1. The simulated transmission coefficients in magnitude and phase of each phase-shift unit cell emitted by plane wave are presented in figure 4 (a) and figure 4 (b).
The lens is rectangular with 76 unit cells in both length and width. Different from the pencil beam planar lens, fan beam planar lens have equal phase-shift along an oval loop instead of a ring. An H-plane horn antenna is selected as the wave source which can emit fan beam, and it is placed at F=100mm from the centre of the lens. The performance of the H-plane horn antenna is shown in section 3.

3 Simulation and experimental results

The lens occupies a volume of 152mm*152mm*0.5mm much smaller than lens working in the same frequency. The return loss at feeding port of the H-plane horn antenna with lens is shown in figure 5 and is in comparison with the return loss of the horn antenna without lens. According to the figure 5, the horn antenna is matched well from 76 to 77GHz as well as the planar lens. To verify the enhancement of the fan beam lens antenna, the radiation patterns of the H-plane horn antenna without lens and with lens are presented in figure 6. As shown in the figure 6, the peak gain of the H-plane horn antenna without planar lens is 12.1dB, and the half-power beam-width of the main beam is 69.1° in H-plane and 28.5° in E-plane, while the horn antenna with planar lens has a high gain of 30dB and a half-power beam-width of 4.1° in H-plane and 1.7° in E-plane. Therefore The planar lens increases the gain of the source by 17.9dB, and narrows the half-power beam-width, in other words, we can sum up that the planar antenna sacrifices beam-width for high gain.
4 Conclusion

A design for a planar lens radiating fan beam based on metamaterial was presented. The required phase-shift is achieved by adjusting the shape and size of the metal layer, and the whole phase-shift range is approximated into 8 phase-shift unit cell. At the centre working frequency of 76.5GHz, the peak gain of the fan beam planar lens antenna is 30dB, which is 17.9dB higher than that of an H-plane horn antenna. The half-power beam-width is more narrow than before because of the focusing of the planar lens.

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