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MILLIMETER-WAVE ELLIPTICAL LENS ANTENNA FOR FAN-BEAM MONOPULSE APPLICATIONS

C. Z. Hua[1, 2], X. D. Wu[2, *], N. Yang[2, 3], and W. Wu[1]

[1]Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing, China

[2]Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou, China

[3]State Key Laboratory of Millimeter Waves, Department of Electronic Engineering, City University of Hong Kong, Hong Kong SAR, China

Abstract—A novel two-dimensional elliptical lens monopulse antenna at millimeter-wave frequencies is presented using the technique of dielectric-filled parallel plates where TE_{10} mode propagates. A cavity-backed aperture-coupled elliptical patch antenna array with sum/difference ports is located at the back of the elliptical lens as the feed antenna. The lens antenna is designed, fabricated and tested at 35 GHz. Measurements show that clean and symmetrical fan-beam patterns are realized for both the sum and the difference beams. The measured 3-dB E- and H-plane beamwidths of the sum pattern are 5.3° and 37°, respectively. A gain of 16.7 dBi is realized for the sum beam (86% radiation efficiency), while a deep null of −32.4 dB is achieved for the difference beam. In addition, a 10-dB impedance bandwidth of 7.1% is measured for both the sum and difference beams.

1. INTRODUCTION

Monopulse antennas have been widely used in high-resolution radar, accurate/rapid direction-finding and tracking systems [1]. Traditional monopulse systems utilizing Cassegrain parabolic antennas and waveguide comparators benefit from the advantages of low loss and extremely high power handing capability. However, they are expensive, heavy and complicated. To cope with those problems, many kinds of planar monopulse systems with low cost, light weight and compact

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* Corresponding author: Xidong Wu (xwu@zju.edu.cn).

structure have been designed in recent years [2–5]. The biggest advantage is that these antennas can be easily integrated with planar circuits. However, at millimeter-wave frequencies, antenna printed on a dielectric substrate will suffer from surface-wave losses which deteriorate radiation patterns. One way to reduce surface-wave loss is to use very thin substrate, which will restrict the practicality of planar monopulse antennas [6]. Another way is to place the planar antenna (presumably on a thick substrate) directly on the back of a dielectric lens. The main advantages of this approach include highly directive antenna patterns, compatibility with integrated circuit (IC) techniques, mechanical rigidity, and thermal stability. Dielectric lenses can be hemispherical [7], ellipsoidal [8], or flat-shaped [9]. Various planar feed antennas, such as slot-ring [10] and patch antennas [11], have been successfully utilized for dielectric lenses.

In this paper, a novel elliptical lens based on the technique of dielectric-filled parallel plates is introduced for millimeter-wave fan-beam monopulse applications. The conventional monopulse antenna usually develops from a pair of overlapped pencil beams to produce sum and difference radiation patterns. For some applications, such as Doppler-weather radar, aircraft landing system and other millimeter-wave imaging systems, fan-beam antenna is required, because of its capability of producing a narrow beam in one plane and a wide beam in the other (orthogonal) plane [12]. The proposed antenna can provide a pair of overlapped fan beams to produce sum and difference radiation patterns. A cavity-backed aperture-coupled elliptical patch array with sum/difference ports is designed as the feed antenna, which is placed on the back of the elliptical lens. A commercial software CST-MWS is used to analyze and design the lens antenna at 35 GHz. Details of the antenna design and experimental results are presented and discussed.

2. ANTENNA DESIGN

The geometry of the proposed elliptical lens antenna is shown in Fig. 1. The lens is made out of Rexolite ($\varepsilon_\mathrm{r} = 2.54$) and sandwiched between two parallel plates. The thickness of the lens is chosen to be $h = 5.3\,\mathrm{mm}$ ($\lambda_\mathrm{g}/2 < h < \lambda_\mathrm{g}$) in order to ensure TE_{10} mode propagation between the parallel plates and to avoid TE_{20} mode. The effective index of refraction can be calculated as $n = 1.37$ at the design frequency of 35 GHz [12]. In this design, the minor axis of the elliptical lens is chosen to be $a = 37.0\,\mathrm{mm}$. The major axis and focal length are then calculated as $b = 54.0\,\mathrm{mm}$ and $c = 39.4\,\mathrm{mm}$, respectively [11]. Two patch antennas, which are located at the back of the lens, are employed as feed antenna to launch a sum beam or a difference beam.

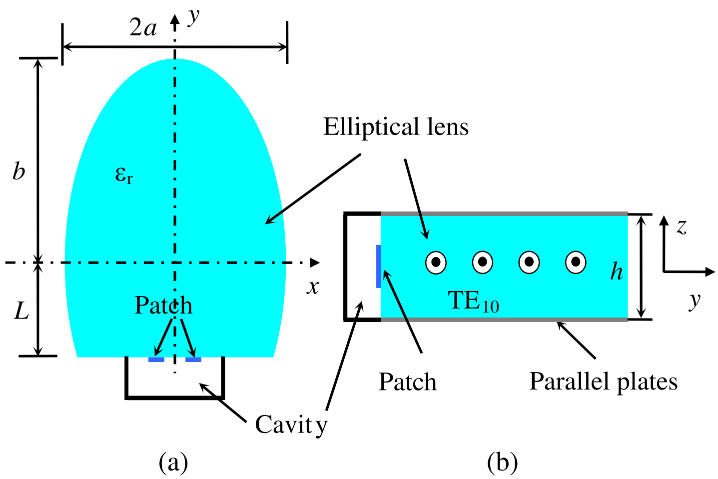

Figure 1. Geometry of the elliptical lens monopulse antenna. (a) Top view, (b) side view.

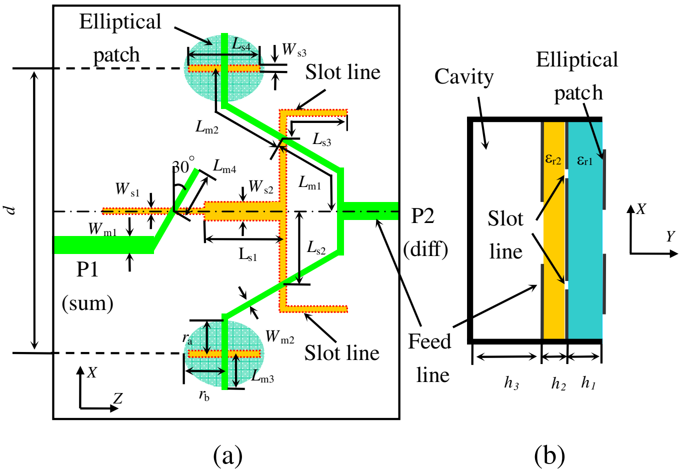

Figure 2. Geometry of the feed antenna array. (a) Top view, (b) side view.

Because the two patches are placed at off-axis position, the length L (see Fig. 1) should be optimized to achieve good sum and difference patterns. Optimization is carried out by using the commercial software CST-MWS. The optimized length is found to be $L = 37.6\,\text{mm}$, which represents the best compromise between the sum pattern and the difference pattern. The two patches are horizontally excited (x-y plane), yielding a TE_{10} mode propagation between the parallel plates.

The radiating element used to feed the lens is realized by an aperture-coupled elliptical patch array, as shown in Fig. 2 [13–18]. The elliptical patch array is printed on a low-permittivity substrate Arlon Di880 ($\varepsilon_{\mathrm{r1}} = 2.2$), which is close to the permittivity of the Rexolite lens and the feed network with sum/difference ports is built on a high-permittivity substrate Arlon TC600 ($\varepsilon_{\mathrm{r2}} = 6.15$). The elliptical patch is employed since it generates a wider illumination beamwidth in E-plane than the traditional rectangular patch does, which leads to a higher illumination efficiency. The center-to-center spacing of the two elliptical patches is chosen to be $d = 4.4\,\mathrm{mm}$ ($\sim 0.7\ \lambda_{\mathrm{g}}$) in order to avoid grating lobes while minimizing the effects of mutual coupling. The feed network is realized by a planar magic-T, which consists of microstrip and slotline T-junctions coupled by microstrip-to-slotline transitions [19]. The advantages of this approach lie in its planar structure, compact size, high isolation, and fabrication easiness. When the sum port (Port 1) is excited, the two elliptical patches radiate in-phase, leading to a sum beam. On the other hand, when the difference port (Port 2) is excited, the two elliptical patches radiate out-of-phase, resulting in a difference beam. Finally, the feed antenna array is placed inside a rectangular-shaped cavity to minimize back radiation. The values of the design parameters are listed in Table 1.

Table 1. Design parameters.

Parameter	Value (mm)	Parameter	Value (mm)
W_{m1}	0.39	L_{s1}	1.34
W_{m2}	0.19	L_{s2}	1.36
W_{s1}	0.10	L_{s3}	1.30
W_{s2}	0.27	L_{s4}	1.80
W_{s3}	0.18	r_{a}	0.90
L_{m1}	2.06	r_{b}	1.00
L_{m2}	1.40	h_1	0.508
L_{m3}	1.01	h_2	0.254
L_{m4}	1.02	h_3	10.0

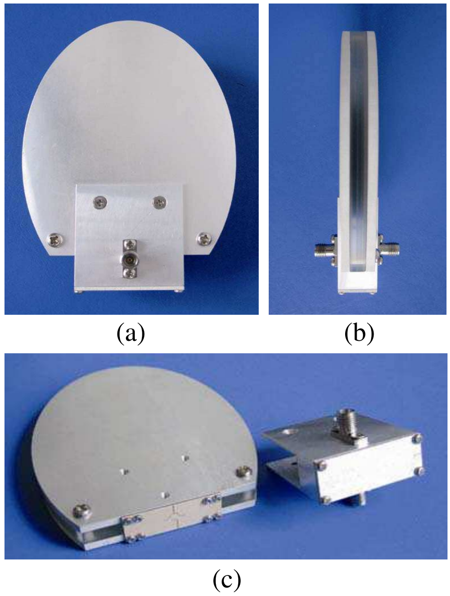

Figure 3. Photographs of the fabricated monopulse antenna. (a) Top view, (b) side view, (c) 3D view.

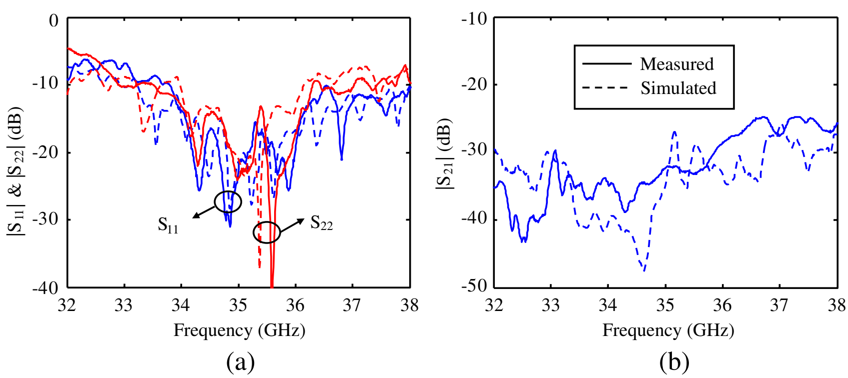

Figure 4. Simulated and measured S-parameters. (a) Return loss, (b) isolation.

3. RESULTS AND DISCUSSION

Figure 3 displays the photographs of the fabricated elliptical lens antenna. The simulated and measured S-parameters are given in

Fig. 4. As shown, the return losses for both the sum and the difference ports are better than 10 dB from 33.8–36.3 GHz, corresponding to an impedance bandwidth of 7.1%. Within this band, the isolation between the sum and the difference ports is better than 27.3 dB. The slight discrepancy between the simulated and measured results can be attributed to the fabrication tolerance. Fig. 5 demonstrates the simulated and measured sum and difference patterns at 35 GHz. The measurements show good agreement with the simulations. The measured 3-dB E- and H-plane beamwidths of the sum pattern are 5.3° and 37°, respectively, and the sidelobe level in the sum E-plane pattern is -15.5 dB. The measured null depth in the difference pattern

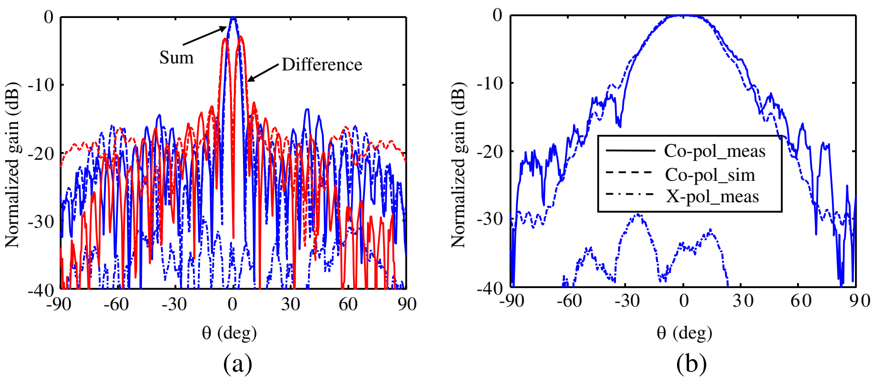

Figure 5. Simulated and measured radiation patterns at 35 GHz. (a) E-plane (x-y plane), (b) H-plane (y-z plane).

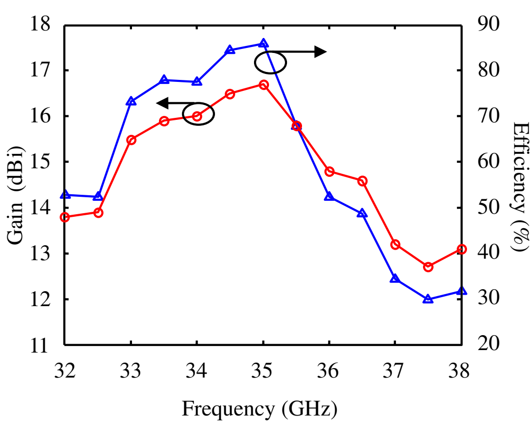

Figure 6. Measured gain and efficiency.

is -32.4 dB. In addition, the measured cross-polarization levels are at least -28 dB below peak in both E- and H-plane.

The radiation efficiency of the fabricated elliptical lens antenna is defined as $\varepsilon = G_0/D_{\max}$, where G_0 is the measured gain and $D_{\max}$ is the maximum directivity of the TE_{10} mode distribution aperture which can be calculated as

$$D_{\max} = \frac{8}{\pi^2}\left[4\pi\left(\frac{2ah}{\lambda_0^2}\right)\right] \tag{1}$$

Figure 6 illustrates the measured gain and the corresponding radiation efficiency as a function of frequency. At the design frequency of 35 GHz, the measured gain is 16.7 dBi and the corresponding radiation efficiency is about 86%. Within the 10-dB impedance bandwidth from 33.8–36.3 GHz, the measured radiation efficiency is better than 50%.

4. CONCLUSION

This paper has presented a novel kind of fan-beam elliptical lens monopulse antenna at millimeter-wave frequencies. Experimental results at 35 GHz prove that the designed antenna has clean and symmetrical fan-beam patterns. A deep null of -32.4 dB is achieved in the difference pattern owing to the circuit symmetry. The 10-dB impedance bandwidth of 7.1% is measured for both the sum and difference beams. The main features of the proposed antenna include its compact structure, light weight, low cost, and good fan-beam patterns. All these characteristics make this antenna configuration well suitable for millimeter-wave fan-beam monopulse applications.

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