Design and Characterization of Single and Multiple Beam MM-Wave Circularly Polarized Substrate Lens Antennas for Wireless Communications

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1. Introduction

As the need for broadband wireless communication systems is growing, the corresponding operating frequency is gradually shifting towards millimeter-wave (mm-wave) frequencies [1]. This has generated in recent years an increased interest in developing mm-wave integrated circuit (IC) antennas for indoor and outdoor wireless communications. A successful technique for implementing mm-wave subsystems has been the integration of planar antennas and electronics at the back of substrate lenses [2]-[7].

In this paper, we present the design of single and multiple beam circularly polarized (CP) substrate lens antennas for wireless applications at 30 GHz. Circular polarization and high directivity are desirable features as they can effectively reduce multipath effects and maintain a proper link margin [1]. In addition, multiple beam antennas can be utilized either for space division multiple access (SDMA) or for incorporating "smart" antenna features [8]. The approach taken here is to use an aperture coupled patch antenna as the lens feed in combination with low-cost plastic materials for making the lens [2], [5], [6]. For the single-beam design, an ellipsoidal lens is utilized which leads to diffraction limited patterns on-axis [5]. For the multiple-beam design, we choose a hexagonal arrangement of printed patch elements at the back of the lens to maximize scan coverage. Also, the extension length of the ellipsoidal lens is optimized to launch beams with roughly equal power densities.

2. Single Beam Antenna

A general schematic diagram of the substrate lens antenna is shown in Figure 1. The lens is made out of Rexolite which leads to a reduced cost. Because of its low permittivity (ε_r=2.54), an anti-reflection coating is not necessary which is another advantage for low-cost applications. For generating diffraction limited patterns, an elliptical lens with circular cross-section and a cylindrical extension is chosen, with $R = H\sqrt{(\varepsilon_r - 1)/\varepsilon_r}$ and $L = H/\sqrt{\varepsilon_r}$, where H, R are the major and minor axis of the ellipsoidal lens respectively, as shown in Figure 1.

The radiating element used to feed the lens is realized by a single feed cross-slot coupled CP patch antenna, as shown in Figure 1. The cross-slot coupled antenna is designed using HP/ Momentum, with the lens modeled as an infinite half space of ε_r=2.54. The radiation patterns through the ellipsoidal lens are computed using a geometrical-optics/diffraction theory approach [4]. For this purpose, the cavity model is utilized to generate the feed patterns for the lens.

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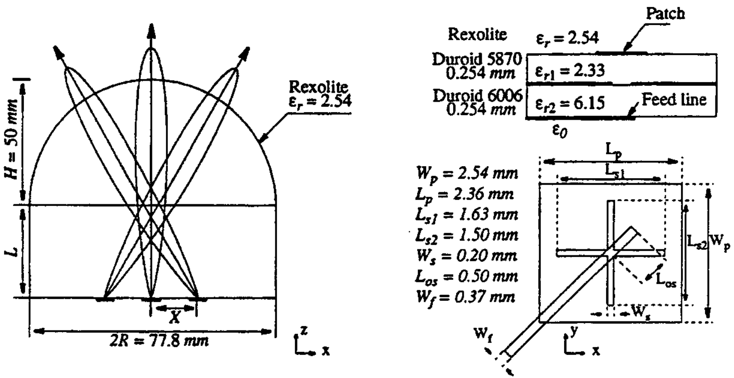

Figure 1. Circularly polarized ellipsoidal substrate lens antenna

The measured and calculated radiation patterns for the E_θ component, along the $\phi = 90^\circ$ cut at 30 GHz are shown in Figure 2. The E_ϕ component exhibits a similar pattern. The simulation includes not only 1st-order ray tracing, but 2nd-order multiple reflections as well. As shown in Figure 2, the simulations are getting closer to the measurements after taking the 2nd-order reflections into account. The measurements and simulations agree quite well within the main lobe and first sidelobe, as well as the second sidelobe. The measured and computed 3 dB full-beamwidth is 6.4° and 6.8°, and the corresponding measured and computed first sidelobe level is -13.5 dB and -14.0 dB, respectively. Both simulations and measurements indicate that at broadside, the CP is unaffected by any depolarization effects through the lens and good axial ratio (AR) is maintained within the main lobe. Figure 3 shows the measured and simulated AR values as a function of frequency. For these simulations, HP/Momentum was used to predict the feed-patterns rather than the cavity model. The best AR of 0.5 dB is achieved around 30 GHz and the 3 dB AR bandwidth is 2.6%.

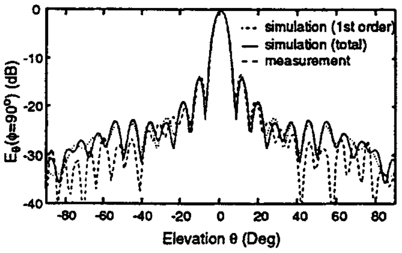

Figure 2. Radiation pattern

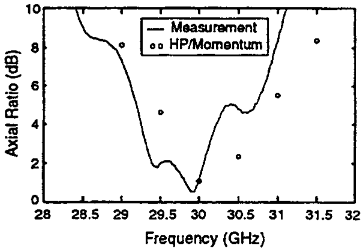

Figure 3. Axial ratio

3. Multiple Beam Antenna

The lens antenna can be used to launch multiple beams by printing an array at the back of the lens [3], as shown in Figure 1. The scan angle depends on the off-axis displacement X/R (see Fig. 1). For wireless communications, one of the most important features for multiple beam antennas is scan coverage. As demonstrated in [3], the off-axis total internal reflection loss is the limiting factor in the design of larger multiple beam arrays on substrate lenses. For the present CP design, another possible limitation is off-axis depolarization.

In order to launch beams with equal radiation power density and minimize reflection losses, the extension length L has been optimized and found to be $L \approx R/\sqrt{\varepsilon_r}$, where R is the minor axis of the designed elliptical lens (see Fig. 1). Figure 4 shows the calculated scan angle, reflection loss as well as the axial ratio as a function of the off-axis displacement X/R. Again here, the cavity model is used to feed the lens for carrying out the simulations. As shown, the reflection loss is only 0.29 dB on-axis and increases rapidly after off-axis displacements of $X/R = 0.16$. The reflection loss remains smaller than 1.8 dB for a maximum off-axis displacement of $X/R = 0.34$. On the other hand, the corresponding axial ratio exhibits a value of 0 dB on-axis and remains less than 0.2 dB within an off-axis displacement of $X/R = 0.40$. This indicates that the induced depolarization can be neglected within the useful off-axis displacement range of $X/R \leq 0.34$. From the above discussion, it can be concluded that the designed lens structure can be used up to off-axis displacements of $X/R = 0.34$, which corresponds to a scan angle of ±20° (i.e. a total of 40°).

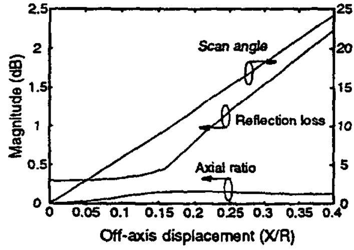

Figure 4. Off-axis characteristics

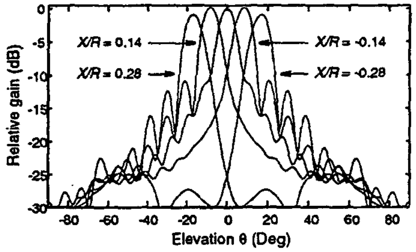

Figure 5. Off-axis radiation patterns

Figure 5 shows simulated radiation patterns for a designed linear array with a 3 dB beam overlapping level. To get the 3 dB beam overlapping, the distance between adjacent elements d_{3dB} is found equal to 0.14 R. The peak gain loss in the off-axis patterns is caused by the larger reflection loss. Figure 6 shows a hexagonal arrangement of a planar array at the back of the lens for maximizing scan coverage with minimum array elements. The distance between neighbor elements A should be optimized based on the beamwidth of adjacent beams and the required beam overlapping level (e.g. 3 dB). The maximum radius of this hexagonal array is limited by the allowed off-axis displacement of 0.34 R. For the shaded equilateral triangle of Figure 6, the point of minimum overlapping power among beams 0,1 and 2 occurs at the center of the triangle (point O'). In order to get 3 dB beam overlapping at point O', $\overline{OO'}$ should be equal to $d_{3dB}/2 = 0.07R$. The distance between neighbor elements A can then be determined as equal to $\sqrt{3} \times \overline{OO'} \approx 0.12R$. As shown in Figure 6, the allowed largest off-axis

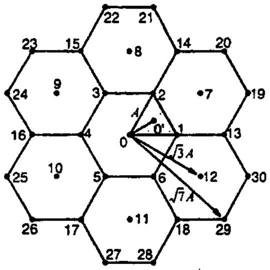

Figure 6. Hexagon arrangement of antenna array

Beam	Relative Gain (dB)	Overlapping Beams	Overlapping level (dB)
#0	0	#0 ∩ #1(#2)	-2.0
#1	+0.2	#1 ∩ #2	-2.0
#2	+0.2	#0 ∩ #1 ∩ #2	-2.7

Table 1. Relative gain and beam overlapping level in shaded equilateral triangle in Figure 6

displacement is therefore $\sqrt{7}A \approx 0.32R$. The hexagon array uses 31 elements and achieves a 3dB scan coverage of 45.4°. Table 1 lists a summary of beam overlapping levels within the shaded area of Figure 6. The worst case is -2.7 dB at point O'.

4. Conclusions

A design of single and multiple beam CP substrate lens antennas has been presented in this paper. For the single beam design, an ellipsoidal lens is used which leads to diffraction limited pattern on-axis. The measured and computed 3 dB full-beamwidth is 6.4° and 6.8°, respectively. For the multiple beam design, an optimum hexagonal arrangement of planar array is chosen to maximize the scan coverage. The extension length is optimized to launch multiple beams with equal power density. The hexagon array uses 31 elements and achieves a 3dB scan coverage of 45.4°. Good circular polarization is maintained within the main lobes for both on- and off-axis beams indicating no detrimental depolarization effects. The presented substrate lens antenna is well suited for low-cost broadband point-to-point or point-to-multipoint wireless communications.

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