Two-Lens and Lens-Fed Reflector Antenna Systems for MM-Wave Wireless Communications

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1. Introduction

Recently the substrate lens antenna has been proposed for mm-wave broadband wireless communications [1-3]. The main advantages of this approach include highly directive antenna patterns, compatibility with IC techniques, suppression of surface-wave losses and the capability of multiple beam formation in a simple way. In [2], a realistic circularly polarized (CP) substrate lens antenna system operating at 30 GHz was demonstrated for single beam applications. Based on the same single lens antenna, a multiple beam circularly polarized antenna suitable for mm-wave broadband wireless communications was presented in [3]. However, both the reported single and multiple beam antennas employ a single lens which becomes bulky for high directivity applications at the low end of the mm-wave band.

In this paper, the characterization and design of 30 GHz two-lens and lens-fed reflector antenna systems is presented. In this approach, a hyperhemispherical substrate lens feeds either a larger but thin hyperbolic lens or a parabolic reflector. The attractive feature of these two-antenna systems is that it leads to a 75% reduction of the lens material, while maintaining about the same length and on-axis characteristics as the single lens antenna. In these 2-antenna systems, limited scan capability is possible which can lead to relaxed alignment requirements between a receiver and a transmitter for line-of-sight broadband wireless links.

2. Two-Lens Antenna

Figure 1a shows a schematic diagram of the two-lens antenna system. In this structure, a printed CP aperture coupled patch antenna [2] is used to excite a hyperhemispherical substrate lens which feeds a larger but thin hyperbolic objective lens. The system is focused when the hyperhemispherical lens is placed so that its virtual focus *F* coincides with the focal point of the hyperbolic lens *f*, as shown in Figure 1a. The lens is made out of Rexolite (ε_r=2.54) which is easy to machine and leads to a reduced cost. The radiation patterns through the lens are computed using a geometrical-optics/diffraction theory approach [4].

The characterization strategy employed here is to determine the optimum f/D number for different radii R of the hyperhemispherical lens in terms of system efficiency. The diameter of the hyperbolic lens is fixed to D=12cm aiming at a system directivity D_{sys}=30dB. The system directivity is calculated from $D_{sys}=4\pi U_{max}/P_{rad}$, where U_{max} is the maximum radiation intensity and P_{rad} is the power radiated by the printed patch. The corresponding system efficiency is defined as $\eta_{sys} = D_{sys} / (\pi D/\lambda_0)^2$, where λ_0 is the free space wavelength. The system efficiency can be decomposed according to $\eta_{sys} = \eta_1\eta_2\eta_s\eta_t$, where η_1, η_2 are the

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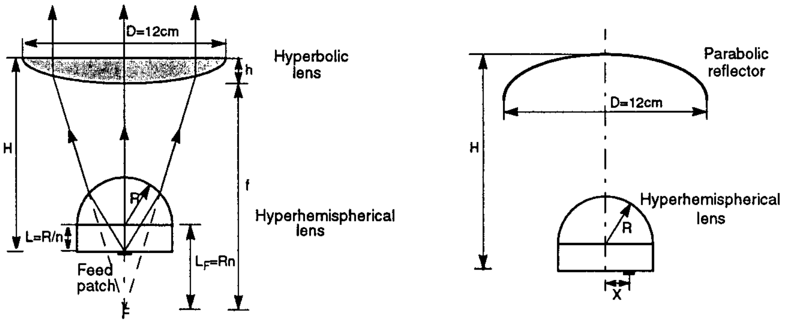

a) Two-lens system

b) Lens-fed reflector

Figure 1. Schematic diagram of the two-antenna systems at 30 GHz

transmission efficiencies through the feed and objective lenses, η_s is the spillover efficiency and η_t is the taper efficiency on the objective lens. Figure 2 shows the simulated system efficiency and its breakdown as a function of the f/D number for three different feed lens radii. The transmission efficiency η_1 is independent of the f/D number and is equal to 94.9% for various substrate lens radii R. As shown in Fig. 2, the optimum f/D numbers for R=1.0cm, 1.5cm and 2.0cm are about 0.90, 0.80 and 1.00, respectively. The corresponding system efficiencies are 43.2%, 43.8% and 43.1%. Among these three different radii, R=1.5cm is the best choice since it results to a greater weight reduction than R=2.0cm, while maintaining almost the same system efficiency. Indeed, the optimized two-lens system can achieve 75% lens material reduction compared to a single lens solution of the same directivity [2], [3].

The two-lens antenna can also be used to launch multiple beams by printing an array at the back of the hyperhemispherical substrate lens. The scan angle depends on the off-axis displacement *X/R* where *X* is the off-axis distance, and *R* is the radius of the hyperhemispherical lens. Figure 3 shows the scan characteristics of the optimum focused two-lens antenna system with R=1.5cm and f/D=0.80. The overall height H for the focused system is equal to 10.54cm. As shown, only limited scan angle, about 6.0° at *X/R* of 0.3, can be achieved for the focused system. One way to increase the scan capability is to reduce the distance between the substrate and objective lenses, leading to a defocused system. Figure 3 also shows the scan characteristics for two defocused systems with an overall height H of 9.14cm and 7.73cm. The scan angle is increased up to 9.6° at *X/R* of 0.3 for H=7.73cm. However, this is accompanied by a penalty of 2.0 dB reduction of the on-axis directivity. Similarly to the single lens antenna [3], there is no appreciable CP depolarization introduced in the two-lens system. In order to get a 3dB beam overlapping, the off-axis distance *X* for H=7.73cm is found to be 0.36cm (*X/R = 0.24)*. This implies that a patch array design with 3dB overlapping beams is possible since the maximum dimension of the used printed patches at 30 GHz is 0.25cm [3]. With the requirement of a system directivity degradation smaller than 1.5dB from the peak value, which corresponds to an allowed largest off-axis displacement $X/R = 0.30$ (See Fig. 3, H=7.73cm), the substrate lens can house 7 patches in a hexagonal arrangement. The resulting 3dB scan coverage is about 16.8^o, which can provide relaxed alignment requirements between a receiver and a transmitter for line-of-sight broadband wireless links.

3. Lens-Fed Reflector

The diagram of the lens-fed reflector is shown in Figure 1b, in which a reflector is used instead of an objective lens. This structure potentially provides improved system efficiency compared with the two-lens system, since the reflector introduces no reflection losses. In order to compare with the two-lens system, the diameter of the reflector D is also fixed at 12cm. Figure 4 shows the simulated system efficiency and its breakdown as a function of the f/D number for different substrate lens radii. As shown, the optimum f/D numbers for R=1.0cm, 1.5cm and 2.0cm are about 0.75, 0.83 and 0.92, respectively. The corresponding system efficiencies are 57.2%, 61.3% and 57.2%. Similarly to the two-lens system, the optimum radius of the hyperhemispherical lens occurs at R=1.5cm. From the efficiency analysis, both the two-lens system and the lens-fed reflector exhibit a similar taper efficiency. However, the two-lens system suffers from an additional 11% transmission loss (η_2=89%), and demonstrates lower spillover efficiency (η_s=68%) than that of the lens-fed reflector (η_s=80%). Figure 5 shows the scan characteristics of the lens-fed reflector with R=1.5cm and f/D=0.83 for H=8.55cm (focused position), H=7.36cm and H=6.16cm. The scan angle is about 11.0^o at X/R of 0.3 for H=6.16cm.

4. Conclusions

Compared with a single substrate lens antenna, the described 2-antenna systems can achieve up to 75% reduction of the lens material while maintaining about the same length and on-axis characteristics. The lens-fed reflector provides higher system efficiency than the two-lens system. This makes the lens-fed reflector appealing for single beam applications. In these 2-antenna systems, limited scan capability with multiple beams cross-coupled at a 3dB level is possible, which can lead to relaxed alignment requirements between a receiver and a transmitter for line-of-sight broadband wireless links.

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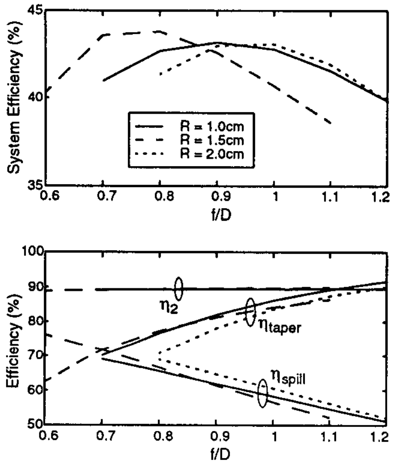

Figure 2. System efficiency of the focused two-lens system and its breakdown

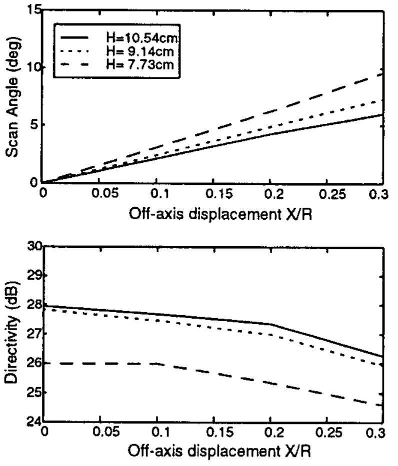

Figure 3. Scan characteristics of the two-lens antenna: R=1.5cm, f/D=0.80

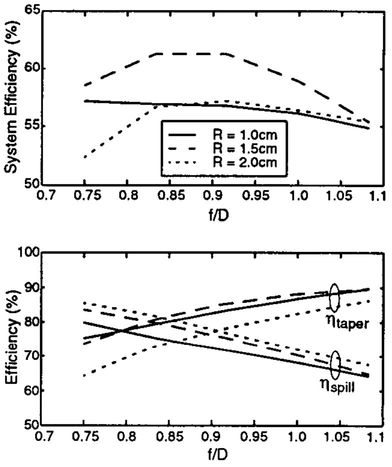

Figure 4. System efficiency of the focused lens-fed reflector and its breakdown

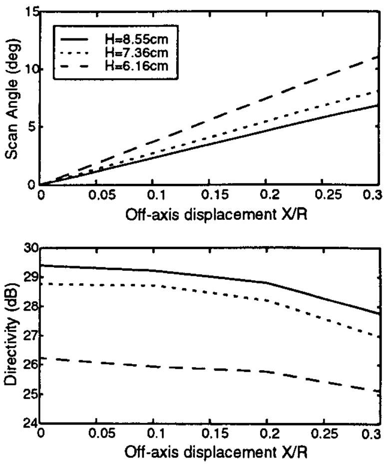

Figure 5. Scan characteristics of the lens-fed antenna: R=1.5cm, f/D=0.83