Compact Multibeam Imaging Antenna for Automotive Radars

Bernhard Schoenlinner and Gabriel M. Rebeiz

Abstract—**A compact multi-beam 77 GHz antenna has been developed for automotive applications. The antenna consists of a hemispherical Teflon lens with backside metallization, which is fed by endfire tapered slot antennas (TSAs) on a 127μm-thick Duroid^{TM} substrate. The TSAs are arranged in a circular arc covering 40° around the hemispherical lens. The measured patterns result in E and H-plane patterns with a 3-dB beamwidth of 5.5°, a sidelobe level of -18 to -20 dB and a cross-polarization level of -19 dB. The calculated efficiency of this antenna system is 54%. The off-axis antenna patterns are identical to the broadside patterns due to the symmetrical structure of the antenna. The antenna can provide 35-40° coverage using a circular feed array around the hemispherical Teflon lens.**

I. Introduction

Radars at 60 GHz to 94 GHz are currently being developed for control systems in a variety of mobile applications. Most systems employ 3-5 beam switched antenna using a standard focal-plane system with a collimating lens of f/0.7-f/0.9 [1][2]. A focal-plane system with f/0.9 allows the formation of 9-11 beams, but the scanning performance is limited due to off-axis aberrations. The challenge is to develop a compact, low-cost solution to wide-angle scanning systems at mm-wave frequencies.

There are several methods of achieving a wide-angle system without mechanical scanning. An excellent design is given by Demmerle, Kern and Wiesbeck [3] using a bi-conical antenna and radial feed points, but this is applicable up to 3 GHz. Another method is the use of a Luneburg lens [4], but this requires a graded dielectric lens which is expensive to manufacture at mm-wave frequencies. Instead of a Luneburg lens, a simple uniform spherical lens can be used which results, when well designed, in excellent patterns [5], and is therefore a good candidate for wide-angle scanning systems.

This paper shows a compact version of this technique, using a hemispherical uniform lens with backside metallization. The compact version occupies half of the space of the standard spherical lens design.

II. Design of the Hemispherical Lens

A hemispherical Teflon lens with a dielectric constant $\varepsilon_r = 2.1$ is shown in Fig. 1. The radiating aperture is $2R$, where R is the lens radius. The optical focal point, defined for small angles from the lens axis ($\phi = 0°$), is:

$$F = \frac{Rn}{2(n-1)} \qquad (1)$$

and for a Teflon lens we find that $F = 1.61R$. However, at microwave/mm-wave frequencies, the feed antenna illuminates the entire lens surface and a full electromagnetic analysis is needed. The analysis is done by taking the pattern of the feed antenna ($f(\theta, \phi)$), propagating it to the hemispherical lens surface, calculating the TE and TM transmission coefficients at the lens surface, propagating the wave into the lens until it hits the metal layer, where it is reflected, propagating the wave further until it hits the lens surface a second time, calculating again the TE and TM reflection coefficients at the lens surface, and finding the total electric field at the output surface of the hemispherical lens [6]. This is basically a ray-optics analysis but including polarization effects. In this analysis, we have neglected the power which is reflected from the lens surface at the second transition, which bounces 2-3 times inside the lens before it is finally radiated. The total electric field on the aperture of the lens is then integrated using a Fraunhofer calculation to determine the far-field pattern.

The EM analysis results in the spillover loss, the amplitude taper loss, and the non-uniform phase loss. Fig. 2 presents the results for a Teflon lens with a feed pattern given by $\cos^n \theta$, and n is chosen so as to result in a -10 dB beamwidth of 60, 80, and 100°. The simulations indicate that the optimum position of the feed antenna with respect to the lens is at a distance between $0.3R$ and $0.5R$ away from the lens surface. A system efficiency of 50-55% is achievable for a large range of feed pattern beamwidths. This is in contrast to standard f/0.7-0.9 lens systems where one can achieve a system efficiency of 70-75%. As usual, the 60° feed antenna suffers from a large taper loss, while the 100° feed antenna suffers from a large spillover loss. We have chosen to implement our design with a feed antenna with a -10 dB beamwidth of $\simeq 70°$ beamwidth.

III. Pattern Measurements

The feed antenna is an endfire tapered slot antenna with parameters given in Fig. 3. This antenna has been developed by Sugawara et al. and has been scaled for 77 GHz applications [7]. The antenna is fabricated using standard lithography and copper etching on a 127μm-thick Duroid substrate with $\varepsilon_r = 2.2$. A slot-line to microstrip transition is defined at the end of the tapered-slot antenna and a planar Schottky diode is used as the mm-wave video detector. The transmitted signal from a Gunn diode is modulated at 1 kHz, and the detected video signal is sent to a lock-in amplifier. The signal to noise ratio is limited by the measurement chamber, the linearity of the lock-in amplifier, and the diode responsivity, and is 30 dB at 77 GHz.

The measured feed patterns are shown in Fig. 3 and result in a -10 beamwidth of 70-74° in the E and H-plane patterns. The cross-polarization levels are lower than -10 dB. The E-plane patterns with the hemispherical lens were measured by placing feed antennas in a circular fashion around the lens, starting from $\phi = 0°$ all the way to $\phi = -90°$. The distance between feed antenna and lens was 10 mm ($0.4R$) and the feeding antennas

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were placed in a distance of 5.3 mm or 8° from each other in order to achieve a −6 dB overlap of adjacent antenna patterns. The feed antennas are all fabricated on one piece of substrate, which causes scattering of the electromagnetic field, especially for the feed antennas close to $\phi = 0°$. This scattering, however, is kept small, because the substrate is very thin. The best pattern occurs around an angle of $\phi = -25°$ since the radiated pattern from the lens does not interact with the feeding antennas.

The measured E-plane pattern with the hemispherical lens with R =25 mm for an incident angle of $\phi = -25°$ is shown in Fig. 4. The sidelobe level is −20 dB and the cross-polarization level is below −19 dB. The −3 dB beamwidth is 5.5° and the −10 dB beamwidth is 9.5°. The measured and normalized E-plane patterns for different antennas are shown in Figure 5. The optimum performance is achieved at an arc-angle between $\phi = -10°$ and −45°. For angles greater than −10°, scattering from the feed results in −14 dB sidelobes. At angles smaller than −45°, the power is scattered by the edge of the groundplane. Also, there is a substantial amount of spill-over loss. The spill-over efficiency due to the angle tilt is shown in Figure 6. The measured gain at different incident angles is compared to $\phi = 0°$, which is normalized to 1. Any loss in gain is due to the increased spill-over at incident angles $\phi < 0°$.

IV. Gain Measurements

For the absolute gain measurement, a spherical lens was used instead of the hemispherical lens with backside metallization for easier measurement. The absolute gain was measured using the standard-gain technique (with a calibrated transmitting horn antenna) and the Friis transmission formula. The TSA is replaced by a small pyramidal waveguide horn with an aperture of $2.7\lambda_0 \times 1.9\lambda_0$ to result in a −10 dB beamwidth of 70°. The transmitted power from the Gunn diode and the received power were both measured using a mm-wave power meter.

The measured radiation patterns of the horn/spherical-lens are nearly identical to the patterns shown in Figure 5 and will not be repeated. The measured gain, G_m, and system efficiency vs. position are shown in Fig. 8. The efficiency is defined as G_m/D, where $D = 4\pi A/\lambda^2$ is the maximum directivity of the lens aperture. As seen in Fig. 8, the measured efficiency agrees fairly well with theory. Differences can be explained by the loss in the Teflon lens, which was not taken into account in the calculations. The absorption coefficient of Teflon at 77 GHz is around 0.012 Np/cm [8] which results in a loss of around 0.5 dB. Also, the location of the phase center of the horn may be the reason for additional deviations.

V. Conclusions

This paper presented a 77 GHz antenna system. This system is an excellent solution for multibeam wide scan-angle systems as it is used in automotive applications through its compactness and low cost of fabrication. The system consists of a 5 cm hemispherical Teflon lens with backside metallization, which is fed by endfire tapered slot antennas on a Duroid^{TM} substrate, which are placed around the lens in a semi-circular fashion. The maximum scan angle is 35° with excellent patterns and a sidelobe level of −18 dB. The tapered-slot antennas can be placed on an arc as close as 5.5° next to each other, resulting in a −3 dB overlap of adjacent antenna patterns. The measured system efficiency is close to 50%. The system efficiency includes spillover loss, amplitude taper, non-uniform phase, reflection and lens-absorption loss. The size of the antenna-lens system is 8 cm×5.5 cm×5 cm.

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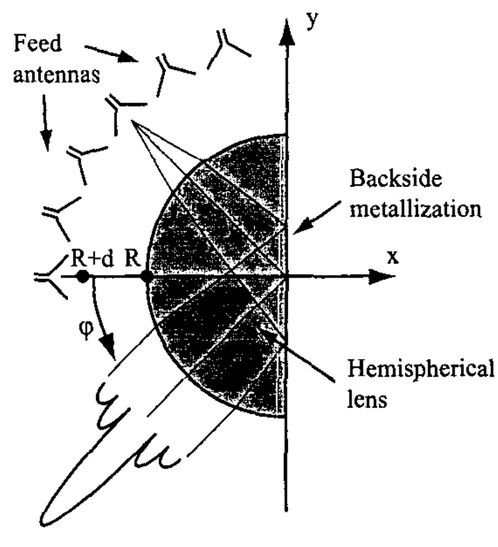

Fig. 1. Layout of the hemispherical lens antenna system with a backing reflector.

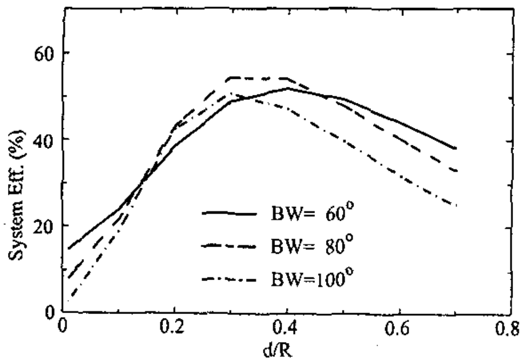

Fig. 2. Calculated system efficiency for different feed antenna beamwidths vs. position from the lens.

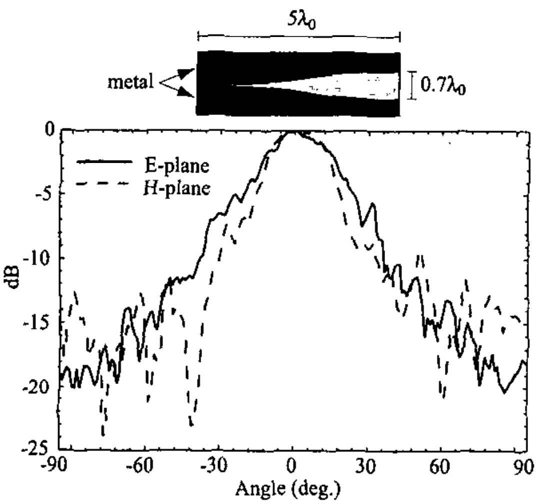

Fig. 3. The 77 GHz tapered slot antenna and the measured E and H-plane feed patterns.

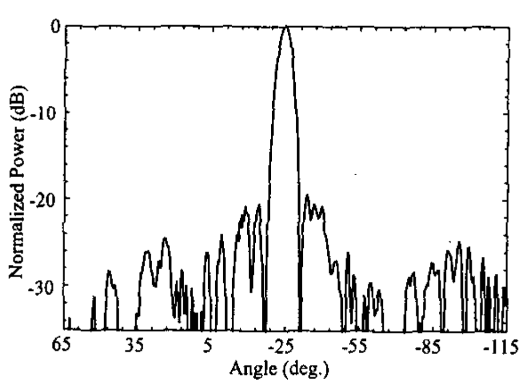

Fig. 4. Measured E-plane patterns for an incidence angle of $\phi = -25°$.

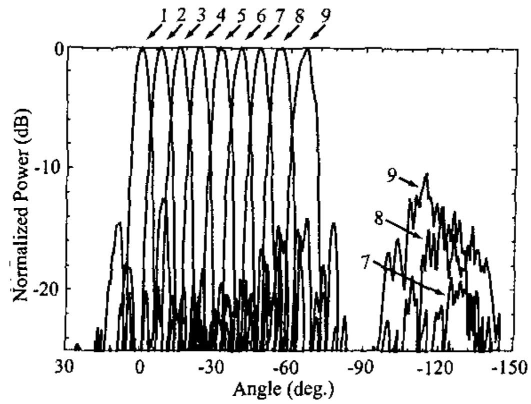

Fig. 5. Measured and normalized E-plane patterns for incident angles of $\phi = 0°$ to $\phi = -64°$. The cross-over is -6 dB.

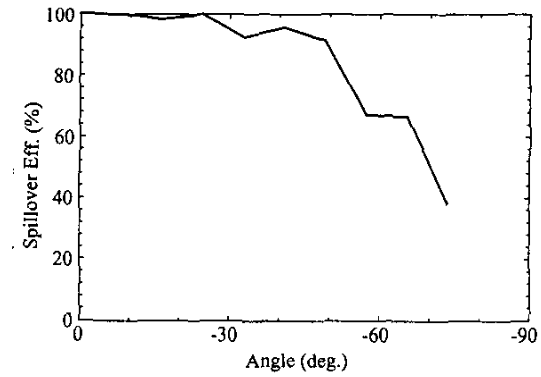

Fig. 6. Measured spill-over efficiency vs. incident angle normalized to $\phi = 0°$ for the hemispherical-lens system.

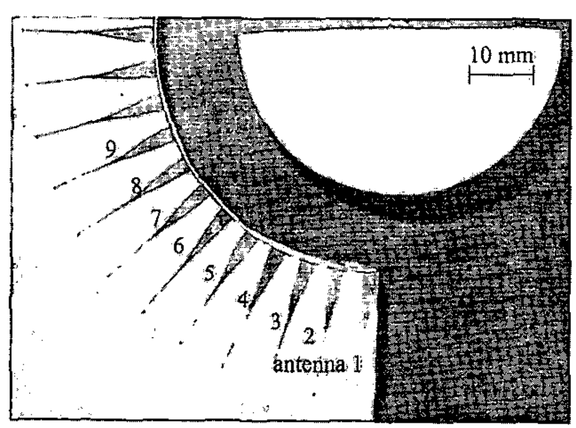

Fig. 7. Picture of the antenna system with hemispherical Teflon lens with backside metallization and different feed antennas, resulting in a -6 dB crossover of adjacent beams.

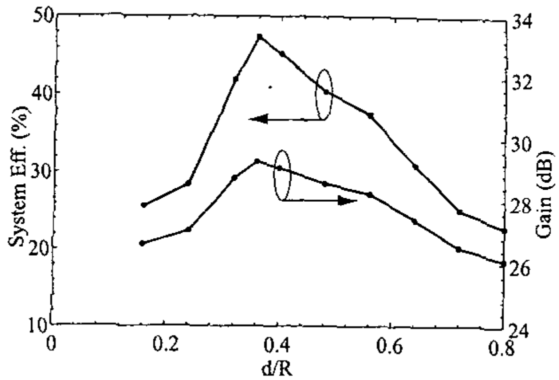

Fig. 8. Measured system efficiency and gain vs. distance between the feed antenna and the Teflon lens.