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Thornton, J. (2004) A low sidelobe asymmetric beam antenna for high altitude platform communications. IEEE Microwave and Wireless Components Letters. pp. 59-61. ISSN 1531-1309

https://doi.org/10.1109/LMWC.2003.822566

A Low Sidelobe Asymmetric Beam Antenna for High Altitude Platform Communications

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Abstract—**In a communications network served by a high altitude platform, the antenna beams illuminating each cell require minimized sidelobe powers. Asymmetric beams are advantageous so that cell footprints remain circular. At millimeter wavelengths a lens antenna can have the desired properties. We have chosen a 6 km diameter cell at 32° elevation angle and shown how the required beam asymmetry can be implemented using an optimized polynomial for describing the lens profile. The measured average sidelobe level is below −42 dB.**

Index Terms—**High altitude platform, lens antenna.**

I. Introduction

THIS work stems from current interest in high altitude platforms (HAPs) and their potential for delivering broadband wireless services [1], [2]. The work focuses on the band at 28 GHz, but may scale to higher frequencies, e.g., 47/48 GHz which are allocated for HAPs worldwide [3]. HAPs present a promising vehicle for exploitation of these bands by supporting line-of-sight links. To allow spectral re-use in cellular networks, each cell is served by a spot beam antenna on the HAP. Low sidelobe levels are important to minimize co-channel interference. Another objective is an asymmetric beam which has a circular power footprint on the ground, illustrated by Fig. 1(a) which shows power contours for a cell of 6 km diameter served by a HAP at a height of 17 km. The example is taken from studies of a network of 121 cells covering a 60 km diameter region [2], [4]. A circular beam yields an elongated power footprint as shown in Fig. 1(b). Circular power contours present advantages: geographic coverage is better, and the link budget across the coverage area is more uniform. Also, communications performance may be investigated with established tools and models for terrestrial cellular networks [5].

To minimize sidelobe levels it is necessary to use a severely tapered aperture distribution. A uniform distribution maximizes directivity but is accompanied by the highest sidelobe levels, while a tapered distribution yields lower sidelobes, a wider main lobe and hence reduced directivity. Often a compromise must be reached where the aperture area is not excessive for a given required directivity and sidelobe level. However for this application the cell size dictates the required beamwidths [4] and hence maximum directivity is not sought.

In general, a rectangular or elliptic aperture will yield an asymmetric beam, and candidates could be a waveguide horn or a section of a parabolic reflector. The former has poor sidelobe performance. The latter is a popular choice for many applications, but requires a suitably tapered illumination to keep sidelobe levels acceptably low. This is often achieved by using a short, wide-angle corrugated horn but this yields a circularly symmetric beam. As the beam shape is a function of the illuminated region of the aperture, a parabolic reflector would require an asymmetric primary feed to yield an asymmetric secondary field. The problem is thus one of choosing a low-sidelobe primary feed with an asymmetric beam which is sufficiently narrow to provide the required amplitude taper. The need to offset-feed the reflector so as to avoid aperture blockage presents a further complication. This lead us to consider instead

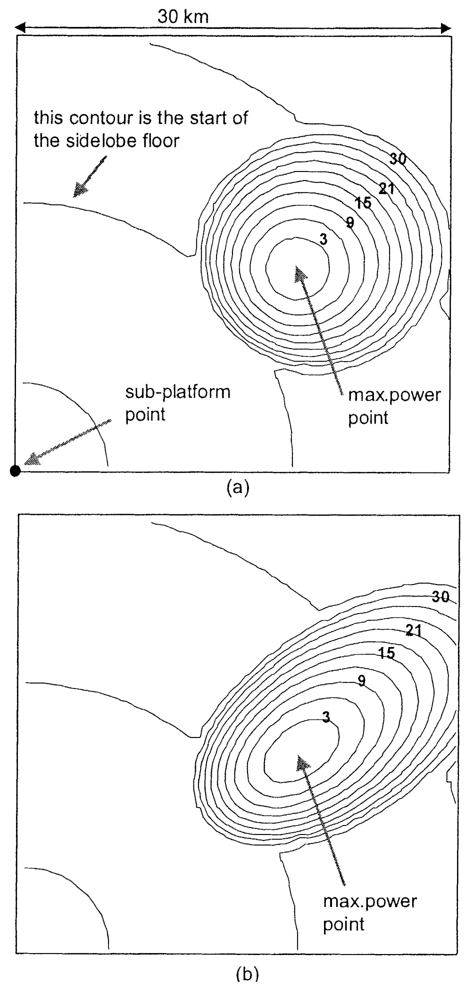

Fig. 1. Power footprint of HAP cell for: (a) an asymmetric beam and (b) a circular beam. (Labels:- dB power relative to cell maximum).

Manuscript received July 15, 2003; revised November 6, 2003. The review of this letter was arranged by Associate Editor Rüdiger Vahldieck.

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Digital Object Identifier 10.1109/LMWC.2003.822566

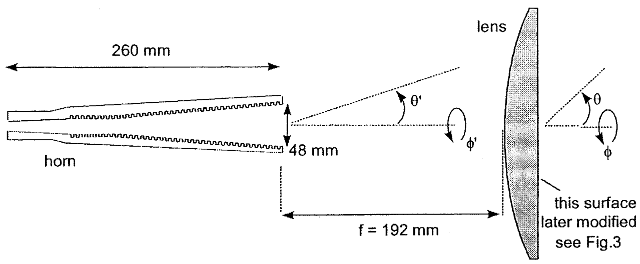

Fig. 2. Geometry of primary feedhorn and lens.

the properties of a lens as the secondary aperture, as this is a popular choice for medium-to-high gain mm-wave antennas and suffers no inherent blockage by the primary feed. A lens is also more tolerant to surface manufacturing errors. The following section reviews the properties of the lens antenna and describes the asymmetric beam variant which was developed.

II. Design Rationale for Asymmetric Beam Lens Antenna

The properties of dielectric lenses as microwave antennas are discussed by [6]–[8]. Our target half power beamwidths (HPBW) are 5.0° and 9.4°. As a starting point, we constructed a lens with one refracting surface (called "type 1" in [7]). The aperture field distribution after [6] is

$$A(r) = \sqrt{\frac{(n\,\mathrm{Cos}\,\theta' - 1)^3}{f^2(n-1)^2(n - \mathrm{Cos}\,\theta')}} F_p(\theta') \qquad (1)$$

where n is the lens refractive index, r the normalized aperture radius, and f the focal length. $F_p(\theta')$ is the primary feed far field pattern as a function of angle θ'. The radiation pattern may be computed from the transform of the aperture field (1) to the far field. We have used a corrugated horn of 17° HPBW as the primary feed, whose far field pattern after [7] is given by

$$F_p(\theta') = (1+\cos\theta') \int_{r=0}^{r_1} \mathrm{J}_0[k\,r\,\sin\theta']\mathrm{J}_0\left[2.405\frac{r}{r_1}\right] \times \exp\left(-j\frac{kr^2}{R}\right)\frac{r}{r_1}\,dr \qquad (2)$$

where k is the wave number, the horn aperture radius is r_1, and its flare radius—a consequence of the conical horn's taper—is R. The horn used had length 260 mm and aperture diameter 48 mm. Using a polyethylene lens of 160 mm diameter with this feed (see Fig. 2) yielded a 5° symmetric beam with low sidelobes and giving an excellent agreement between measurement and the above theory for the main lobe pattern and HPBW. We then sought to modify the aperture phase distribution to yield an asymmetric beam, i.e., to broaden the beamwidth in one plane while leaving the orthogonal plane substantially unaltered. It is known that a linear phase error across an aperture results in scanning of the far field, while a quadratic term tends to broaden the main lobe which in the extreme leads to bifurcation. Our method was to investigate the effect of various functions for phase shift across the aperture x axis illustrated in Fig. 3

$$\beta = f(r\,\cos\phi') \qquad (3)$$

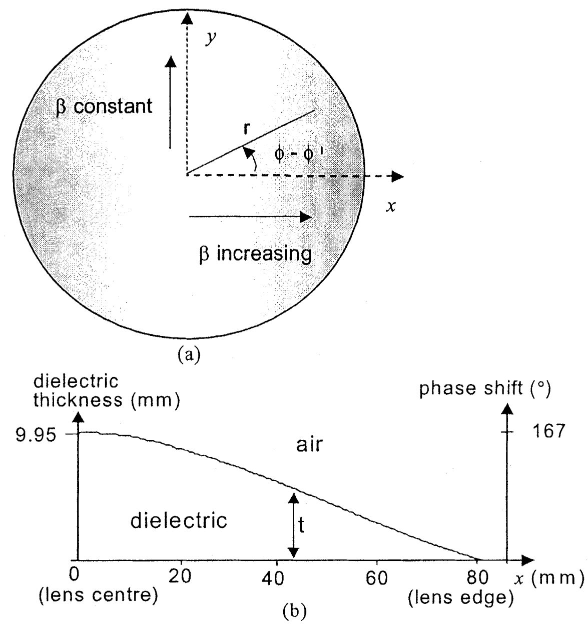

Fig. 3. Phase slope across lens aperture: (a) geometry of phase term and (b) machined convex surface.

where phase shift β is a function of normalized radius r. The test functions used were polynomials in $r\cos\phi'$, hence β varies along x but not along y.

The new lens aperture function is now (1) multiplied by $\exp(-jk\beta)$. The far field can be computed from the two dimensional integration of the aperture distribution to allow for the azimuth (ϕ) dependency

$$E(\theta,\phi) = \int_{\phi'=0}^{2\pi}\int_{r=0}^{1} A(r,\phi') \times \exp(jk\sin\theta\, ra\cos(\phi-\phi'))r\,dr\,d\phi'. \qquad (4)$$

The far field pattern (4) was evaluated numerically for various experimental functions, e.g., cubic polynomials

$$\beta = a|x| + b|x|^2 + c|x|^3 \qquad (5)$$

where

$$x = r\cos(\phi-\phi'). \qquad (6)$$

A function of type $(\cos\theta)^{\mathrm{m}}$ [4] was used to represent the "target" 9.4° main lobe. The coefficients a, b, c for the phase slope polynomial were varied, initially using small values so as to give a phase shift of a few degrees per wavelength over the aperture. A linear function was found to give a poor fit to the target curve. A quadratic term gave a much better fit, and this could be fine-tuned with the addition of a smaller cubic term. Following an optimization process, the best fit for the required 9.4° HPBW in the plane $\phi = 0$ was obtained using

$$a = 0, \quad b = \frac{\pi}{180} \quad \text{and} \quad c = -0.07\frac{\pi}{180}. \qquad (7)$$

To physically yield this phase slope across the lens surface, the dielectric thickness as a function of distance x [see Fig. 3(b)]

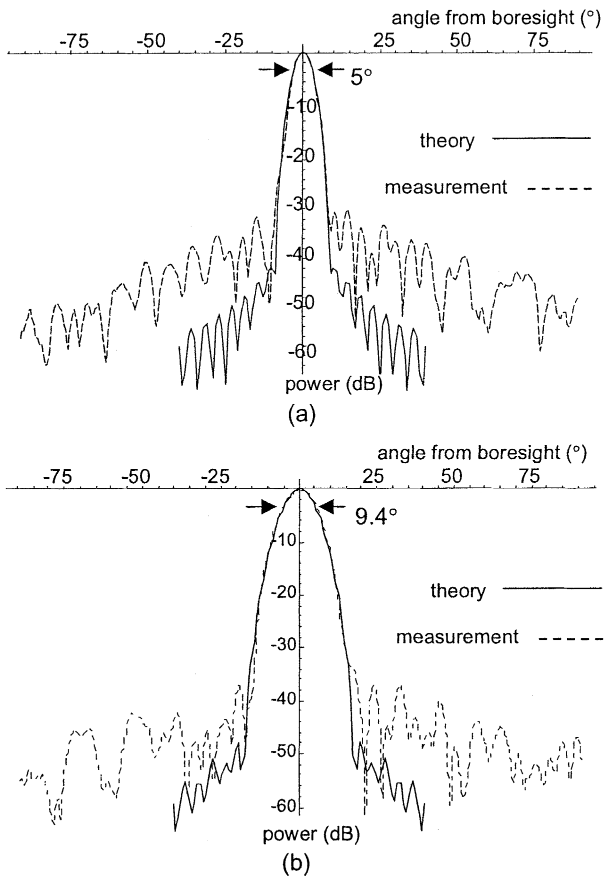

Fig. 4. Asymmetric lens antenna measured radiation patterns at 28 GHz. (a) $\phi = (\pi/2)$, narrow beam and (b) $\phi = 0$, wide beam.

was derived by considering the phase shift introduced by a dielectric of thickness t where

$$t = \frac{\lambda\beta}{2\pi\,(n-1)}. \tag{8}$$

For polyethylene $n \approx 1.5$. The phase slope was yielded physically by machining the cubic profile into the front face of the lens i.e., the face which is otherwise flat.

III. Results

The measured radiation patterns of the asymmetric lens with the corrugated feedhorn are shown in Fig. 4. We do not refer to E-plane and H-plane patterns, because the very high symmetry of the primary feed renders the measurements invariant to the E-field orientation of the feed.

The measured first sidelobes are at -32 dB and -38 dB, respectively, for the narrow and wide beams. For a system of many co-channel beams, the mean sidelobe level is the more important parameter [4], this being -42 dB and -44 dB, respectively. This corroborates the assumption that a sidelobe level of between -40 dB and -50 dB is valid for modeling co-channel interference [2], [4] in a network of many cells.

IV. Conclusion

For equal size, circular cells in a high altitude platform cellular network, asymmetric antenna spot-beams are advantageous. For the mm-wave bands, these can conveniently be produced using aperture antennas. For suppression of co-channel interference minimized sidelobe levels are vital. We have sought half power beamwidths of 5° and 9.4° at 28 GHz. A 160 mm diameter polyethylene lens, initially with one refracting surface and illuminated with a corrugated horn primary feed exhibited a 5° circular beam. A method was developed where a cubic phase function across one lens axis widened the beam in one plane only, thus yielding the required asymmetry. This was optimized in an iterative routine. The phase term was realized physically by machining the second lens surface (the surface which would otherwise be flat). The measured radiation pattern showed excellent agreement with the theoretical main lobe shape and beamwidths, while the mean sidelobe levels remained below -42 dB relative to boresight gain.

Acknowledgment

Thanks to R. Easton and staff at the University of York's Physics and Electronics mechanical workshops for machining the dielectric lens.

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