Performance Characteristics of Phase-Correcting Fresnel Zone Plates

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ABSTRACT

This paper gives specific measured and/or theoretical characteristics of phase-correcting zone plate antennas. Parameters described include off-axis performance, axial intensity dependence, efficiency, distortion and aberrations, and bandwidth. Measured data are summarized for 10, 94, and 140 GHz. This type of zone plate has advantages (compared to a lens) of reduced loss, weight, volume, cost, and planar construction, with similar diffraction-limited beamwidth and major-sidelobe performance, but lower efficiency.

Introduction

The Fresnel zone plate is a planar device which has lens-like properties and can be used for focusing and imaging electromagnetic waves, as shown in Figure 1. These functions are produced by diffraction and interference, rather than refraction. The zone plate transforms a normally-incident plane wave into a converging wave, concentrating the radiation in a small region about a point which has the characteristics usually associated with the focal point of a lens. The zone plate offers advantages compared to a lens in terms of simplicity (flat construction, no curvature) and reduced thickness, weight, and absorption loss (1-5). There are two basic types: one where alternate concentric zones are made opaque and the second where phase correction is introduced in successive zones. Figure 2 compares the zone plate with other lens-type devices. The partially-opaque version is not efficient, since it rejects about half of the available energy, and is of limited interest in practice. However, numerous analyses have been carried out for the partially-opaque plate, and these results are relevant to the phase-correcting case. The analyses have dealt with aberrations (such as chromatic and off-axis aberrations) (6), the axial and lateral intensity distribution near the focus (3,7), and off-axis imagery (7).

Fresnel zone plates have been used at frequencies from the microwave range (8) to the x-ray region (6). Our interest, however, is in understanding and using phase-correcting plates at millimeter and microwave frequencies. Such zone plates have not been fully characterized theoretically or experimentally. For example, a useful analytical expression for the far-field pattern has not been obtained, although antenna patterns have been measured for a variety of specific designs. In the present paper results will be given involving bandwidth, efficiency, distortion, aberrations, and quasi-optical filtering possibilities.

Zone Plate Design

The phase-correcting zone plate typically consists of a set of planar concentric annular rings cut into a flat piece of low-loss dielectric material such as polystyrene. For a phase-reversing plate, the successive radii of these zones are chosen so that the distance from the focal point on the central axis increases by one-half wavelength in going from the inner to the outer radius of any ring. Assuming a plane wave to be normally incident on the zone plate, the portions of the radiation which pass through different zones on the plate all reach the focal point with phases which differ by less than one-half period. This phase-correction leads to the focusing action of the zone plate. The radius of each zone, r_n, for the phase-reversing case, is given by

$$r_n = \sqrt{nf\lambda_0 + (n\lambda_0/2)^2}$$

where n is the zone number, f is the focal length and λ_o is the wavelength of the incident radiation. The different phases for each zone are implemented by cutting annular grooves into the dielectric material. For the phase-reversing plate, grooves of depth d are cut into alternating zones with d given by

$$d = \frac{\lambda_0}{2(\sqrt{\epsilon_r}-1)}$$

where λ_o is the free space wavelength and ϵ_r is the dielectric constant of the material.

Another example of the phase-correcting zone plate is that of the quarter-period plate. In the quarter-period case, the phase correction is introduced every quarter-wavelength instead of every half-wavelength. The intensity at the focal point is greater for the quarter-wave plate than for the phase-reversing case. However, the relative increase in focal intensity diminishes noticeably for a phase-correction beyond that of a quarter period.

Measurements and Applications

Early investigations developed formulas for calculating the radii and depth of annular cuts,

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measured the axial intensity variation near the focus and measured antenna patterns at 10, 140, and 210 GHz (1,3). Measurements have been made of off-axis image intensity and image position errors at 140 GHz, and the results are excellent. For a variance in the source direction of ± 22° the image point angle (with respect to the optical axis) was found to vary only within a range of ± 0.4°. For a source angle variation of ± 20°, the image distance was found to remain within 2% of the focal length. Finally, if the source angle varied within a range of ± 11°, signal strength remained within 3 dB of peak signal strength. For angles of ± 20°, signal loss was less than 6 dB. In related measurements at X-band, Sanyal and Singh (3) have determined the lateral variation of intensity at the focal plane, and they also measured the axial intensity distribution (sometimes exhibiting double foci) for the partially-opaque zone plate. They also used a "dielectric ring" plate, but it was not properly designed to be a phase-correcting device because the groove depth was much too small. The pattern obtained essentially was that of two partially opaque zone plates (located in the same plane) with differing focal points, resulting from the different thicknesses of the plates.

The zone plate can be used as a transmission element or, with a conducting plane, as a reflecting element (2,5). Van Buskirk and Hendrix (5) demonstrated that a partially-opaque zone plate can have a focus for reflection as well as transmission. If the opaque rings are constructed from conducting material, they can be used as sources of reflection. When a ground plane is used just behind the zone plate, both foci are brought into coincidence. Using this method, Huder and Menzel (2) have investigated a flat, printed reflector antenna. This antenna, with a diameter of 12.5 cm, was fabricated from RT/Duroid 5880 (Rogers Corporation), and its metallic annular rings were made by etching techniques. An open-ended WR-10 waveguide was used as a feed. Measured radiation patterns at 94 GHz show a clean mainlobe (1.6° half-power beamwidth) and a sidelobe level of about -25 dB, as shown in Figure 3 (taken from their paper) (2).

Another potential application of the zone plate is in the area of integrated optics and integrated circuitry. Young (6) shows zone plates to be useful in a situation where a "closely spaced array of high-aperture imaging optics" is needed. The individual zone plates may be used in an overlapping fashion to produce the required imaging, thus giving a considerable advantage over lens optics.

Performance Parameters

Since the zone plate accomplishes focusing through diffraction and interference, rather than refraction, the overall efficiency for collecting the radiation flux that passes through the aperture is an important consideration. This efficiency has been determined analytically to be approximately 40.5% for a phase-reversal plate and 81% for a quarter-period plate. Thus the intensity at the focus relative to that produced by a hyperboloidal lens is 3.9 dB down or 0.9 dB down, respectively, for the phase-reversal or quarter-period cases (3,4).

A lens exhibits known aberrations, of course, and by analogy one can consider aberrations of the zone plate. Young (6) has demonstrated that the zone plate may have a "spherical" aberration if not properly designed. He found that this would become more significant as the number of zones is increased. In addition, he demonstrated that coma, astigmatism, and field curvature are also dependent on the number of zones. It was found that for a large number of zones coma dominates, while for a small number of zones the latter two aberrations dominate. Since no distortion term appears in the aberration expressions, the zone plate is completely distortion-free over a large image field. Young as well as Black and Wiltse (1) and others (3) have investigated the frequency-dependent nature of the zone-plate structure. Different frequencies focus to different points along the zone-plate axis. This effect is analogous to the chromatic aberration found in the optical regime. This has been analyzed by Sussman (7), and analysis and measured results have been compared by Sanyal and Singh (3), but in both cases the results were obtained for a partially-opaque plate. The characteristic can be used for focal isolation, frequency filtering, and spatial filtering. Zone plate bandwidth has been shown to be considerable. For example, Black and Wiltse (1) showed the 3-dB bandwidth for one particular half-period zone plate to be approximately 15 percent of the plate's design frequency, and this is similar to the bandwidth shown in Figure 7(a) of Reference 3.

Far-field Pattern

A subject that is under investigation is the development of an analytical expression for the far-field antenna pattern. Since the zone plate consists of a series of concentric annuli, the far-field pattern of the entire plate may be obtained by superimposing the contributions from each individual annulus, or zone. Given a specific phase and amplitude illumination in the annular aperture, the Kirchoff-Fresnel integral is used to obtain the diffraction pattern resulting from each zone. This integral expression also contains a factor which indicates the relative phase change induced by passage through the particular zone.

Numerous workers (9-13) have attempted a closed-form solution of the zone plate pattern, but their results have been unsatisfactory. The approximations made in the Kirchoff integral were unsuitable for typical microwave and millimeter wave applications. In these solutions, the focal length was assumed to be quite large with respect to the aperture diameter (large f-number). However, an f-number on the order of one is desirable for most microwave and millimeter-wave systems. The key problem in the quest for a pattern solution is in the solving of the integral for a single annulus. Many others (9, 11-13) have given a fairly simple prescription for the summation of the contributions from each annulus. If a solution were obtained for this "core" integral, one could simply calculate the algebraic sum of each zone's integral solution. Given the unlikely prospect for obtaining an analytical expression for the Fresnel zone plate antenna pattern, future investigation may turn to a numerical solution. Even though a numerical calculation lacks insight into the physical aspects of the solution, it provides a basis on which to compare theoretical results with those of the experimentally determined far-field patterns.

Conclusion

It is evident that a great deal of work with Fresnel zone plate antennas has been done by numerous investigators in recent years. The equivalency between the zone plate and the hologram has also been shown (14). A significant amount of specific information is now available to quantify the use of zone plates, and these results have been pulled together and summarized. Applications include such transmit or receive cases as communications, radar, and missile seekers, particularly where low weight, loss, and cost are important.

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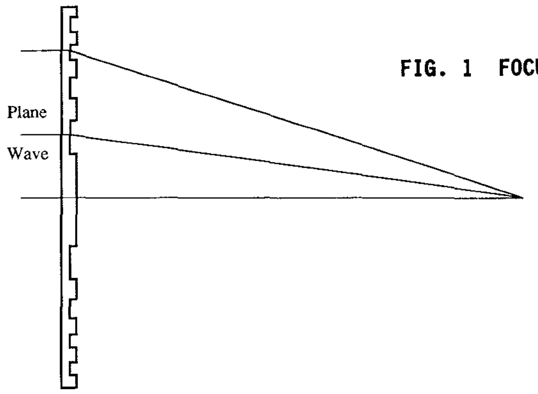

FIG. 1 FOCUSING EFFECT OF A PHASE-CORRECTING ZONE PLATE

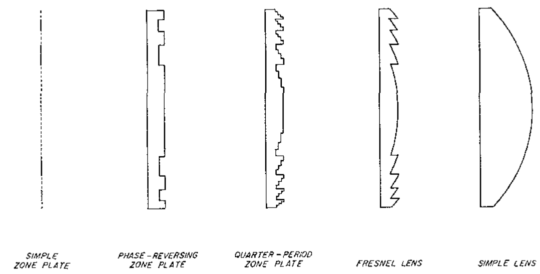

FIG. 2 RELATION BETWEEN LENSES AND ZONE PLATES

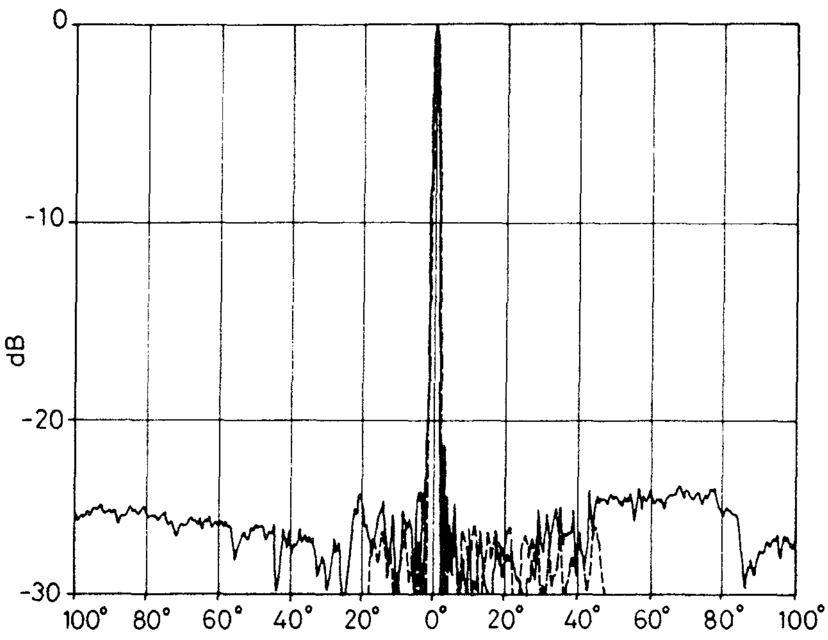

FIG. 3 MEASURED RADIATION PATTERNS AT 94 GHz (Ref. 2)

_________ H-plane
\- - - - - - - - - E-plane