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# MILLIMETER-WAVE FRESNEL ZONE PLANAR LENS AND ANTENNA

H. D. Hristov*, and M.H.A.J. Herben**

* Technical University of Varna, Department of Radiotechnics, Varna , Bulgaria
** Eindhoven University of Technology, Department of Electrical Engineering, The Netherlands

## Abstract

A new variety of millimeter-wave Fresnel zone planar lens with enhanced focusing quality is described. Each full-wave zone is divided into four quarter-wave subzones covered by equal in thickness dielectric rings having different permittivities. More precise expression for the lens thickness is deduced. On the base of this planar lens configuration a Fresnel-zone lens antenna with about 52% aperture efficiency for a frequency of 62.1GHz is developed and examined theoretically.

## 1. Introduction

The Fresnel zone lens with transparent/reflecting (absorbing) rings has inadequate focusing properties and the radiation efficiency of the corresponding lens antenna is less than 15%.

To utilize the destructive zone apertures and increase the lens focusing quality Wiltse (1976) replaced the reflecting (absorbing) rings by phase-reversing dielectric ones and thus a half-wave planar dielectric lens was introduced [1,2]. This lens configuration has much better focusing properties and compared with grooved Fresnel lens [3] it shows a shape advantage that the front and back surfaces are flat.

Based on the planar phase-reversing dielectric lens transmissive-type antennas have been developed and examined [3-7]. For these antennas a radiation efficiency of about 25-30 % is typical. But from a commercial point of view the overall antenna efficiency of microwave aperture antennas has to be at least 50 % .

In this paper a new quarter-wave Fresnel zone planar lens for millimeter waves with an enhanced focusing quality is described. A more precise expression for the lens thickness is deduced.

A corresponding millimeter-wave lens antenna design with a diameter of 150 mm and focal length of 130 mm was studied theoretically for the frequency band of 54-68 GHz. The calculations have shown a maximum antenna radiation efficiency of 52 % for a frequency of 62.1 GHz.

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## 2. Lens description

Each full-wave zone in the Fresnel zone plate is divided into four quarter-wave subzones. The central subzone is open and the next three subzones are covered by dielectric rings with different, properly chosen permittivities. The next full-wave zones have a similar arrangement.

The idea behind the multiple-dielectric Fresnel zone planar lens is not a new one [3] but to the authors' knowledge there is no publications on the specific lens design and its electromagnetic analysis.

To accomplish a quarter-wave stepwise phase-correction the relative permittivities were found to be as follows: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 6.25$, $\varepsilon_{r3} = 4$ and $\varepsilon_{r4} = 2.25$. This was evident from the computed "infinite" transmission phase-shift characteristics of dielectric plates having the above permittivities, and the thickness of the ideal dielectric phase-shifter, i.e. $\lambda/2$ for $\varepsilon_r = 4$.

By using printed (microstrip) technology lighter and cheaper phase-shifting structures, and thus quarter-wave quasi-optical Fresnel lenses and antennas can be fabricated.

## 3. Planar lens thickness versus angle of incidence

The thickness $d$ of the phase-reversing dielectric zone plate is usually calculated by the following equation [2,3]

$$d = \frac{\lambda_o}{2(\sqrt{\varepsilon_r} - 1)} \quad (1)$$

which is strictly valid only in the case of normal ray incidence; here $\lambda_o$ is the free-space wavelength.

But this is not the case for the Fresnel dielectric lens with an open first zone because the normal rays do not impinge on dielectric rings at all.

Thus, in examining the plate transmission characteristics one should take in account their dependence on the incident angle.

The phase variation due to the presence of the dielectric plate rings, called also insertion phase difference between the refracted ray $rQ'Q''r_2$ and the free-space direct ray $rQ'Q'''r_1$ (Fig. 1) can be found approximately as follows

$$\Delta\Phi_t \approx k_o[(l_2\sqrt{\varepsilon_r} + r_2) - (\Delta l + \Delta r + r_1) \quad (2)$$

where

$k_o = 2\pi / \lambda_o$, $l_2 = d / \cos\psi_t$, $r_2 = r_1 + \Delta r$

and $\Delta l = d\cos(\psi - \psi_t) / \cos\psi_t$

The multiple reflection/transmission phenomenon and wave polarization dependence are neglected here.

Therefore, for the phase difference $\Delta\Phi_t$ it can be written

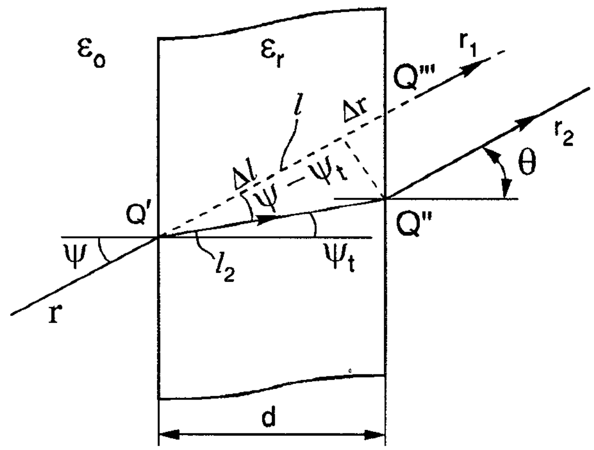


Fig. 1 Ray tracing for finding plate thickness .

$$\Delta\Phi_t = \frac{k_o d}{\cos\psi_t}[\sqrt{\varepsilon_r} - \cos(\psi - \psi_t)] \quad (3)$$

From the second Snell's ( refraction law ) $\cos_t = [\sqrt{\varepsilon_r - \sin^2\psi}] / \sqrt{\varepsilon_r}$, and after some trigonometric manipulations eq.(5.6) becomes

$$\Delta\Phi_t = \frac{2\pi}{\lambda_o} d(\sqrt{\varepsilon_r - \sin^2\psi} - \cos\psi) \quad (4)$$

For the phase-reversing plate $\Delta\Phi_t = \pi$ and in this case the dielectric plate thickness $d$ can be obtained by the following expression

$$d = \frac{\lambda_o}{2(\sqrt{\varepsilon_r - \sin^2\psi} - \cos\psi)} \quad (5)$$

For a normal incidence $\psi = 0^o$ and then eq.(5) reduces to eq.(1).

In the general case different phase shifts can be defined using the phase-correction factor $q$ (for example, $q = 0.5$ for the phase-reversing zone plate, and $q = 0.25$ for the quarter-wave zone plate)

(6) $$d = \frac{q\lambda_o}{\sqrt{\varepsilon_r - \sin^2\psi} - \cos\psi}$$

It is evident that the plate thickness essentially depends on the angle of incidence.

In Table 1 several values of the plate thickness d for different angles of incidence, calculated for $\varepsilon_r = 4$, $q = 0.5$ and $\lambda_o = 5$ mm are given.

Table 1
Plate thickness of phase-reversing plate for several angles of incidence

| $\psi$[deg] | 0 | 20 | 40 | 60 | 80 |
|---|---|---|---|---|---|
| $d[mm]$ | 2.50 | 2.42 | 2.22 | 1.92 | 1.60 |

For the axially symmetric Fresnel zone antenna however the incidence angle does not exceed $45^o$, i.e. $\psi_{max} = a\tan(b_{max}/F)$.

On the other hand, the minimum angle of incidence from which the refraction into dielectric rings starts is $\psi_{min} = a\tan(b_1/F)$.

Therefore, in calculating the lens thickness it is acceptable to choose for the angle of incidence approximately the average value

$$\psi_{av} = 0.5(\psi_{min} + \psi_{max}).$$

## 4 Millimeter-wave lens antenna

The quarter-wave Fresnel planar lens described above was used for designing a transmissive-type (lens) Fresnel zone antenna (FZA) with a scalar horn feed having an axial radiation sym-metry and Huygens-source polarization proper-ties. The antenna far-field radiation characteris-tics were calculated by the use of the multiple reflection/transmission coefficients for a real die-lectric plate and vectorial Kirchhoff diffraction theory [6,7].

In Table 2 the main radiation parameters of the new quarter-wave Fresnel antenna design (1) are compared to those comprising a half-wave lens (2) with phase-reversing dielectric rings, and classical Fresnel lens (3), with transparent /ab-sorbing (reflecting) zones, respectively. All of them are 150mm in diameter, and 132mm in focal length. They are designed for an edge illumination level of -12dB and for a frequency of 62.1GHz. The dielectric rings are supposed to have $\tan\delta = 0.0001$.

Table 2
Comparison between three varieties of the Fresnel-zone planar lens antenna

| Antennas/ /Parameters | Directive gain, [dBi] | Efficiency, [%] |
|---|---|---|
| (1) Quarter-wave FZA | 36.8 | 52.0 |
| (2) Half-wave FZA | 34.5 | 30.4 |
| (3) Classic FZA | 30.1 | 11.1I |

It is concluded that for the same antenna dimensions and design parameters the quarter-

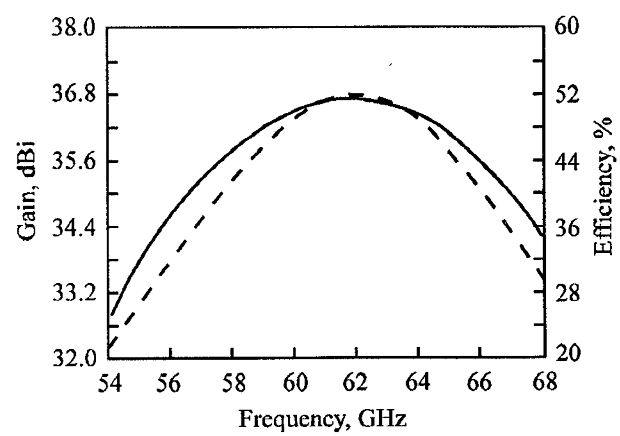


Fig. 2 Directive gain (solid line) and aperture efficiency (dashed line) versus frequency

wave FZA with a directive gain of 36.8dBi and aperture efficiency of 52% surpasses 2.3dB in gain and 1.7 times in efficiency the half-wave FZA, and 6.7dB in gain and 4.5 times in efficiency the classical FZA.

Calculated directive gain and aperture efficiency of the quarter-wave FZA versus the frequency are drawn in Fig.2. The 3dB antenna gain bandwidth due to the lens frequency properties only is about 22%.

## 5. Conclusions

A quarter-wave planar Fresnel zone dielectric lens for millimeter waves with an enhanced focusing quality is proposed and designed. A more exact expression for the lens thickness was given which accounts for the angle of incidence of the incoming rays.

On the base of the new lens configuration a transmissive-type (lens) antenna with 52% aperture efficiency for optimum frequency of 62.1GHz is described. It was examined theoretically using the multiple reflection/transmission coefficients for a real dielectric plates and vectorial Kirchhoff diffraction antenna theory.

## Acknowledgment

At the end the authors wish to express their sincere thanks to the Commission of the European Communities, Division of Telecommunications , Brussels for granting COST Research Contract CIPA 3510 CT926503/1993 on the analysis and design of transmissive-type Fresnel-zone antennas.

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