W-band Mutli-layer Perforated Dielectric Substrate Lens

Abd-Elhady Mahmoud[1,2,3], Wei Hong[1], *Fellow, IEEE*, Yan Zhang[1], *Member, IEEE* and Ahmed Kishk[2], *Fellow, IEEE*
1 Southeast University, Nanjing, China
2 Concordia University, Montreal, Quebec, Canada
3 Benha University, Benha, Elkaliobeya, Egypt

Abstract – W-band planar perforated dielectric substrate lens antenna is designed and implemented. The lens utilizes a perforated dielectric multilayer substrate that converts spherical wave front into planar wave front. The dielectric perforation is performed with air holes and each hole has a uniform diameter through all layers for simplicity. The transmission coefficient phase is controlled locally. The lens is designed at 94 GHz and composed of 29 × 29 elements that cover an area of 58 × 58 mm^2. The lens is center fed by a WR-10 rectangular waveguide located at 44.5 mm from the lens making an aperture angle of 42º. Two lenses are investigated, a single layer lens and a six-layer lens. The six layers lens provides 30 dB gain, which is 1.7 dB higher than the gain provided by the single layer lens at 94 GHz. The numerical and measured results are found to be in good agreement.

Index Terms - Millimeter waves, perforated dielectric substrate, Lens antennas, planar arrays.

I. Introduction

The W-band is used for satellite communications, millimeter wave radar research, military radar targeting and tracking applications, and some non-military applications. A number of passive millimeter-wave cameras for concealed weapons detection operate at 94 GHz. The atmospheric radio window at 94 GHz is used for imaging millimeter-wave radar applications in radio astronomy, defense, and security applications. Lens antennas can be used as an alternative to reflector antennas for high-gain microwave applications [1]. Recently, lens antennas are somewhat reviving for such applications due to their light weight [2]. Artificial dielectrics have been a good candidate to reduce the weight of lens antennas since they are basically fabricated by the collection of discrete metal particles sustained in a supporting material, which could be a foamed plastic or sparsely aligned plastic bars [3]. Phase of transmitted signal can be controlled by changing the diameters of printed conducting discs over a high dielectric constant [4]. Artificial materials have been of interest in microwave and millimeter-wave areas in recent years due to the distinctive features. Arbitrarily high permittivity that is realized in artificial dielectrics makes it possible to fabricate a very thin lens antenna for microwave and millimeter wave frequency bands. Photolithography technology is adopted to realize the artificial planar dielectrics to control the permittivity on the lens surface, which is different from the conventional convex or concave counterparts. The artificial dielectric exhibits a wide range of variation in its effective refractive index, making it suitable for use in planar gradient index (GRIN) microwave lens and other quasi-optical devices. Finite element simulations are used in conjunction with material parameter retrieval techniques to design an artificial dielectric unit cell with an optimum refractive index range [5]. A very thin and flat lens antenna is designed and fabricated using perforated dielectric for far field focusing by simply putting it in front of a small low gain antenna. The ease of handling would allow us to call it an "ad hoc antenna" [6]. The main drawback of former lenses is that fabricated from metallic disc shapes (square or circle). As a result, there is high coupling between cells especially at millimeter-wave that suffered from losses of metallic surfaces. So, overcoming these losses by using perforated substrates techniques had been utilized [7-11].

Here, we present an artificial dielectric with perforated substrate lens designed at 94 GHz. Full-wave simulation is used in conjunction with material parameter retrieval techniques to design an artificial dielectric unit cell with an optimum transmission coefficient and minimum reflection coefficient. A six layers lens is designed with the consideration of cost, space, and ease of fabrication in mind. A variable holes’ diameter provided the required phase shift at each cell on the lens surface. The new approach is based on drilling a fixed number of holes on each cell of the substrate for transmission coefficient phase control using the multilayer technique. The effective dielectric constant is varied as holes’ diameter changed. As a result, the transmission coefficient phase of propagated waves that illuminates the cell and transmits to the other side is controlled. The transmission coefficient and reflection coefficient response of a unit cell versus the variation of holes’ diameter are computed by waveguide method [12] using CST microwave studio package.

II. Numerical Analysis

The feed that is axially exciting the planar lens has a spherical phase front that reaches the lens with different path lengths as we move away from the lens center. The phase can be controlled by changing the effective dielectric constant and ray theory can be used to predict the proper dielectric constant for the required phase. Proper perforation of the dielectric is used to achieve the required dielectric constant. Here, the lens is divided to N×N equal cells and each cell is supposed to achieve certain transmitted phase compensation with certain permittivity. However, we preferred to deal directly with the physical perforation of each cell by air holes to obtain the transmission coefficient phase and design curves are created to facilitate the lens design and after that full wave analysis are used to obtain the far field of the lens.

A. Waveguide method:

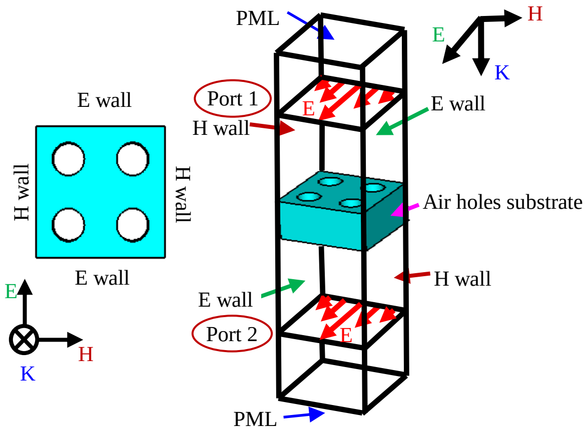


Fig. 1 Waveguide cell model for infinite array simulation.

The waveguide method is used as illustrated in Fig. 1. A plane wave is considered incident from the top (port 1) and transmitted to the bottom (port 2). The side walls of the cell are two parallel walls to the incident electric field of magnetic conductor (H-wall) and two electric conductor walls (E-wall) perpendicular to the incident electric field. The top and bottom walls are perfect matching ends of perfect matching layers (PML). The lens cell material is placed in the middle as shown in Fig. 1. This is representing an infinite planar array of this cell that accounts for the mutual coupling between the cells. The transmission and reflection coefficients are obtained and a design curves are computed as a function of the hole diameter and the angle of incidence at 94 GHz.

B. Single Layer Perforated Lens Antenna:

The cell consists of four (2 × 2) air holes. The diameter of each hole is D and the four holes are arranged symmetrically around the cell center as shown in the insert of Fig. 2. The lens is designed from Arlon's AD1000 substrate, with ε_r = 10.75, tan δ = 0.0023 at 10 GHz, thickness 3.25 mm (1.02 λ_o), low water absorption (0.03%), and good mechanical stability. The transmission coefficient phase of cell element is calculated as shown in Fig.2.

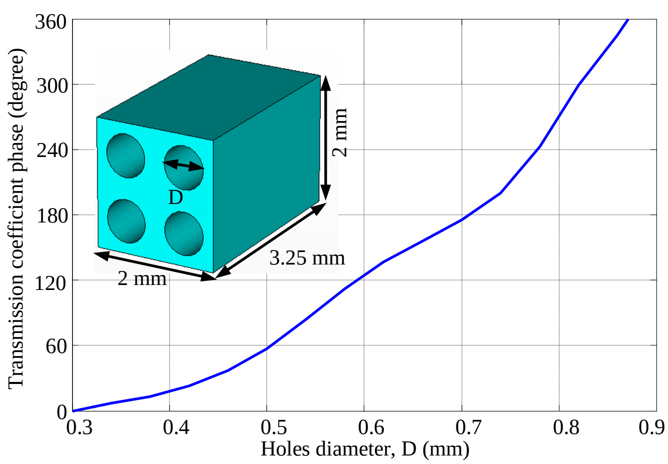
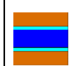
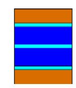
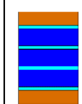
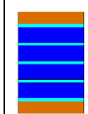


Fig. 2 Cell transmission coefficient phase versus hole diameter for a single layer case.

A 360° phase coverage can be achieved as the hole diameter varies from 0.3 to 0.9 mm. Many cell models are considered for best performance, i.e. maximization of the transmitted power and reduction of the reflected power of the lens. Four multilayer lens models were investigated. In all models, the upper and lower substrates have thickness of 0.5 mm (0.156 λ_o), which are used as a quarter wavelength matching layers having (ε_r = 2.2) between the free space (ε_r = 1) and the interlaced substrates (ε_r = 10.2) at 94 GHz for minimizing the reflection from the upper surface interface with the lens as shown in Table I.

Table I Models of different Perforated lenses

Lens \ Layers	One	Three	Four	Five	Six
Schematic					
Thickness	3.25 mm	1.89 mm	2.66 mm	3.425 mm	4.19 mm

The cause of increasing the interlaced layers (blue color layers) is for increasing the transmission coefficient phase range to achieve full period (360°) as shown in Fig.3. The phase of the transmitted waves versus holes diameters is computed for normal incident for four different cases and at different oblique angles for the six layers case. There is 142° phase shift for 42° (at lenses corners) oblique angle away from normal incident. The comparisons of reflection coefficient amplitude for single and multilayer lenses are illustrated in Fig.4. It is concluded that the six layers lens provided best results where transmission coefficient phase satisfied the required 360° with acceptable reflection coefficient amplitude below -10 dB for all the range of holes' diameters. The multilayer lenses consist of upper and lower layers of Rogers 5880 with dielectric constant 2.2 and thickness 0.5 mm. The middle four layers are made of Rogers 6010 with ε_r=10.2 and thickness, 0.635 mm while adhesive material's layers have ε_r=3.8 and thickness of 0.13 mm.

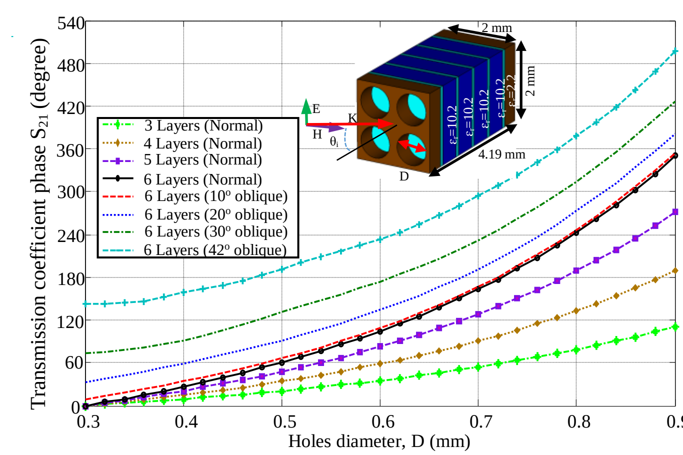


Fig. 3 Cell transmission coefficient phase with different layers and angle of incidence versus hole diameter.

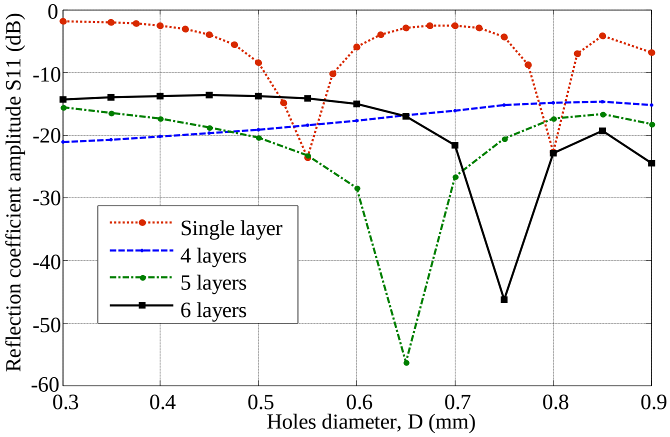


Fig. 4 Reflection coefficient amplitude versus hole diameter.

The case of a cell with common four holes in all layers is implemented with a total thickness of 4.19 mm (2 × 0.5 mm + 4 × 0.635 mm + 5 × 0.13 mm), which is equivalent to 10.31 λ_o and cell's period of 2 mm. The reflection coefficient amplitude's oblique angle effect is also calculated as in Fig.5. Cells with lager hole diameter is less reflective as compared to the cells with smaller hole diameter, which will affect the transmission magnitude.

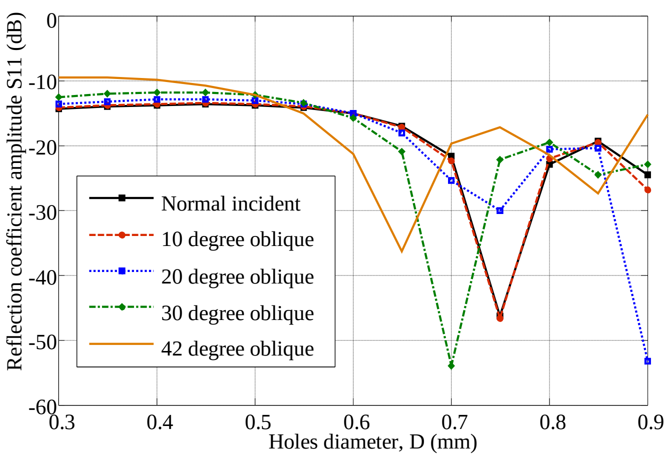


Fig. 5 Reflection coefficient amplitude versus hole diameter for different oblique angles.

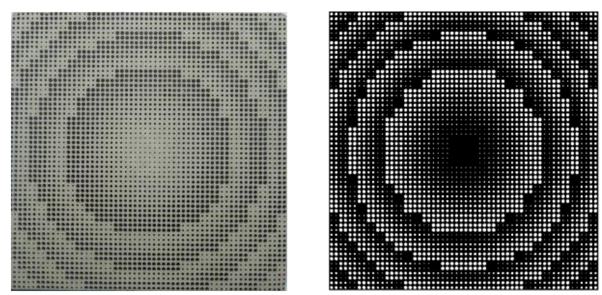
To show the advantages of six layers over a single layer design, both are fabricated. The reflection coefficient amplitude is presented in Fig. 4 for a single layer of thickness 3.25 mm and the six layers of 4.19 mm thickness. The single layer shows a reflection coefficients variation between -35 dB to -2 dB, but for the six layers provided variations between -33 dB to -12 dB.

D. Lens design:

Considering an array on the x-y plane illuminated by a feed with a phase center located at (x_f, y_f, z_f), the required phase distribution, Φ (x_i, y_i), at each element of the array to collimate a beam in the (θ_o, φ_o) direction is determined as:

$$\Phi(x_i, y_i) = k_o(d_i - \sin\theta_o(x_i \cos\varphi_o + y_i \sin\varphi_o)) \quad (1)$$
$$d_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_f)^2}$$

where k_o is the propagation constant in vacuum, d_i is the distance from the feed phase center location to the element i of the array and (x_i , y_i) are the coordinates of the cell center. The feed is a standard WR-10 rectangular waveguide with aperture size of 2.54 mm × 1.27 mm. In both designs, the focal point of the lens is 44.7 mm while the area of lens is 58 × 58 mm^2 (18.17 × 18.17 $\lambda^2{}_o$) as shown in Fig. 6. It can be seen that because the achieved phase variation is limited to 2π, the choice of phase larger than that is rounded back to start from zero phase again. This creates discontinuity in the holes sizes and makes discontinuities in the reflection coefficients and in turn in the transmission coefficients that make the lens aperture, magnitude distribution is not monotonically decreasing from the center to the edge. The lens is center-fed and the radiation patterns are measured using the setup shown in Fig. 7. The normalized H-plane far field patterns of the single layer and six layers lenses are measured and compared with the simulated radiation patterns at 94 GHz showing good agreement as shown in Figs. 8, and 9, respectively. The side-lobe levels are below -20 dB. Fig.10, shows a comparison between the gain of the single layer lens and the six layers lens indicating a 1.7 dB gain increase for the six layers lens over the single layer lens at 94 GHz. The 1 dB gain bandwidth is 15.9 % for six layers lens while it is 7% for the single layer lens. It should be stated that the design is based on the normal incident phase variation.



a) Single layer b) Six layers

Fig. 6 Photograph of lenses

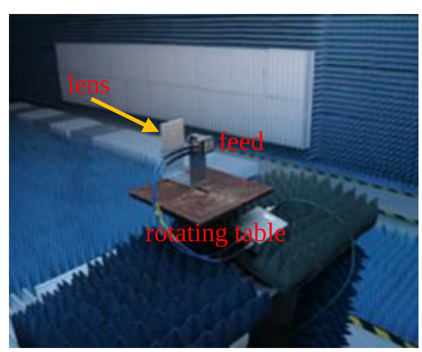


Fig. 7 Farfield radiation patterns setup.

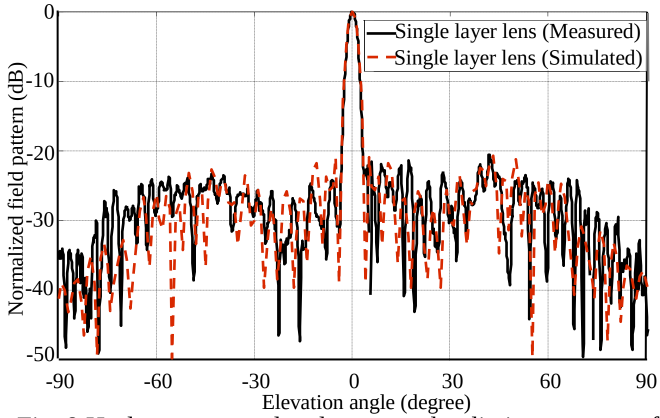


Fig. 8 H-plane measured and computed radiation patterns of single layer lens.

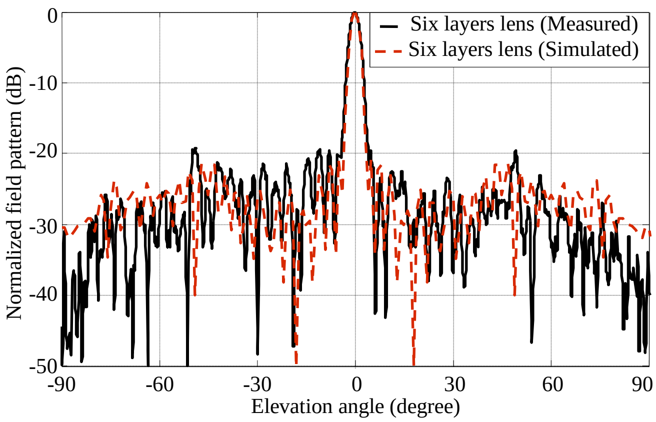


Fig. 9 H-plane measured and computed radiation patterns of six layers lens.

Considering oblique incident information did not improve the antenna gain as the cells cannot provide phase compensation larger than 2π, which in turn affect the aperture magnitude distribution and creates some low transmission coefficients at the radii with abrupt change in the holes radius as seen in Fig. 5. It should also be stated that the antenna efficiency is about 25% at 94 GHz. In the presented design, several factors are causing a reduction of the antenna efficiency. (a) It should be mentioned that the lens is illuminated by a 15 dB edge tapering feed for low side-lobe level and less contribution of the feed spillover in the forward region. This edge tapering has about 1 dB of gain loss, which reduces the lens aperture efficiency. (b) Possible phase error due to the misalignment of the waveguide feed. (c) Standing waves between the feed and the lens so the reflection coefficient of the feed reduces the gain by $(1-|\Gamma|^2)$ as we are providing the gain value. (d)The magnitude aperture distribution is not smoothly tapered to the -15 dB at the edge. The aperture magnitude has some dip losses due to the reflection from the lens at some angles. (e) Losses from the lens materials at the W-band.

III. CONCLUSION

A design for a multilayer planar perforated dielectric lens was presented. The required phase variation of the transmitted signal is controlled by varying the dielectric constant using perforations, but the analysis was performed based on the actual physical cell geometry that had four air holes. The six layers lens had the best performance and compared with single layer lens. Good agreement between the measured and simulated results of the six layers lens, which had a better gain level than the single layer lens. The 1 dB gain bandwidth is significantly enhanced when multilayer lens used and achieved 15.9% bandwidth.

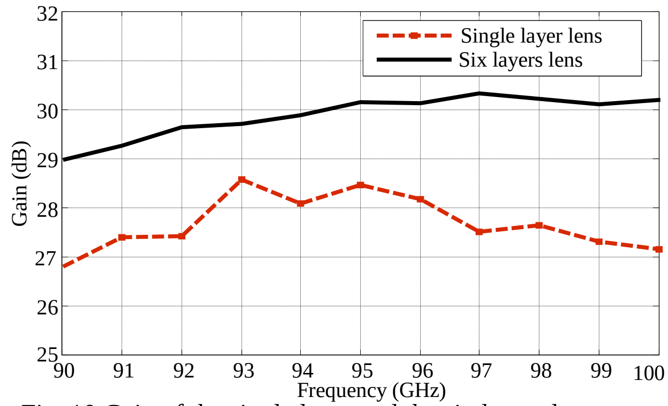


Fig. 10 Gain of the single layer and the six layers lenses versus frequency.

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