Analysis and Design of Inhomogeneous Single Layer Slotted Dielectric Flat Lens

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***Abstract*-This paper presents the design and results of low cost, light weight, planar, high gain, no feed blockage and single layer slotted dielectric flat lens for high gain antenna applications at 73.5GHz. The proposed flat lens is completely dielectric where no metal used to construct it so the ohmic losses, mutual coupling and the surface waves are expected to be lower. The unit cell that forming the lens is based on cutting slots having same depth in the both sides of a commercial non magnetic low loss host dielectric substrate to produce a phase compensation from $0^o \rightarrow 360^o$ by controlling the width of the cut slot with losses less than -1dB. A 21 cell × 21 cell lens that is occupied an area of 42 mm × 42 mm and illuminated by a pyramidal horn antenna is designed and simulated. A peak gain of 28dBi is achieved at the design frequency with almost flat gain from 71GHz to 76GHz, beamwidth of 5.1^o and aperture efficiency of 47.41%. The radiation characteristics of the lens are calculated using Finite integral technique (CST Microwave Studio) and finite element method (HFSS).**

I. Introduction

In modern wireless communication systems such as radar (Military and civil), satellite systems and deep space exploration systems high gain antennas are highly required. Parabolic reflector antenna is the most used high gain antenna in many applications such as point to point communication systems [1]. Although these parabolic reflector antennas are efficient high gain radiators but parabolic reflectors are too heavy, bulky and can not be installed easily. To overcome these drawbacks of conventional curved parabolic reflector, reflectarrays were first introduced in 1963 by Berry and Malech [2]. Reflectarray antennas have been used in many applications when a high gain is required and for many years considered to be the future high gain alterative antenna candidate because of its important characteristics such as light weight, low side lobe levels, ease of fabrication, narrow beam width and ease of installation [3].

Reflectarray is combining the best features of phased arrays and the reflector antennas where its passive and operate principally on the basis of its geometrical shape. Reflectarray consist of number of repeated unit cells in both *x*-axis and *y*-axis printed on a grounded dielectric slab in order to make the reflectarray having a flat aperture and thus reduce the volume and the mass of the reflector [4-6]. These unit cells which are composed the flat reflectarray is usually illuminated by a horn antenna as a feed source . The unit cells is designed in such away to correct the phase delay of the incident EM-waves that are radiated by horn antenna with spherical phase front and reflect them with planar phase front in front of the reflectarray and direct the main reflected beam toward the desired direction. However at millimeter and sub-millimeter regimes the ohmic losses, excitation of surface waves and mutual coupling is sever which increases the amount of losses of the reflectarray used for these frequency bands. Further more, using the feed source in front of the reflectarray will increase the blockage of the reflected waves. Although that shifting the feed antenna by a certain degree to reduce the blockage is a good technique but sometimes results in high side lobe level and it might destroy the symmetry of the radiation pattern.

Quite recently, there is an increasing interest in the design of planar dielectric lenses (also called Transmit-array and discrete lens) for millimeter and sub-millimeter waves where the lenses become adequate in terms of weight and size for many applications in this region of EM spectrum. Besides, very low loss dielectric materials are available, and present-day numerically controlled machines enable low-cost fabrication of quite sophisticated lenses made with very good tolerances [7,8]. In this paper a low cost, light weight, high gain, no feed blockage and having flat geometry dielectric lens is presented for 73.5GHz. The proposed lens is completely dielectric where no metallic layers used to construct it so the mutual coupling and excitation of surface waves is expected to be lower. Using only single dielectric layer to build the proposed lens make it a good candidate for integration with other planar devices.

II. Principle of Operation of the Lens

The operation principle of dielectric flat lens type structures presented in this paper can simply be explained as follows: when the lens in the transmitting mode the lens will collimating the incoming divergent EM waves with a spherical wave front on one side, processing it by prevent it from spreading in undesired directions and then retransmitted a narrow shaped beam of EM wave of enhanced directivity with planar wave front on the other side after correcting the phase of the incoming EM waves just like the parabolic reflectors. On the other hand, in the receiving mode the lens will focus the incoming EM waves with planar phase front onto the feeding point. In other words, the lens is resembles to a two set of receiving and transmitting antennas connected to each other via phase shifters. These phase shifters are used to correct the phase delay of the incoming EM waves and controlling the direction of the transmitted beam.

III. PROPOSED LENS DESIGN AND RESULTS

The design of the unit cell that forming the proposed dielectric lens is based on phase correction technique. The proposed unit cell is achieved by cutting slots having the same depth on both sides of a dielectric slab. Cutting slot in the host dielectric substrate will increase the amount of free space that having dielectric constant of ε_{r1} and make it along with the host dielectric substrate that having dielectric constant of ε_{r2} compose a new martial having dielectric constant of ε_{eff} as depicted in Fig.1 .

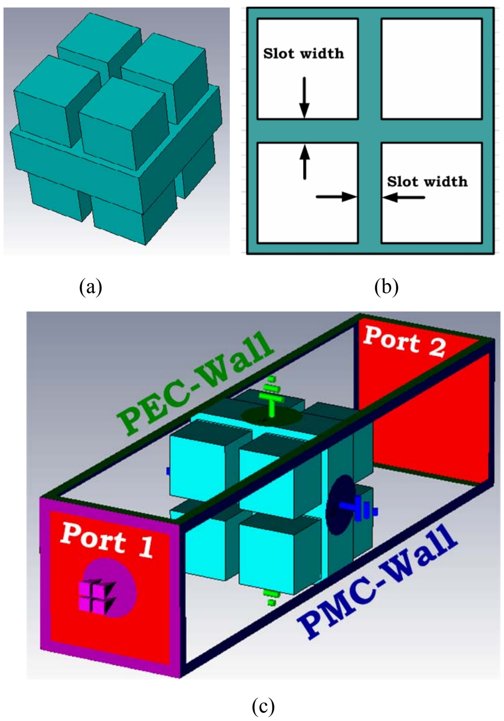

Figure 1. Geometry of the proposed unit cell (a) 3D view, (b) top view and (c) Simulation setup in CST.

The dielectric substrate used is RO6010 that having dielectric constant of 10.2 and dissipation factor of 0.0023 and thickness of 3.175 mm . Choosing the unit cell is an important point in the design of such lens.

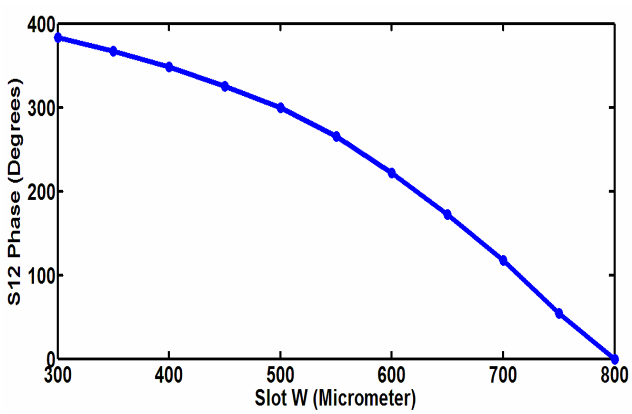

Figure 2. Transmitted wave (S_{12}) phase versus slot width.

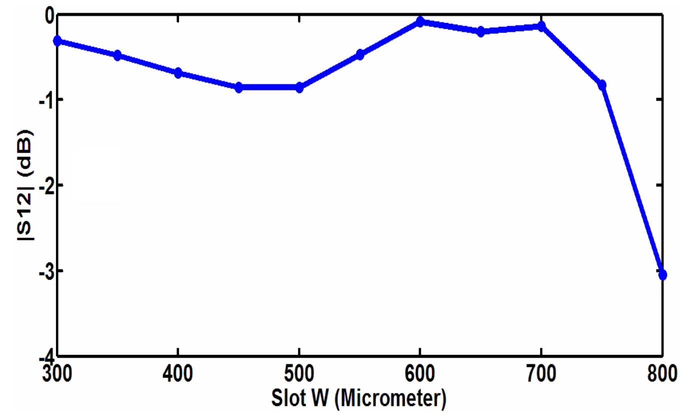

Figure 3. Transmitted wave (S_{12}) magnitude versus slot width.

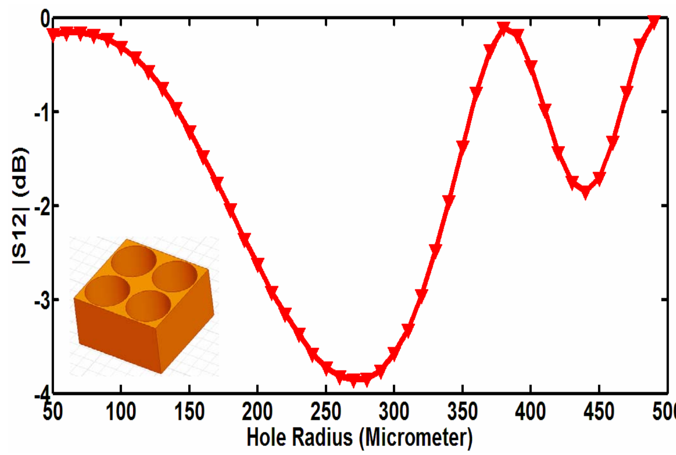

Figure 4. Transmitted wave (S_{12}) magnitude for perforated unit cell.

After detailed analysis it's found that the unit cell size will highly affect the resulted side lobe level. In this paper the unit cell size is set to 2mm × 2mm (the distance between any two adjacent unit cell centers). First the phase diagram which is represents the transmitted wave phase (and magnitude) as a function to the slot width is calculated and presented in Fig.2. The CST simulation setup in Fig. 1 (c) is used to compute the phase diagram. A single unit cell of the proposed lens is placed at the center of TEM-waveguide. The side walls of the TEM-waveguide are formed by two E-walls boundary condition and two H-walls boundary condition and the other open ends are terminated to two waveguide ports and then the phase of the transmitted signal is recorded at the surface of the unit cell.

It's clear that the proposed unit cell can correct the phase from $0^{o}\rightarrow 360^{o}$. Further more, the magnitude of the transmitted signal versus the slot width is computed too. As depicted in Fig. 3 the transmitted losses is less than -1dB for the whole range of slot width expect for slot width from 0.78 to 0.8 mm and compared to perforated type unit cell that having the same size, the proposed unit cell exhibit lower losses as in Fig.4. So, The performance of the proposed lens is expected to be better than perforated type lens having the same dimensions. Furthermore, in order to obtain a almost flat gain a horn antenna with almost flat gain over 71-76GHz band is used to illuminate the lens.

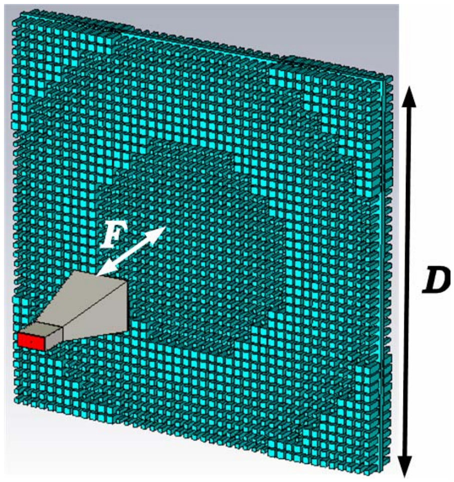

Figure 5. 3D view of the proposed lens with the feeder.

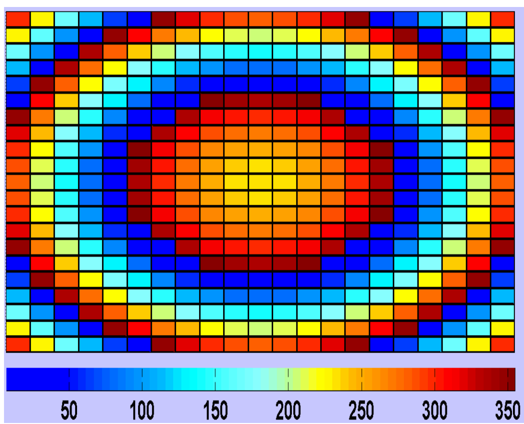

Figure 6. The required phase correction (in degrees) at each unit cell.

A flat dielectric lens consist of 21 cells × 21 cells and occupied an area of 42mm × 42mm and having a thickness of 3.175mm is designed and simulated. The layout configuration of the proposed center fed lens is presented in Fig. 5. The lens is assumed to be along *x*-axis and *y*-axis, then required phase correction $\Phi(x_i, y_i)$ at each unit cell to collimate the beam in the desired direction is calculated by the fowling formula:

$$\Phi(x_i, y_i) = k_o\left[d_i - \sin(\theta_o)(x_i\cos(\varphi_o) + y_i\sin(\varphi_o))\right] \quad (1)$$

$$d_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_f)^2} \quad (2)$$

Where $k_o = (2\pi/\lambda_o)$ is the free space propagation constant, d_i is the distance from the unit cell positioned at (x_i, y_i, z_i) to the feed antenna positioned at (x_f, y_f, z_f). The values of the required phase correction at each unit cell were obtained using MATLAB® code and the results are presented in Fig. 6. The proposed lens is illuminated by an E-band linearly polarized pyramidal horn antenna of size W × H × L is 6 mm × 5.6mm × 13.6 mm. The dimensions of the horn antenna are chosen to get almost a flat gain over the frequency range 71-76GHz. Determining the phase center point (the point at which the EM waves propagates spherically outwards) of the horn antenna is very important and for the horn antenna used in this paper its found to be at (0, 0, 13.2) mm. Then the lens along with the horn antenna was simulated using the time domain transient solver of the full wave CST Microwave studio package. In order to shirink the simulation volume and the required time for simulation, symmetry boundary conditions are used. A computer having 16-GB of RAM and 8-CPUs is used. The simulation time is around 14 hours. The design of the proposed lens is based on the phase transformation and as depicted in Fig. 7 the incoming EM waves received on one side of the lens with spherical wave front is converted to planar wave front on the other side or the lens.

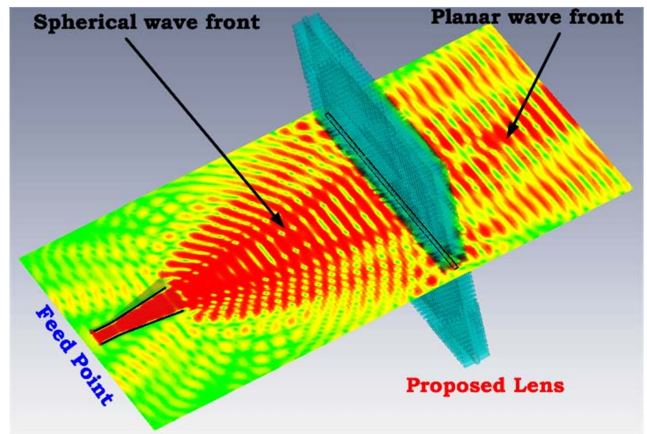

Figure 7. 3D view of the phase transformation concept of the proposed lens.

A gain of 28dBi at 73.5GHz is achieved. The lens physical area of 42 mm × 42 mm provides an aperture efficiency of 47.41% according to the following formula.

$$\eta_{app} = \frac{G \times \lambda^2}{4\pi \times A_{physical}} \quad (3)$$

Figure 8 shows the achieved gain over the 71-76GHz band for the horn antenna with/without the proposed lens.

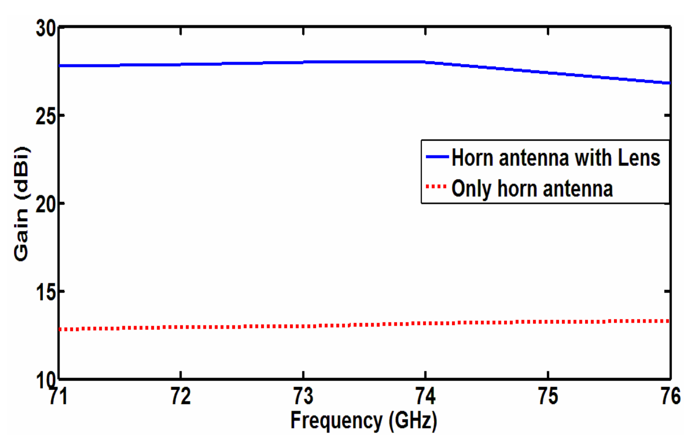

Figure 8. Achieved gain with and without the lens.

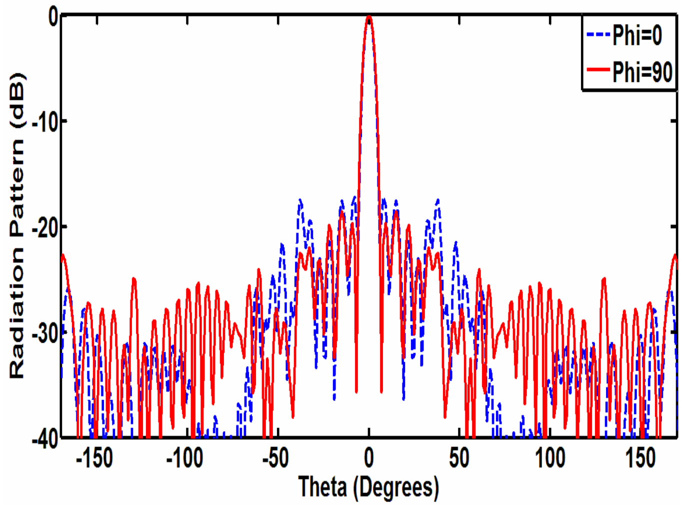

Figure 9. Gain Pattern for F/D=1 at 74GHz.

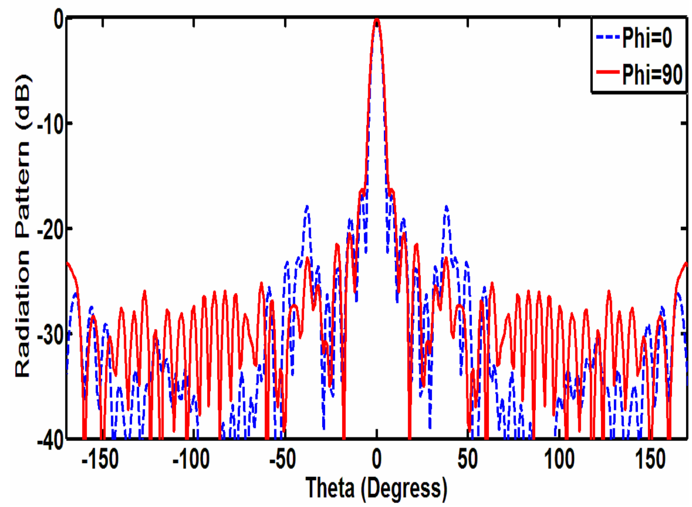

Figure 10. Gain Pattern for F/D=0.9 at 74GHz.

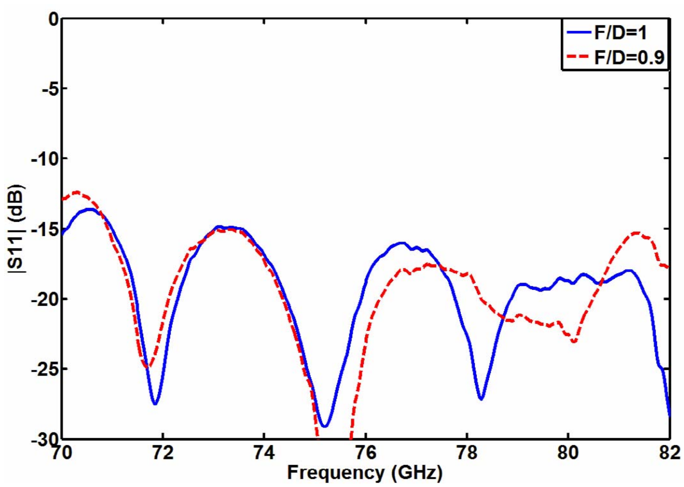

Figure 11. Return loss of the horn antenna with the proposed lens.

The computed radiation pattern plot for $\Phi=0^o$ plane and $\Phi=90^o$ plane is presented in Fig. 9 and Fig. 10. Focal length-to-diameter ratio (F/D) of the lens is adjusted carefully and optimized in order to have the highest possible peak gain with lower side lobe levels and the radiation gain pattern for F/D=1 and F/D=0.9 cases are presented here. As depicted in Fig. 9 and Fig. 10 the transmitted beam is broad side with peak gain of 27.7 dBi (F/D=1) and 28 dBi (F/D=0.9) and the main transmitted beam have 3-dB beamwidth of 5.1^o and SLL around -13.7 dB. Its important here to point out that the standard gain horn antenna that have been used have maximum gain of 13.2 dBi, compared with 28 dBi gain that achieved using the proposed lens it means that a 14.8 dBi gain improvement is the result of using the proposed lens as in Fig.8. The return loss at the horn antenna port within the design frequency band is presented in Fig. 11 where $|S_{11}|$ <-10dB for the whole frequency band for the two cases F/D=1 and F/D=0.9.

IV. Conclusion

In this paper the design of light weight, high gain, low cost, no feed blockage and single layer slotted dielectric flat lens for high gain antenna applications is presented. The unit cell consists of only dielectric material having slots of same depth on both sides which makes the fabrication process easier. A lens consists of 21cell × 21 cell and occupied an area of 42mm × 42mm and having a thickness of 3.175mm is designed and simulated. The design of the unit cell and the whole lens was verified using CST and HFSS software. A gain of 28dBi at 73.5GHz is achieved with 3-dB beam width of 5.1^o, SLL of -13.7 and aperture efficiency of 47.41% with a highly shaped radiation pattern in both E-plane and H-plane. The results show that the proposed lens could be a good alternative solution for the conventional dielectric lens (hyperboloid or spherical shape lens which are difficult to machine and a bit heavy with some complexity in integrating it with other devices) due to its simple configuration and high radiation performances.

References

[1] W. L. Stutzman and G. A. Thiele, "Antenna Theory and Design", 3rd edition, John Wiley & Sons: New York, 2012.

[2] D. G Berry and R. G. Malech, "The Reflectarray Antenna," IEEE Trans. Antennas Propagat., Vol. 11, Nov. 1963.

[3] D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter Wave Microstrip Reflect Arrays," IEEE Trans. Antennas Propagat., Vol. 45, No. 2, Feb. 1997.

[4] W. Hu, M. Arrebola, R. Cahill, J. A. Encinar, V. Fusco, H. Gamble, Y. Alvarez and F. Las-Heras, " 94GHz Dual-Reflector Antenna With Reflectarray Sub-Reflector", IEEE Trans. Antennas Propag., vol. 57, Oct. 2009.

[5] W. Menzel, M. Al-Tikriti and R. Leberer, "A 76 GHz Multiple-Beam Planar Reflector Antenna", EuMC, Milano, Italy, Sept. 2002..

[6] J. Huang and J. A. Encinar, Reflectarray Antennas, John Wiley & Sons Inc., Hoboken, NJ, 2007.

[7] J. Thornton and K. C. Huang, "Modern Lens Antennas For Communications Engineering", John Wiley & Sons, Inc., Hoboken, New Jersey , 2013.

[8] A. Petosa, N. Gagnon, A. Ittipiboon, "Effects Of Fresnel Lens Thickness On Aperture Efficiency", ANTEM 2004, Ottawa Canada, pp. 175–178, July 20–23 2004.