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Particle Swarm Optimization of Luneburg Lens Antenna and Its Comparative Reformulation for Complex Medium

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Abstract: *The particle swarm optimization (PSO) represents a novel approach to optimization problems which is effective at finding good solutions to a number of complicated electro-magnetic design problems. In our work it is used for the optimization of a Luneburg lens antenna for complex medium. In this paper, optimization and comparative reformulation is carried out for of inhomogeneous dielectric filled Luneburg lens antenna with respect to the Luneburg lens made from a material with a constant value of the dielectric permittivity with the introduced discontinuities. The comparison is carried out based on the creation of the electromagnetic models. The different stages in creating models and the design difficulties are also discussed.*

Keywords: *Particle swarm optimization, Luneburg lens, inhomogeneous dielectric, lens reformulation, lens optimization.*

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I. Introduction

A Luneburg lens is capable of focusing a plane wave incident on one side to a point diametrically opposite to the incident field. In the modern design of modern antennas for telecommunications, radar and radio navigation an important consideration is the design of multi-beam and scanning antenna systems. Often, those designs involve phased array antennas. However, their radiation pattern starts degrading at large scanning angles. In the case of scanning, it requires a complex beam forming scheme. For the use of reflector antennas, a rotary mechanism is required to ensure the scanning. One of the easiest ways to preserve the radiation pattern while scanning is the use of Luneburg lenses. They are useful for the multi-beam and scanning antenna systems. Due to its design, these lens antennas allow scanning in a large range of angles without the distortion of the radiation pattern [1, 2]. The lens proposed by Rudolf Luneburg, due to the radially inhomogeneous medium, allows concentrating the radiation of non-directional antennas in the desired direction [3]. The refractive index of the lens material varies from 1.414 in the centre to 1 on the edge according to the equation,

$$n(r) = \sqrt{\varepsilon^1(r)} = \sqrt{[2-(r/a)^2]} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \ (1)$$

where ε' is the relative dielectric permittivity of the lens material; r is the radial coordinate in a spherical or cylindrical coordinate system; a is the outer radius of the lens. Luneburg lens antennas are characterized by the possibility of multi beam scanning in a wide range of angles and high directivity. The focus of this paper is on the cylindrical Luneburg lens allowing the scanning only in one plane but much simpler than the spherical lens system. It consists of concentric dielectric layers or rings with decreasing permittivity from the center to the edge.

In most cases, the shields (ground planes) on the bottom and the top sides are introduced in the structure to obtain reduced size. It is not easy to create a Luneburg lens from a dielectric with a smoothly varying refractive index according to the law (1). There has been a lot of research on the construction of different types of structures, with a change in the refractive index close to the law (1). There are contemporary papers taking into consideration various ways of creating structures that behave the same way as the Luneburg lens. For example, design of planar metal-dielectric flat lens with Electric Band Gap (EBG) structures is presented in [4]. In [5] microwave spherical Luneburg lenses using a broadband meta-material composed of radially diverging dielectric rods are describes and studied, the continuous permittivity change is achieved through arranging identical thin dielectric rods with a radially variable cross section with a sub wavelength separation. In [6] using the technique of transformation optics curved focal surface is transformed to a flat plane while maintaining the focusing behavior of the Luneburg over a wide field of view. Considered techniques are applied to a refractive Luneburg lens and the design with a meta-material composed of a semi- crystalline distribution of holes drilled in a dielectric is implemented.

Hence, it can be inferred that, taking as a basic homogeneous dielectric with a constant permittivity and introducing inhomogeneities changing the effective dielectric permittivity and bringing it closer to the law (1), it is possible to obtain a structure that behaves like a cylindrical Luneburg lens. The approaches described in [7] were adopted to accelerate the modeling process without losing the accuracy of the results obtained in the study of these structures.

II. Luneburg Lens Optimization

In this paper an optimized electromagnetic design of a Luneburg lens antenna is accomplished by Particle Swarm Optimization (PSO). A non-uniform Luneburg lens is designed using the particle swarm to specify the layer thickness and dielectric constants. PSO can be understood by imagining a swarm of bees that encounter in their travels in an open field spotted with wild flowers. The natural desire of the swarm is to locate the position in the field that has the highest density of flowers. Because the swarm has no priori knowledge of the field, the individual bees spread out and begin their search in random locations. Each bee remembers the location that it finds and communicates this information to the rest of the swarm. Because of the difficulty in manufacturing a Luneburg lens with continuously varying dielectric constant, Luneburg lens is approximated by a number of homogeneous concentric shells, each with constant permittivity.

When each of the shells has equal thickness, then the approximation is uniform. Figure 1 shows a schematic model of a uniform Luneburg lens. In our simulations, a Luneburg lens fed by a horn antenna placed close at the outer surface of the lens is considered.

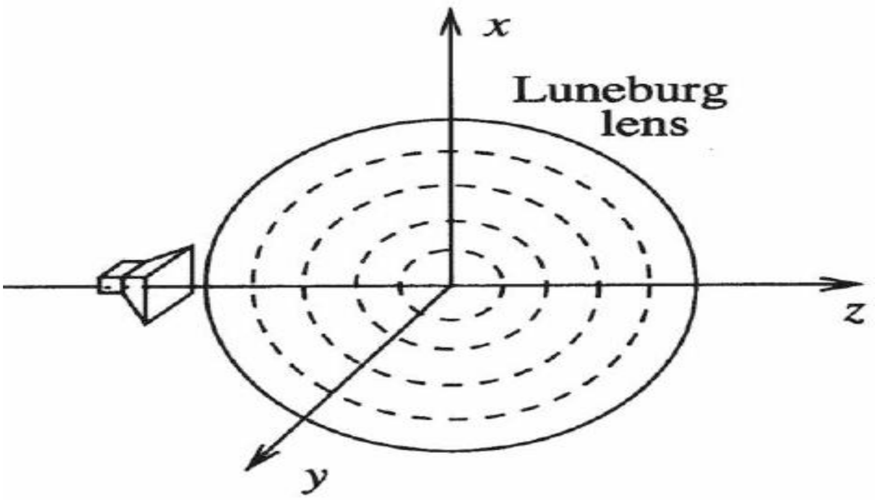

Figure 1: Geometrical model of horn fed Luneburg lens antenna

Due to the focusing effects of the lens, the radiation pattern is generated in the far-field. It is the properties of this pattern that we propose to optimize in our work. Global optimization techniques have been used in the past for optimizing the lens antenna. In [8] a Genetic Algorithm was used. Following this, we propose using PSO for the design of a optimized Luneburg lens approximated by five concentric shells.

The PSO is used for specifying the thickness and dielectric constant of each layer. The fitness function of the proposed design is carefully chosen such that the optimizing design goals are properly met. For lenses with less number of shells grating effects significantly increases the side lobe levels in the lens radiation pattern for certain angular regions. Hence, the primary goal of the optimization is to improve the side lobe performance of the lens and at the same time maximizing the bore sight gain of the lens. The fitness function that can achieve a trade-off between the two proposed objectives is given by equation (2)

$$F = (40 - G)^2 + (E)^2 \qquad \ldots\ldots\ldots\ldots.. \quad (2)$$

where G is the bore sight gain of the antenna and E is a composite parameter which represents how well the side lobe level envelope matches the desired envelope. Using trial and error, it is determined that good design can be achieved if the parameter E is average of the difference between side lobe that are above the desired envelope and the envelope itself given by equation (3)

$$E = [1/N]\, \Sigma\, [f(\theta_i) - G(\theta_i)] \qquad \ldots\ldots\ldots\ldots \quad (3)$$

where N represents the number of side lobes that are above the desired envelope, θ_i is the angular location of these side lobes and G(θ) is the radiation pattern of the lens.

III. Methods Of Reformulation

The proposed reformulation work starts by considering the structure of a cylindrical Luneburg lens consisting of six uniform layers with a step change of dielectric permittivity. The value of the dielectric constant from the center to the edge: 1.76, 1.59, 1.42, 1.26, 1.09, which can be regarded as optimal [9]. The effect of focusing the radiation and the alignment of the phase front of the radiation of the weakly directed feed passing through the Luneburg lens occurs due to refraction in the layered dielectric and at the same time, the rays passing through different electrical paths in the layers with different parameters experience different delays.

Hence, we propose to replace the homogeneous layer with the structure made of the dielectric with higher permittivity containing air cavities or gaps introducing the same phase delay to the wave passing through an initial layer of the same width. It makes possible to use only one material for the lens, which significantly eases fabrication process. After performing simulation for each of the five layers of the lens, we created a full-size model of the cylindrical Luneburg lens and further investigated it.

We compared three designs of partially filled lenses with the original one having layers of homogeneous dielectric. In the proposed models, the structure of the cylindrical lens at the top and bottom is limited to metal plates separated from each other. In partially filled dielectric layers of the cylindrical lens, the dielectric used has a constant value of dielectric permittivity equal to 2.6.

(i) Cylindrical Luneburg lens with homogeneous dielectric layers:

As a standard for comparing the results generated, a model of a five-layer cylindrical Luneburg lens was created using five homogeneous dielectric layers with the desired values of the dielectric constant. Fig. 2 shows the structure without feed.

(ii) Cylindrical Luneburg lens made up of layers with cylindrical holes:

The first design considered is of a cylindrical lens is made of homogeneous layers with a set of azimuthally equidistance cylindrical holes, which regularity and dimensions varying from layer to layer. The design is shown in Fig. 3.

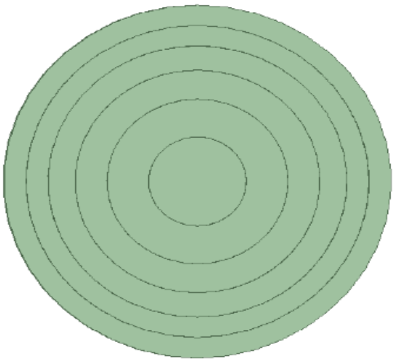

Figure 2: Basic Layered Cylindrical Luneburg lens

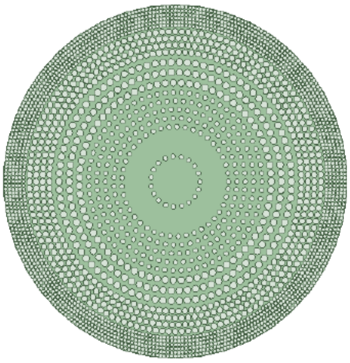

Figure 3: Layered Cylindrical Luneburg lens with azimuthally equidistance cylindrical holes

(iii) Cylindrical Luneburg lens made up of layers with concentric grooves:

The second design considered is of a partially dielectric filled cylindrical Luneburg lens with concentric grooves, which depth, width and quantity varied depending on the layer properties. It is shown in Fig. 4.

(iv) Cylindrical Luneburg lens of layers with a smooth change in the height of the dielectric from the edge to the center :

The third design considered is of a partially filled cylindrical Luneburg dielectric lens with a change in the proportion of the dielectric- filled space. The height of dielectric changes from edge to edge of each layer, increasing from the outer edge of the lens to the center. It is shown in Fig. 5.

Figure 4: Layered Cylindrical Luneburg lens with partial filling of Dielectric with concentric grooves

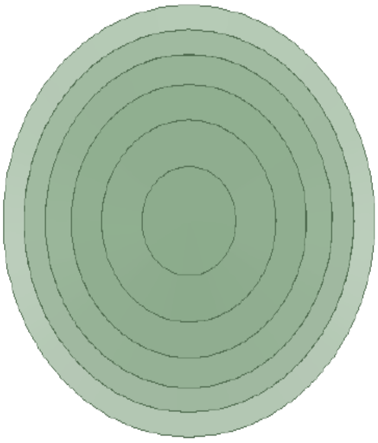

Figure 5: Layered cylindrical lens with partial filling of dielectric by changing its height

IV. Results And Analysis

The results of the optimization are shown in Table 1 which indicates the PSO specified values for the dielectric constant and thickness of each layer. The lens pattern that corresponds to these values is shown in Figure 7 along with the pattern of the uniform five shell lens and the desired side lobe level envelope.

Table 1: Optimized design criteria for a Luneburg lens

shell	ε_r	Thickness
1	1.152	2.725
2	1.609	3.003
3	1.722	1.585
4	1.826	1.438
5	1.932	6.253

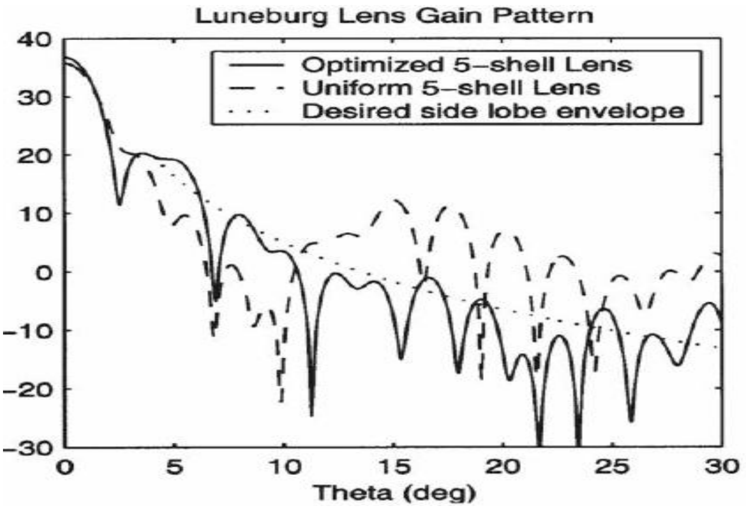

Figure 7: optimized radiation pattern (solid line) with performance improvement over uniform shell Lens pattern (dashed line) with desired side lobe level as reference (dotted line)

It can be seen that the impact of grating effects has been significantly reduced by the optimization while the peak gain magnitude is increased by approximately 1 db. The parameters of the optimized design are inline with expectations; the dielectric constant of the outer layer is very low while that of the inner most layer is equal to 2. Further, the inner-most layer is very thick because focusing the energy alone or near the diameter is not as difficult as it is towards the outside of the lens.

For the lens reformulation with different designs the Luneburg lens with homogeneous dielectric layers is taken as reference for comparison, whose radiation pattern is shown in Fig. 8. Simulations of this design show that gain of such a lens in the direction of maximum radiation is 7.16 dB and the side lobe level is -15.97 dB.

The radiation pattern of the investigated lens design with azimuthally equidistance holes is shown in Fig. 9. The resulting antenna has a gain in the direction of the maximum radiation of 7.08 dB and side lobe level is -18.38 dB.

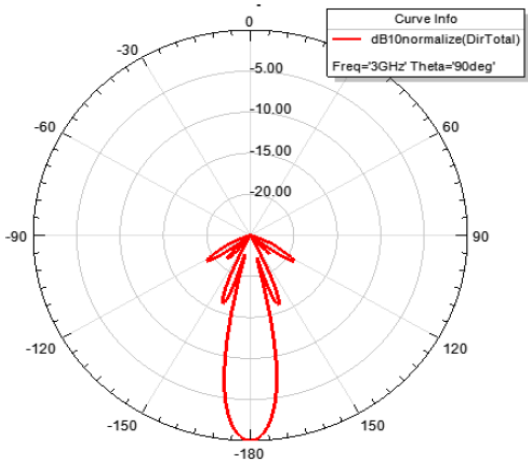

Figure 8: Radiation pattern of Luneburg lens with homogeneous dielectric layers

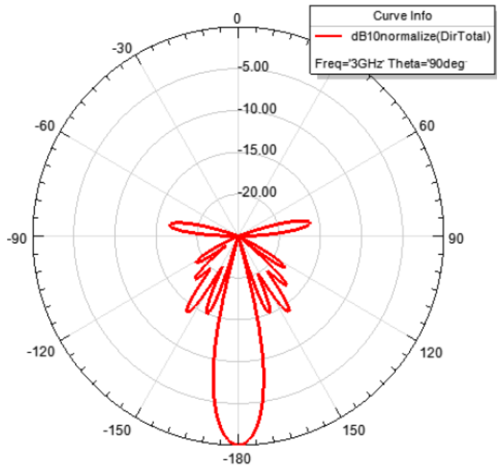

Figure 9: Radiation pattern of Luneburg lens with azimuthally equidistance holes

The radiation pattern of the Luneburg lens with concentric grooves is shown in Fig.10 having a gain in the direction of maximum radiation of 6.97 dB and the side lobe level of -14.08 dB. And finally, the radiation pattern of the Luneburg lens with a smooth in the dielectric height is shown in Fig. 11 having a gain in the direction of maximum radiation of 7.21 dB and the side lobe level of -16.08 dB.

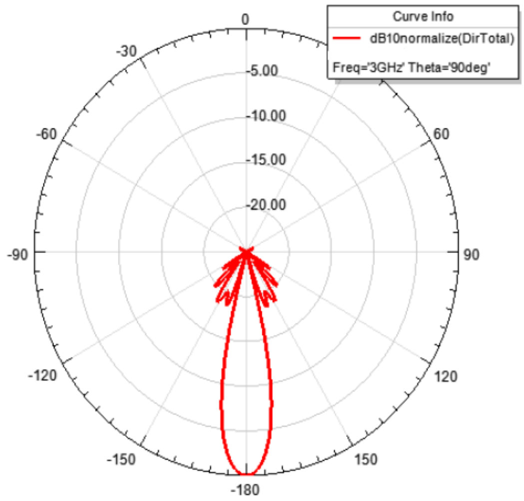

Figure 10: Radiation pattern of Luneburg lens by Partial dielectric of concentric grooves

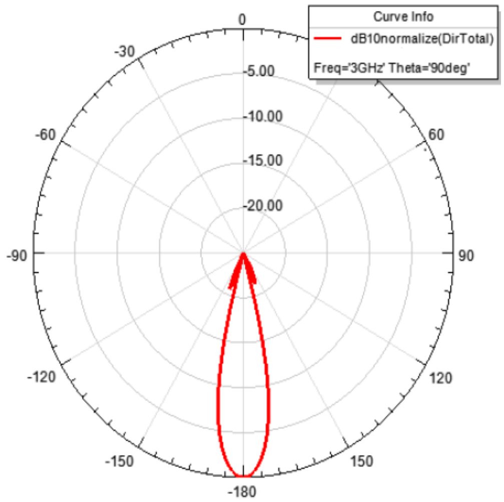

Figure 11: Radiation pattern of Luneburg lens by partial dielectric with change in height

V. Conclusion

The PSO is used for the optimization of Luneburg lens antenna because it is relatively simple and intuitive to apply for multi-objective scenarios, because the goal of the real-world antenna design is concerned with multiple factors including gain, side lobe level, size and weight. Our work proposed the optimized designs for complex design of real-world problems. Assessing and comparing the results we conclude that Luneburg lens designs based on partially filled dielectric structure can be made almost equal to homogeneous layered lens and even obtaining better results. Our design solves one of the most important problems of Luneburg lens design optimization, which is the determination of the required permittivity of the dielectric material.

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