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Research Article

Energy Transfer Using Gradient Index Metamaterial

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The gradient refractive index structure in this paper is used to increase the quantum of energy transfer. This is done by improving the directive gain of the pyramidal horn antenna at a frequency of 10 GHz. A three-dimensional array of closed square rings is placed in front of the horn antenna aperture to form a gradient refractive index structure. This structure increases the directive gain by 1.6 dB as compared to that of the conventional horn antenna. The structure nearly doubles the wireless power transfer quantum between the transmitter and the receiver when placed at both ends. The increase in the directivity is achieved by converting the spherical wave emanating from the horn to a plane wave once it passes through the structure. This transformation is realized by the gradient refractive index structure being placed perpendicular to the direction of propagation. The gradient refractive index is constructed by changing the dimensions of a closed square ring placed in the unit cell of the array. The change in the refractive index gives rise to an improvement of the half power beam width and side lobe level compared to that of the normal horn. The design and simulation were done using CST Studio software.

1. Introduction

Wireless power transfer (WPT) efficiency depends on the distance between the source and the receiver. Based on the distance, WPT can be classified as near field or far field. In the near-field domain, inductive loops are used for energy transfer [1]. By the introduction of metamaterial in between the loops, the distance of energy transfer can be increased [2–4]. Most of the work in the far field is carried out in the microwave region [5–8]. In the far-field region, the range of WPT depends on one or more of the following parameters, namely, transmitter power, directive gain of the transmitting and receiving antennas, and receiver sensitivity. The output power is enhanced by placing left-handed material slabs in between the transmitting and receiving antennas [9]. The left-handed material is comprised of an array of split-ring resonator (SRR). It is an artificial structure that provides negative permittivity and permeability [10]. In WPT, having a material in between the transmitter and receiver becomes a hindrance. Hence, the array is brought close to the source and the receiver so that the space between them is clear. This can be achieved by the introduction of an array of metamaterial with gradient refractive index at the aperture or inside the conventional horn [11, 12]. Such a configuration can transform the spherical wave at the antenna aperture to the plane wave. In this work, we propose a method to enhance the energy transfer by introducing a flat structure near the aperture of the pyramidal horn antenna at 10 GHz. As we know, the conventional horn is used in applications such as point-to-point communication where high directivity becomes an essential requirement. It can also be used in satellites for global earth coverage where minimum side lobe level is the key requirement [13]. The proposed structure enhances the directivity and improves the side lobe level suitable for these applications. We also discuss the design of the pyramidal horn operating at X band which can be used for high-power application and higher directivity. The design parameter of the structure is provided, and its merits are discussed. The WPT system results have been analyzed and discussed.

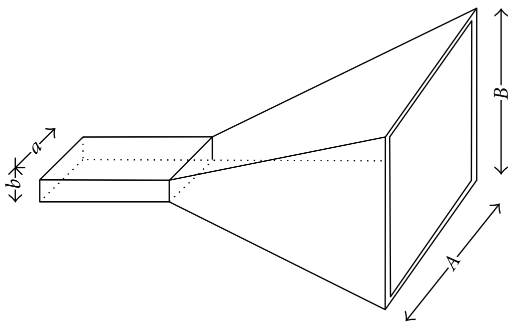


FIGURE 1: Pyramidal horn antenna.

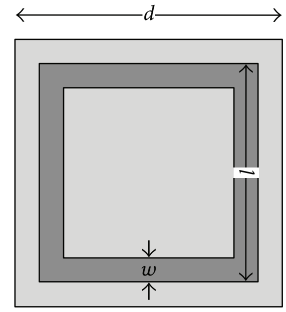


FIGURE 2: CSR unit cell.

2. Design of Pyramidal Horn Antenna

A pyramidal antenna is an amalgamation of E-field and H-field horn antennas. The horn antenna is an impedance matching device between the feed and free spaces. The impedance of the horn gradually changes over the length of the horn. The structure of an X band pyramidal antenna is shown in Figure 1. The antenna is designed to operate at 10 GHz for a directivity of 20 dB. The feed WR-90 with dimensions 22.86 mm × 10.16 mm ($a \times b$) has been used. For this design, the aperture efficiency factor represented as "η" is considered to be 0.51. The maximum phase deviations of E-plane "u" and H-plane "s" are chosen to be 0.25 and 0.375, respectively. The apertures of the horn antenna represented as "A" and "B" are given by the following equations [14]:

$$A^4 - aA^3 + \frac{ubD\lambda^2 A}{4\pi s\eta} = \frac{uD^2\lambda^4}{16s\pi^2\eta^2},$$
$$B = \frac{b + \sqrt{b^2 + 4sA((A-a)/t)}}{2}. \tag{1}$$

By substituting the above-mentioned values in (1), the aperture dimensions are found to be 134 mm × 104.85 mm. By using trigonometric relations, the length of the horn antenna is calculated as 165.475 mm. The half power beam width of both H- and E-planes can be computed using the following expressions [15]:

$$\mathrm{HPBW}_H = 78^\circ \frac{\lambda}{A},$$
$$\mathrm{HPBW}_E = 54^\circ \frac{\lambda}{B}. \tag{2}$$

For 10 GHz, the half power beam widths for H- and E-planes are found to be 17.46° and 15.45°, respectively. The directive gain of the horn antenna can be obtained by the following expression when frequency, aperture size, and aperture efficiency factor "η" are known [15]:

$$D = \frac{4\pi}{\lambda^2}(\eta AB). \tag{3}$$

By using the above analytical expression, the theoretical value of the directivity is found to be 20 dB as expected. To increase the directivity further, it is required to increase the size of the antenna. This would lead to an impractical size of the antenna. Hence, to keep the size compact and to enhance the received power in WPT, we have introduced a gradient refractive index structure at the aperture of the horn antenna. This converts the spherical beam from the antenna to the collinear beam when it emanates out of the structure. The design of this structure is explained in the next section.

3. Gradient Refractive Index Structure

The design is comprised of a pyramidal horn and a gradient refractive index structure. The structure is a three-dimensional array of closed square ring (CSR) unit cell. Each CSR unit cell [11] is a square loop placed on top of the substrate as shown in Figure 2. This acts as an electric resonator which is formed by the combination of the inductance of the copper strip and the capacitance between the adjacent unit cells. The size of the unit cell "d" is about one tenth of the wavelength at X band. For 10 GHz operating frequency, the unit cell dimension is 3 mm. This acts as an electrically smaller device to an incident time-varying electromagnetic field; thus, the first-order resonant frequency is well above the X band. The square loop is made up of copper strips of length "l" and width "w." The dielectric constant of the substrate is 2.65 with a loss tangent of 0.001.

To construct a gradient refractive index structure, an array of CSR unit cells with different lengths (1.5 mm to 2.6 mm) and widths (0.2 mm) of square rings is used. Each CSR of different lengths provides a different effective refractive index. The effective refractive index of the inhomogeneous material is extracted from the S-parameters of single CSR by applying the theory given by Smith et al. [16]. They have given an expression for the refractive index as follows:

$$n = \frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}\left(1 - S_{11}^2 + S_{21}^2\right)\right], \tag{4}$$

where "S_{11}" is the reflection coefficient, "S_{22}" is the transmission coefficient, and "k" is the wave number. Figure 3 presents the refractive index of the unit cell for different ring dimensions (1.5 mm to 2.6 mm). To convert the spherical wave into the plane wave, the array has to be a three-dimensional array. The length and breadth are the same as those of the aperture of the antenna while thickness determines the delay in the propagation of the wave at the center

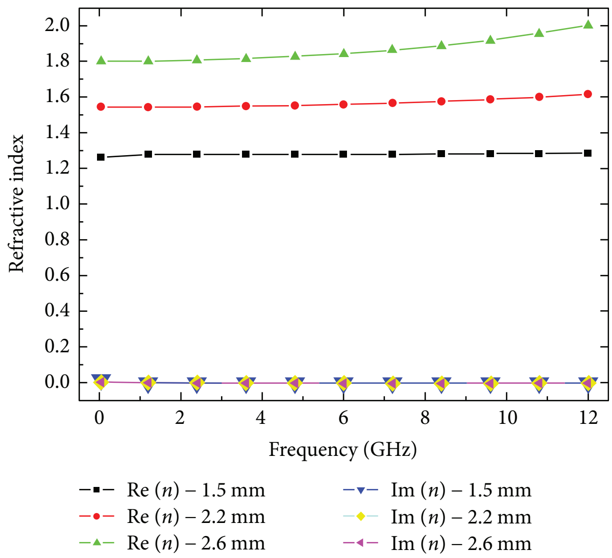


Figure 3: Refractive index of CSR for dimensions 1.5 mm to 2.6 mm.

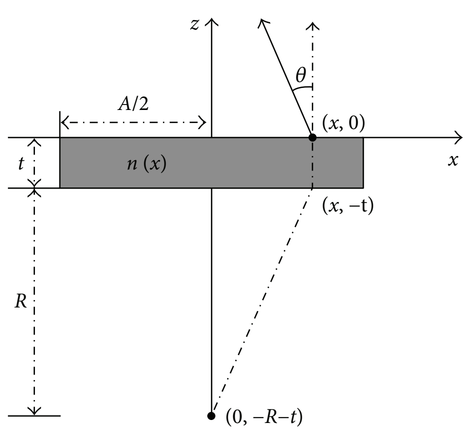


Figure 4: Schematic of the gradient refractive index structure.

compared to that at the edge of the horn antenna. The relation between the edge aperture size "x," focal length "R," and thickness of lens "t" discussed in [17] as described in Figure 4 is related by the following expression:

$$n(x) = n_0 - \frac{\left[x \sin\theta + \sqrt{R^2 + x^2} - R\right]}{t}. \qquad (5)$$

By considering the thickness of the structure as 24 mm, the maximum refractive index "n_0" and minimum refractive index "$n(x)$" values are found to be 1.82 and 1.276, respectively. For the above-mentioned specifications, it is found that the three-dimensional array is formed by $45 \times 35 \times 8$ unit cells each of size $3\,\text{mm}^3$. The three-dimensional CSR array is shown in Figure 5. This array when placed in front of the pyramidal horn antenna as shown in Figure 6 provides better directivity compared to that of the conventional horn antenna.

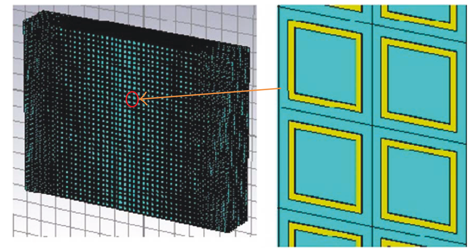


Figure 5: CSR array and unit cell.

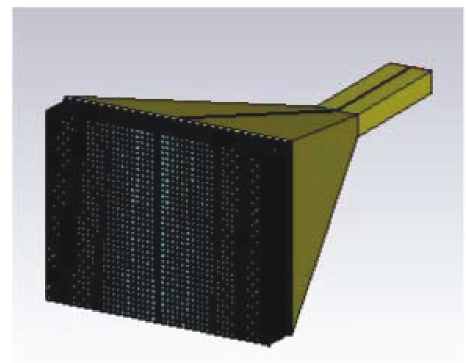


Figure 6: Gradient refractive index structure at the aperture of the pyramidal horn antenna.

4. Wireless Power Transfer System

A typical wireless power transfer system is comprised of a microwave transmitter, a transmitting antenna, a receiving antenna, a rectifier, and a load as shown in Figure 7. According to the Friis transmission formula, the received power "P_r" depends on the transmitted power "P_t," the distance "L" between the transmitter and the receiver, and the directive gain of the transmitting antenna "G_{td}" and receiving antenna "G_{rd}" as expressed in [15]

$$P_r = P_t \left(\frac{\lambda}{4\pi L}\right)^2 G_{td} G_{rd}. \qquad (6)$$

To enhance the received power, the possible options are to increase the transmitted power, to reduce the distance between the transmitting and receiving antennas, or to increase the directivity of the antenna. If the transmitted power has to be increased, the energy needed to generate the required power has to be increased. Reducing the distance between the transmitter and receiver will not be a viable solution as the range is reduced. But if the directive gain of the antenna can be increased, the system efficiency can be improved without sacrificing the energy or the range. This is achieved by focusing the beam to the region of interest. If the conventional horn antenna is replaced with the horn and gradient refractive index structure, there will be an increase of "y" dB of the directive gain. The use of the structure at both the transmitting and the receiving ends will improve the received power of the WPT system to "$2y$" dB.

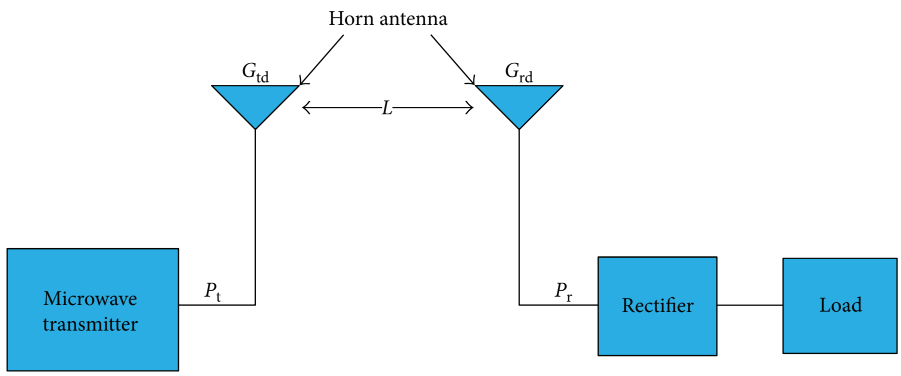


Figure 7: Microwave WPT system.

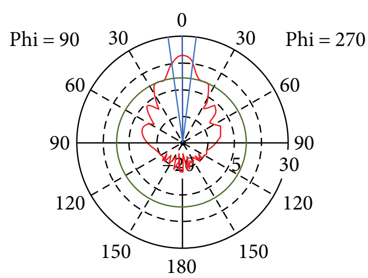


Figure 8: Radiation pattern of the pyramidal horn antenna.

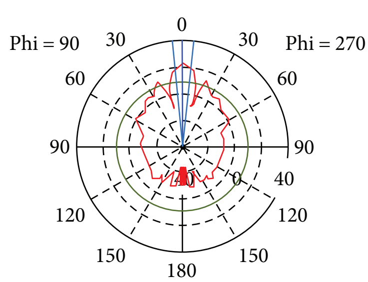


Figure 9: Radiation pattern of the pyramidal horn antenna with the gradient refractive index structure.

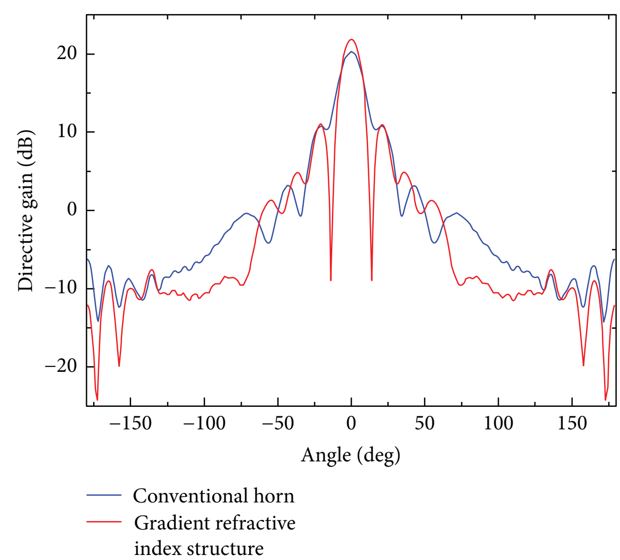


Figure 10: Far-field pattern of the horn antenna with and without the gradient refractive index structure.

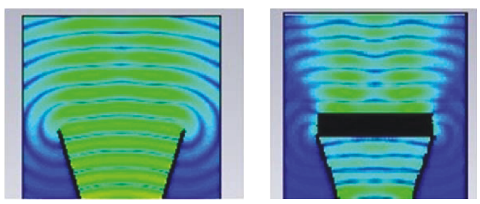
5. Results and Discussion

The standard horn antenna shown in Figure 1 is simulated for an operating frequency of 10 GHz. The radiation pattern of the horn antenna is shown in Figure 8. It is found that the directivity and half power beam width are 20.3 dB and 15.2°, respectively. The simulated result matches with the theoretical calculations discussed in Section 2. Further, the return loss and the side lobe level are found to be −25 dB and −9.6 dB, respectively. After placing the structure at the aperture of the horn, the simulations responded positively by showing an accretion of 1.6 dB in directivity when compared to those in the conventional horn antenna without the structure. Figure 9 shows that the directive gain is increased to 21.9 dB from 20.3 dB after introducing the gradient refractive index structure. This is around 8% higher directive gain as compared to that of the pyramidal horn antenna. The increase in the directivity corresponds to the reduction of half power beam width to 12.2° from 15.2°. This improvement is because the electromagnetic wave is more focused as compared to that in the conventional horn antenna. In addition, the side lobe level is reduced from −9.6 dB to −10.8 dB. The simulated return loss for this structure is found to be −15 dB. The directivity of 21.9 dB is obtained using a standard 166 mm × 131 mm × 264 mm dimension horn antenna. The gradient refractive index structure used to achieve the same directivity has a reduced dimension of 135 mm × 105 mm × 189.475 mm.

Hence, the use of structured metamaterials has been beneficial in terms of reducing the size of the antenna and providing better directivity, as is evident from Figure 10. Table 1 shows the improvement in the antenna parameters of the structure over the conventional antenna. There is especially a significant decrease in the side lobe level in conjunction with an increase in the directive gain. This is achieved because of the introduction of the gradient refractive index structure. The near-field wavefront is converted from spherical to planar as is evident from Figure 11. We

Table 1: Antenna parameters of the horn antenna with and without the gradient refractive index structure.

Antenna parameters	Standard horn antenna	With gradient refractive index structure	% change
Directivity	20.3 dB	21.9 dB	7.9
3 dB beam width	15.2°	12.2°	19.7
First side lobe level	−9.6 dB	−10.8 dB	12.5



(a) (b)

Figure 11: Spherical to plane wave transformation (a) without the structure (b) with the structure.

can infer from our study that using this structure in the WPT system instead of the horn antenna impacts the performance of the system. The improvement in the directive gain of the antenna increases the system gain to 3.2 dB. That is an enhancement of twice the power received with respect to the conventional horn antenna.

6. Conclusion

The directivity of an antenna is a parameter of immense importance. In this study, we have demonstrated a method to improve the directivity and other antenna parameters like the beam width and side lobe level by employing an engineered metamaterial structure whose unit cell is a CSR. The gradient refractive index is achieved by changing the dimensions of the CSR. The distance between the aperture and the metamaterial is a factor which can affect the performance of the antenna. Appropriately positioning the metamaterial structure and choosing the physical dimensions of the CSR unit cell structure can lead to enhancement in the output parameters. This was verified by a simulation in CST Studio software. This software employs finite element analysis to simulate models in the various frequency domains. Using this configuration, we have observed an improvement of 3.2 dB directive gain in the WPT system. This in turn increases the received power by more than twice that of the standard pyramidal horn antenna without the gradient refractive index structure.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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