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Application of Metamaterials for the Microwave Antenna Realisations*

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Abstract: In this paper, the application of left-handed metamaterials for the realisation of microwave antennas has been considered. Special emphasis is placed on lens antennas based on gradient-index metamaterials, and their advantages and enhanced features in comparison with conventional microwave antennas are highlighted.

Keywords: Metamaterials, Gradient-index metamaterials, Lens antennas.

1 Introduction

Artificial structures whose electromagnetic (EM) characteristics do not depend on the chemical composition but on the geometry of the structure units have sparked great interest among scientists in the first decade of the 21st century. These EM structures, known as metamaterials (MTM), exhibit highly unusual properties, such as extreme values of effective permittivity and permeability, phase and group velocity antiparallelism, etc. Metamaterials, particularly left-handed metamaterials (LH MTM) characterised by a simultaneously negative permittivity and permeability as well by a negative refractive index, have been proposed for the realisation of many different types of microwave components having advanced characteristics and small size [1, 2]. Heretofore a numerous MTM applications have been developed. They are novel full-space scanning fan/pencil-beam leaky-wave antennas, resonant antennas, conical-beam radiators, high-directivity arrays, smart multiple-input multiple-output systems, real-time spectrum analyzers, to name but a few [3].

As one of the potential LH MTM-based applications, the composite right-left handed (RH/LH) structures with graded refractive index profile (GRIN MTM) have been studied intensively both theoretically and experimentally in recent years [4 – 6]. Gradient dielectric structures or gradient structures based on artificial dielectrics realised with the array of parallel metal waveguides, are used in lens antennas for the realisation of traditional and planar lenses in order

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to obtain higher directivity at radio and microwave frequencies [7]. As opposed to these structures, due to possibility to gradually change not just the values of permittivity but also the values of permeability GRIN MTMs offer the additional degree of freedom in the design of specified component features and the effortless impedance matching in free space and possibly improved performance at microwave and optical frequencies. Combination of LH MTM layers with different refractive index profiles has enabled the realisation of planar lenses and reflector antennas with very low return losses and therefore the potential applications in a wide frequency range. The Fig. 1 illustrates the application of GRIN MTM lens to redirect the waves to an angle θ with respect to the incidence [8].

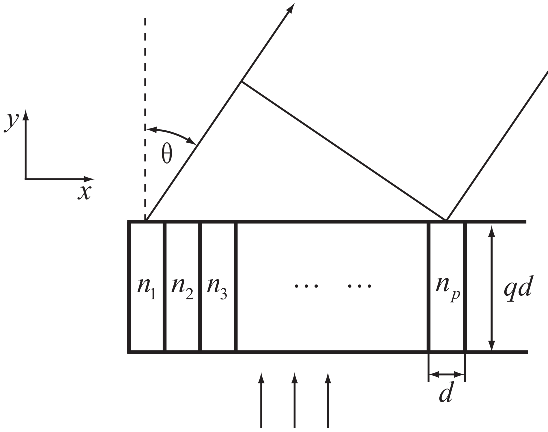


Fig. 1 – *Configuration of* GRIN MTM *lens for directing* EM *radiation* [8]. *The refractive index changes along the x*-axis, $n_1 < n_2 <\ldots n_p$ *with the constant phase shift between adjacent layers.*

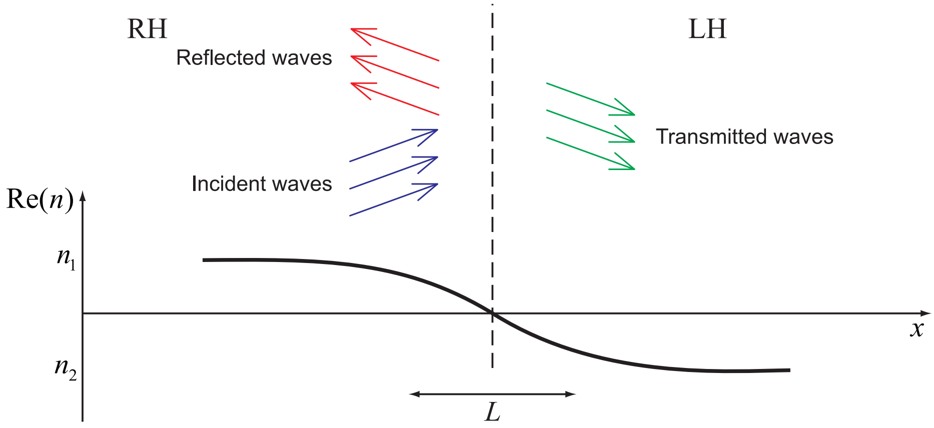
To capture the unusual features of MTM and to enable direct specification of EM parameters of MTM both in the frequency-domain and time-domain, a number of differential and integral numerical techniques have been enhanced for LH MTM analysis. For most problems of practical interest, these numerical techniques typically offer much faster analyses than the implementation of the MTM transmission line networks using circuit simulators. In order to analyse GRIN MTM structures numerical models are necessary since closed analytic solutions for EM field can be derived for a few refractive index profiles, such as hyperbolic tangent, linear, exponential profile [9 – 11]. In addition, these available analytical solutions are of limited application since it is very difficult to implement these GRIN profiles over a wide frequency range. A numerical model used to describe EM parameters of dispersive, lossy MTM over a wide frequency range [12], which is developed by using modified TLM-Z approach

(TLM method based on Z transforms), has been successfully applied for numerical characterisation of GRIN MM structures with different refractive index profiles at microwave and THz frequencies [13]. Similar models have been developed for other numerical techniques including FD-TD method [14].

In this paper, the application of GRIN MTM for the realisation of microwave antennas has been investigated using the above described TLM-Z numerical model of metamaterials, which has been implemented in commercial software. Special emphasis is placed on lens antennas based on gradient-index metamaterials while in a similar way GRIN MTM structures can be used for the realisation of the planar reflector antenna.

2 GRIN Metamaterials and Their Application in Lens Antenna Design

In general GRIN MTM structure can be represented with the gradient change of real part of refractive index across the interface between positive and negative refractive index materials as shown in Fig. 2. The combination of different refractive index profiles profiles (function *f*(*x*) in Fig. 2) offers possibilities for many practical applications such as lenses. For particular applications the transit area of composite RH/LH structure with a gradient refractive index profile where the refractive index is zero is of great interest while in some applications it is sufficient to obtain the gradient of refractive index only in LH area.



$$\mathrm{Re}\{n(x)\}=\begin{cases} n_1 & x \le -\mathrm{L}/2 \\ f(x) & -\mathrm{L}/2 < x < \mathrm{L}/2 \\ n_2 & x \ge \mathrm{L}/2 \end{cases}$$

Fig. 2 – *GRIN MTM.*

Geometrical optics is quite often used for the high-directivity antenna design. In this paper, the basic principles of transformation optics are applied to illustrate the design and realisation of GRIN MTM lens antenna (Fig. 3).

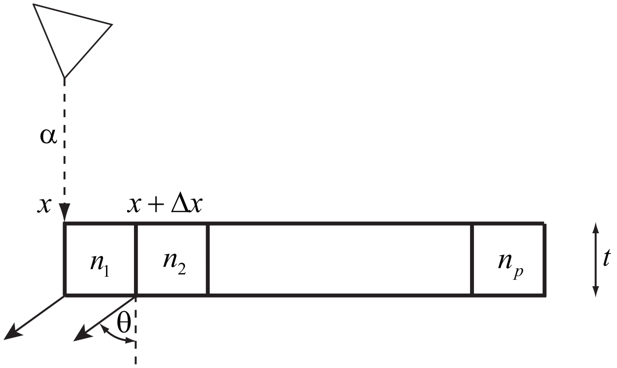


Fig. 3 – *GRIN MTM lens antenna.*

To design high-directivity lens antenna it is necessary to transform the cylindrical excitation waves of a line source into plane waves. Furthermore, the propagation of these plane waves at an oblique angle θ after passing through GRIN MTM lens must be ensured. By geometrical optics the refractive index $n(x)$ and the constant deflection angle θ of the plane waves are related to each other by [6]:

$$n(x) = n_0 - \frac{\sqrt{x^2 + a^2} - a + x\sin\theta}{t}, \tag{1}$$

where a is the distance between the line source and the lens, t is the thickness of MTM layer while n_0 is an arbitrary positive number. The optical path of wave propagation in MTM layer will vary depending on the position (x) of the incident wave of the line source. At the same time due to different values of the refractive index of MTM the redirection of the EM radiation is effortlessly achieved and therefore focused and centered radiation is obtained.

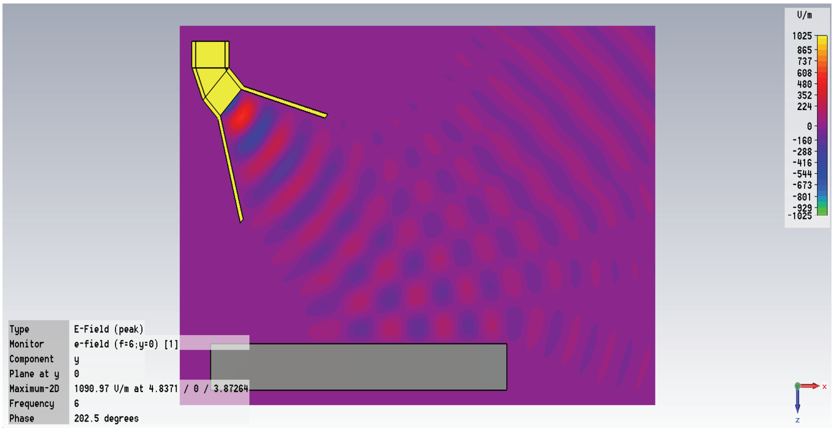
3 Numerical Analysis

In this paper, GRIN MTM lens antenna has been designed. PEC horn antenna with operating frequency range from 3 GHz to 9 GHz has been placed at the distance of 0.2 m from the MTM lens. The MTM lens, long 0.4 m and thick 0.05 m, is divided into 100 layers of the same length but of different refractive indices. The parameters of metamaterials are described by $\varepsilon_r = \mu_r = n(x)$. In Drude function parameters $\omega_{pe,m}$ and $\gamma_{e,m}$, are electric or magnetic plasma frequencies and the corresponding collision frequencies which represent losses in MTM. These parameters are easily calculated for each layer of MTM lens:

$$\varepsilon(\omega) = \varepsilon_0 \left(\varepsilon_\infty - \frac{\omega_{pe}^2}{\omega^2 - j\omega\gamma_e} \right), \tag{2}$$

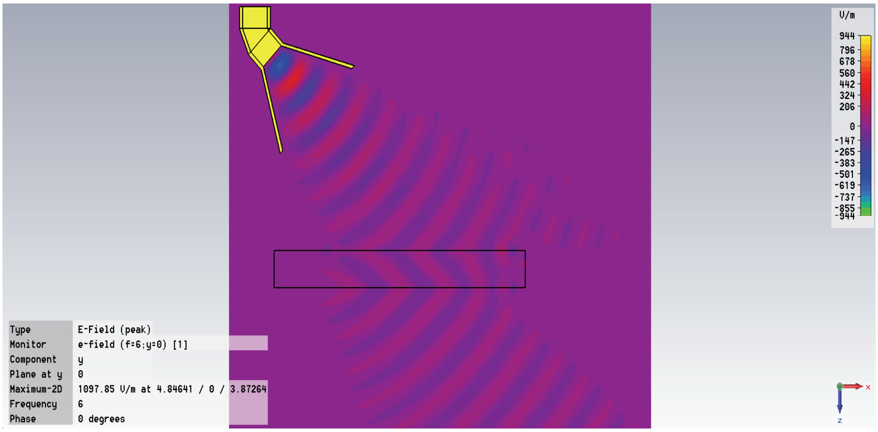
$$\mu(\omega) = \left(\mu_\infty - \frac{\omega_{pm}^2}{\omega^2 - j\omega\gamma_m} \right). \tag{3}$$

Electric field distribution E_y along x-axis of the PEC lens antenna at the frequency of 6 GHz is shown in Fig. 4 while electric field distributions E_y along x-axis of MTM lens antenna and GRIN MTM lens antenna for different radiation angles are respectively shown in Figs. 5, 6 and 7.



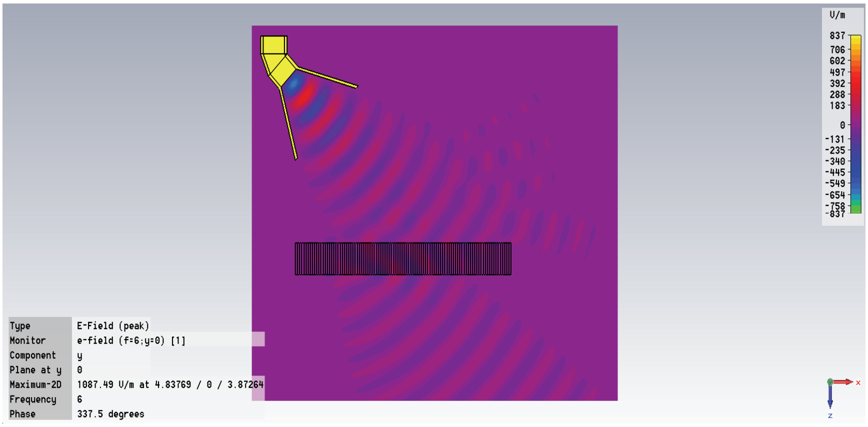
Type	E-Field (peak)
Monitor	e-field (f=6;y=0) [1]
Component	y
Plane at y	0
Maximum-2D	1090.97 V/m at 4.8371 / 0 / 3.87264
Frequency	6
Phase	202.5 degrees

Fig. 4 – *Electric field distribution* $E_y(x)$ *of* PEC *lens antenna.*



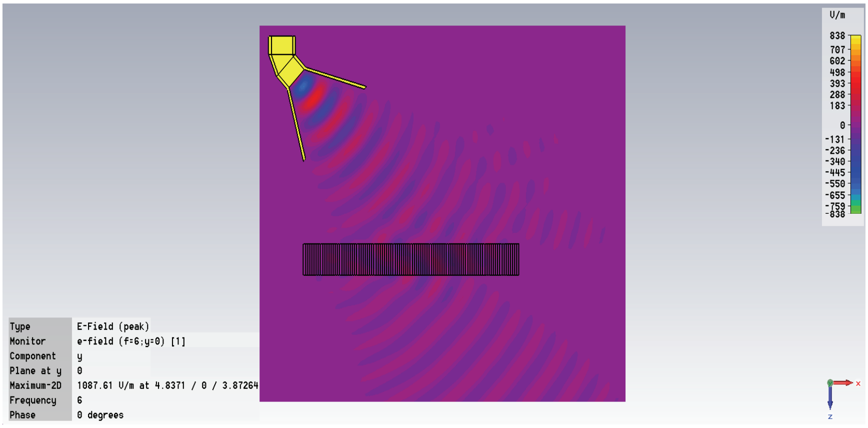
Type	E-Field (peak)
Monitor	e-field (f=6;y=0) [1]
Component	y
Plane at y	0
Maximum-2D	1097.85 V/m at 4.84641 / 0 / 3.87264
Frequency	6
Phase	0 degrees

Fig. 5 – *Electric field distribution* $E_y(x)$ *of* MTM *lens antenna* ($n = -1$).



Type	E-Field (peak)
Monitor	e-field (f=6;y=0) [1]
Component	y
Plane at y	0
Maximum-2D	1087.49 V/m at 4.83769 / 0 / 3.87264
Frequency	6
Phase	337.5 degrees

Fig. 6 – *Electric field distribution* $E_y(x)$ *of GRIN MTM lens antenna* ($\theta = -45°$).



Type	E-Field (peak)
Monitor	e-field (f=6;y=0) [1]
Component	y
Plane at y	0
Maximum-2D	1087.61 V/m at 4.8371 / 0 / 3.87264
Frequency	6
Phase	0 degrees

Fig. 7 – *Electric field distribution* $E_y(x)$ *of GRIN MTM lens antenna* ($\theta = -30°$).

The obtained results illustrate the advantage of GRIN MTM in a design of highly directive lens antennas. These lens antennas are easily realised by choosing properly an arbitrary number n_0. In this paper, lens antenna is designed for $n_0 = 2$ for deflection angle $\theta = -45°$ and $\theta = -30°$.

4 Conclusion

In this paper, possible applications of metamaterials, particularly metamaterials with gradient refractive index, for the realisation of wideband highly directive microwave antennas have been investigated. The examples considered in this paper demonstrated the advantages and enhanced features of GRIN metamaterials antennas in comparison with conventional microwave antennas.

5 Acknowledgment

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