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Original research article

Effects on the focusing of 3D elliptical reflector with strong chiral background supporting both PPV and NPV modes

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ABSTRACT

The reflected electromagnetic waves from a perfect electric conductor (PEC) 3D elliptical reflector with chiral background with high value of chirality parameter $k\beta$ are discussed. The chiral medium supports both negative phase velocity (NPV) and positive phase velocity (PPV) simultaneously by increasing the concentration of chiral objects in the host medium, i.e., with strong chiral medium. For the value of $-1 < k\beta < 1$ only PPV can propagate in the chiral medium with 3D elliptical reflector and out of this range both PPV and NPV are supported by the chiral medium with 3D elliptical reflector embedded in chiral medium. The derived high frequency field expressions with the help of geometrical optics (GO) and Maslov's method are simulated using MATLAB software with different values of chirality parameter $k\beta$ greater than one.

1. Introduction

Negative phase velocity (NPV) phenomenon has attracted the optics and electromagnetic community over the years due to its potential applications in the field optics systems, communication engineering, propagation of wave and radar technology. An electromagnetic (EM) plane wave is described to have NPV, if it is propagating opposite to the time averaged Poynting vector direction [1]. The NPV terminology in electromagnetic waves was introduced by Veslago for the first time [2]. Moreover, the negative refraction phenomenon has also one of the hot topics for the last few decades due to the potential application in the field of radars, material science, optics, medical science, communication and microwave devices. This theory is practically demonstrated for the first time in 2001, in the microwave frequency range by exciting the artificial materials by EM wave [3]. It the early days of NPV phenomenon can only be achieved by optimizing the value of permittivity (ε) and permeability (μ) of the mediums properly [4,5]. Later on Lakhtakia and others investigate the NPV phenomenon further and derive the conditions for the chiral medium to support NPV propagation [6]. Moreover, it is experimentally and theoretically establishes that due to birefringence nature both right circularly polarized (RCP) and left circularly polarized (LCP) waves are propagating in chiral medium. Under different conditions chiral medium can support NPV propagation for both LCP and RCP modes, or NPV for LCP mode and positive phase velocity (PPV) for RCP mode or vice versa [7–10].

The analysis of the interaction of high frequency electromagnetic wave with different focusing systems were done over the years using various techniques and methods such as Method of Moment (MOM), Finite Difference Time Domain (FDTD), Physical Optics (PO), Genetic Algorithm (GA), Geometric Optics (GO), Kirchhoff–Huygens integral method, Debye Wolf focusing integral method and various other methods and tools which are a combination of [11–15]. However, in this paper we

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model the electromagnetic wave using geometrical optics approximation when the 3D elliptical reflector antenna is embedded in strong chiral medium. However due to the shrinking of the volume of the ray beam around the focal points the GO method is not applicable. These focal points are of great practical importance in the design of the reflector system. Therefore, an asymptotic method based on Maslov's theory is applied which uses the already derived expressions using GO approximation and model the wave using a hybrid domain coordinates system. Thus the derived equations using Maslov's method are valid around the focal region. Maslov's method has been used for other focusing systems over the years with the likes of two and three dimensional parabolic and circular reflectors and lenses [16–22]. In this work we extend our previous work to three dimensional case which is used can be in most practical applications. The derived expressions are analyzed with high value of the chirality parameter ($k\beta$) which implies that the 3D elliptical reflector antenna supports NPV and PPV at the same time.

The realization of negative phase velocity in strong chiral medium is illustrated in section 2. In this manuscript, 3D elliptical reflector antenna embedded in strong chiral medium is described and the focal region fields are analyzed with high value of the chirality parameter ($k\beta$). The derived expressions for the 3D elliptical reflector are simulated in MATLAB software and analyzed in Section 3. Finally conclusions are discussed in Section 4.

2. Chiral medium and negative phase velocity

The terminology of NPV and negative refraction was studied experimentally at microwave frequency range [3]. This leads the researcher's community in the field of electromagnetic, optics and materials to investigate and analyze keeping multiple applications in consideration. Over the years the illustration of NPV phenomenon using the conventional dielectric and magnetic materials exhibit a lot of shortcoming due to practical constraints. Therefore the engineered and complex materials such as bi-anisotropic materials, chiral materials, and chiral metamaterials, split ring resonators etc get the attraction of the engineer and scientists. The NPV concept related to strong chiral medium is discussed in the presence of a 3D elliptical reflector antenna. The wave interactions of chiral medium for different interesting theoretical and practical applications are discussed in [22–26]. Drude–Born–Fedorov (DBF) method is one of the many ways to define chiral medium given in [23]

$$\mathbf{D} = \varepsilon(\mathbf{E} + \beta\nabla \times \mathbf{E}), \quad \mathbf{B} = \mu(\mathbf{H} + \beta\nabla \times \mathbf{H}) \tag{1}$$

where, ε, μ, and β are the permittivity, permeability and chirality parameters respectively. The chirality parameter has their dimension equivalent to length. After solving the DBF constitutive relations solution of Maxwell's equations give us coupled differential equations. These coupled differential equations for **E** and **H** are reduced to uncoupled by using the relation [23]

$$\mathbf{E} = \mathbf{Q}_L - j\sqrt{\frac{\mu}{\varepsilon}}\mathbf{Q}_R, \quad \mathbf{H} = \mathbf{Q}_R - j\sqrt{\frac{\varepsilon}{\mu}}\mathbf{Q}_L \tag{2}$$

and $\mathbf{Q}_L$, $\mathbf{Q}_R$ represent RCP and LCP waves respectively and satisfy the general wave equations given by

$$(\nabla^2 + n_1^2k^2)\mathbf{Q}_L = 0, \quad (\nabla^2 + n_2^2k^2)\mathbf{Q}_R = 0 \tag{3}$$

where k describe the wave number and represented by the relation $k = \omega\sqrt{\varepsilon\mu}$. The refractive indices for LCP and RCP waves in term of chirality parameter $k\beta$ is describe by the relation given by

$$n_1 = \frac{1}{1 - k\beta} \tag{4}$$

$$n_2 = \frac{1}{1 + k\beta} \tag{5}$$

The value of the chirality parameter controls the phase velocities of the LCP and RCP modes. For the chirality parameter in the range $-1 < k\beta < 1$, the chiral medium supports only PPV propagation for both LCP and RCP waves due to positive refractive indices. For $k\beta > 1$, $n_1 < 0$ and $n_2 > 0$, so LCP wave propagates with NPV and RCP wave travel with PPV. For the range of values $k\beta < -1$, LCP mode travels with NPV and RCP mode propagates with PPV. It is worth noted that for the values of chirality parameter in the range $-1 < k\beta < 1$ and $\varepsilon < 0$, both RCP and LCP waves propagate with NPV, at the same time. In this paper we discussed the situation when LCP travels with NPV and RCP wave propagates with PPV. Computationally the RCP wave with NPV LCP wave with PPV can be obtained for $k\beta > 1$. However, for $k\beta < -1$, we can get the results from $k\beta > 1$ by interchanging the role of both LCP and RCP modes. A perfect electric conductor (PEC) 3D elliptical reflector antenna is assumed, as shown in Fig. 1.

$$\zeta = g(\xi, \eta) = \frac{a}{b}\sqrt{b^2 - \xi^2 - \eta^2} = \frac{a}{b}\sqrt{b^2 - \rho^2} \tag{6}$$

In the above relation the terms a, b are the radii of the 3D dielectric elliptical reflector antenna along the major and minor axis respectively. Furthermore, (ξ, η, ζ) represents the initial values of (x, y, z), and $\rho^2 = \xi^2 + \eta^2$. In this paper the 3D elliptical reflector system is placed in homogeneous and reciprocal chiral medium. Therefore, due to birefringence nature of the chiral