Omnidirectional Radiation by Arbitrary Sources Embedded in Zero Index Metamaterials

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Abstract

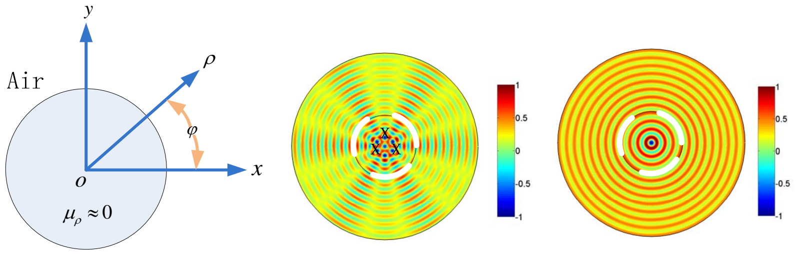
We have shown that the radially anisotropic metamaterials can be utilzed to realize ominidirectional radiation, independent of numbers and relative positions of the sources. When the radial component of the permeability tensor is approaching zero, and the wave impedance in the radial direction is designed equal to that of free space, the waves emitted from the sources will be transformed into perfect cylindrical waves without any reflection. Both the numerical and experimental results have validated our theoretical analysis.

1. Introduction

Among the family of metamaterials, more and more attentions have been paid to zero index materials (ZIM), in which the phase velocity of electromagnetic waves approach infinity. Such materials are proved to be very useful to enhance the directivity of antennas [1-4]. It can also be used in the tunneling of electromagnetic waves at the structural discontinuities. In this paper, we have realized omnidirectional radiation based on radially impedance-matched anisotropic ZIM, which will be discussed in this paper. The proposed ZIMs can change all kinds of wavefronts into perfect cylindrical ones when radial component of the permittivity or permeability tensor approaches zero, and no reflection will occur at the air/ZIM interface, which greatly improves the efficiency of the wavefront transformation.

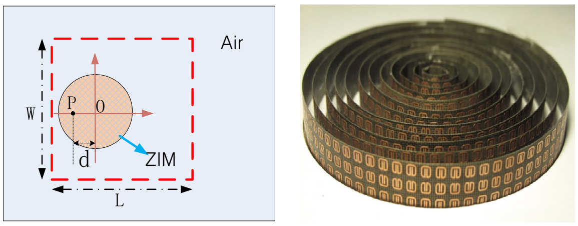
2. Theory and Experiments

We first consider a simple two dimensional problem as shown in Fig.1(a), where the region out of the circle is filled with free space, and inside the circle it is covered by anisotropic ZIM, which can be described as $\bar{\bar{\epsilon}} = \hat{\rho}\hat{\rho}\epsilon_\rho + \hat{\phi}\hat{\phi}\epsilon_\phi + \hat{z}\hat{z}\epsilon_z$, $\bar{\bar{\mu}} = \hat{\rho}\hat{\rho}\mu_\rho + \hat{\phi}\hat{\phi}\mu_\phi + \hat{z}\hat{z}\mu_z$. Here we consider a TE problem where only E_z, H_ϕ, H_ρ exist in above regions. From the Maxwell equations, we can easily get $\nabla \times \bar{E} = i\omega\bar{\bar{\mu}}\bar{H}$. In cylindrical coordinates, the radial component of the magnetic field satisfies $\frac{1}{\rho}\frac{\partial E_z}{\partial \phi} = i\omega\mu_\rho H_\rho$, when $\mu_\rho \cong 0$, the left part of above equation approaches zero, which implies that the internal electric field will have no variation in the ϕ direction. From the dispersion equation in the anisotropic medium, $\frac{k_\rho^2}{\mu_\phi} + \frac{k_\phi^2}{\mu_\rho} = \omega^2\epsilon_z$, it is obvious that the wavenumber in the ϕ direction vanishes in this condition, and $k_\rho = \omega\sqrt{\epsilon_z\mu_\phi}$. In order to achieve no reflection at the air/ZIM interface, a simple way is to keep the relative permittivity ϵ_{zr} and the relative permeability $\mu_{\phi r}$ to be unity, that is, $\mu_{\phi r} = \epsilon_{zr} = 1$, and this is very important for us to realize the wave impedance match at the media boundary, and therefore the waves inside the ZIM region can be expressed as [5]: $E_z = AJ_0(k_0\rho)$. where J_0 is Bessel function of zero order. A is the coefficient determined by the excitation of the source. The radial wavenumber of the cylindrical waves inside the anisotropic ZIM is equal to the wavenumber of free space k_0.



(a) (b) (c)

Fig. 1: (a) A 2D line current source located inside the anisotropic zero index metamaterials with $\mu_\rho \simeq 0$.(b) Distributions of Re(E_z) at the presence of three point sources inside free space, where X represents the positions of the sources. (c) Distributions of Re(E_z) at the presence of three point sources inside anisotropic zero index metamaterials. The sources are located in the same positions as those in Fig. 1(b). The white dashed line indicates the boundary between metamaterials and free space.

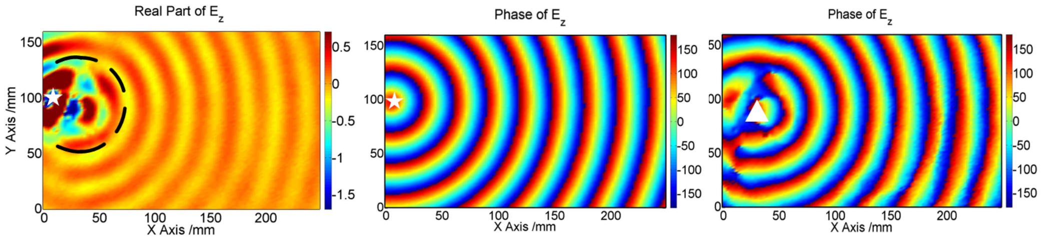


(a) (b)

Fig. 2: (a) Illustration of the relative position between the fabricated sample and the observation region. (b) Fabricated anisotropic metamaterial sample with zero index in the ρ direction.

In order to demonstrate the omnidirectional radiation characteristics discussed above, numerical simulations have been made where three point sources are located at the vertices of a equilateral triangle as shown in Fig. 2(a). The origin of the cylindrical coordinate is set to be the center of the observation circle, and the black crosses stand for the source positions, which are (0,50mm) (-43.3mm,25mm) (43.3mm,25mm) respectively. The radius of the whole observation area is 600 mm. The electric field distributions excited by the sources in free space and in a circular metamaterial disk with $\mu_{\rho r} = 0.001$, $\epsilon_{zr} = \epsilon_{\rho r} = \mu_{zr} = 1$ have been shown in Fig. 1(b) and 1(c). The complicated wavefront in free space has been changed into nearly perfect cylindrical waves, and omnidirectional radiation can be realized easily through the ZIM cover as expected.

To further verify this peculiar property of anisotropic ZIM, an experiment has been designed and carried out. From the sketch shown in Fig. 2(a), the gray region is occupied by the near field scanning system, which is actually a microwave planar waveguide. A circular sample made of anisotropic ZIM has been fabricated with the radius R=40mm as shown in Fig. 2(b). The sample is consisted of twelve layers with the gap between each layer 3.33mm. The unit cell is chosen to be split ring resonator (SRR) with the plasma frequency $f_p = 10$ GHz. From the parameter retrieval, we can get the effective permeability $Re(\mu_{\rho r}) \rightarrow 0$ at f_p. The sample is put inside the circular shadowed region in Fig. 2(a), and an excitation probe is put at the point P instead of the sample center (point O). The region outlined by the dashed line is the total observation area of the near field scanning system. Due to the limit of the scan range, the length L and width W of the observation area is 250mm and 160mm respectively. The transverse distance d between the source and sample center is 25mm. A near field probe has been embedded inside the top plate of the scanning system, which is used to measure the electric field distributions at a plane



(a) (b) (c)

Fig. 3: Measured distributions for the electric field E_z . (a) A point source (indicated by the star) is located inside the anisotropic metamaterials outlined by the dashed line. (b) A point source (indicated by the star) is located inside free space. (c) Phase distributions for the case described in Fig. 3(a).

slightly above the fabricated sample. A vector network analyzer (Agilent N5230C) is connected to the scanning system to provide the excitation signals and collect the scattering signals over the sample. The step resolution in the scan is selected to be 2mm in both directions.

Two separate experiments have been finished to prove the ominidirectional radiation properties of the anisotropic ZIM. In Fig. 3(a), distributions of the real part of the electric field E_z has been plotted. The source is placed at (10,100)mm, marked by the white star inside the figure. The dashed line indicates the position of the sample under test. Obviously the electromagnetic waves out of the sample is transformed into cylindrical waves quickly as expected, and the wave amplitude is nearly uniform outside the sample. Although we can not observe total distributions of E_z due to the limit of the scanning system, an important property can be identified by comparing Figs. 3(b)(c), which shows the phase distributions of a point source without/with the anisotropic ZIM cover. At the absence of the sample, the phase center of the outgoing waves coincides with the position of the source, as marked by the white star in Fig. 3(b). However, in Fig. 4(c), when the source is placed inside the sample, the phase center is shifted to the sample center as marked by the triangle, which is consistent to the results of the numerical simulation in Fig. 1.

3. Conclusion

In conclusion, we have realized the omnidirectional radiation by anisotropic metamaterials with the radial component of the permeability tensor close to zero. Nearly no reflection occurs at the interface of the metamaterial and free space due to the match of wave impedance in both medium. This unique property may offer us a easy method to design omnidirectional antennas.

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