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Investigation on the Near Field Properties of the Lossless Metamaterial Covered Cylinder

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1. Introduction

Quite recently, there has emerged a strong interest in exploring and exploiting the electromagnetic characteristics and properties of artificial materials, broadly referred to as metamaterial, left-handed material or negative index material, in which the real parts of both the permittivity and the permeability are negative. The metamaterial has some interesting physical phenomena, such as the reversal of the Doppler effect, the reversal of the Vavilov-Cerenkov effect, and perhaps most importantly, the negative refraction at a plane interface separating two conventional material and metamaterial [1-2].

The lossless metamaterial slab has been of interest due to the so-called "perfect lens". Cylindrical as well as spherical configurations involving metamaterial has been investigated, as well. A considerable amount of work with regard to the development and applications of metamaterial, in general, has already been accomplished [3]. Nevertheless, there is a continuing interest in further exploring the properties and potential applications of these materials in microwave and optical domain.

The purpose of this paper is to investigate the near field properties of the infinitely long lossless metamaterial covered cylinder, illuminated by a close-by electric line source(ELS). The cylinder are assumed to be the perfectly conductor and the air. As this electromagnetic model possesses a finite cross section and a localized source, it may thus reveal effects that are absent in configurations with one-dimensional(1D) slab and/or plane-wave illumination. The paper is organized as follows: In section 2, the model configuration is presented.3. The near field property of the infinitely long lossless metamaterial covered perfectly conductor cylinder is presented. 4. The near field property of the infinitely long lossless metamaterial covered air cylinder is presented. Throughout the investigation, the case of a conventional material covered cylinder is utilized as a reference.

2. The model configuration

The model configuration is depicted in Figure 1. It consists of a lossless metamaterial covered cylinder, illuminated by an ELS of a constant electric current, $I_e[A]$ placed close and parallel to the cylinder. The ambient medium is free space, i.e., its material parameters are ($\varepsilon_{0,}\mu_0$), where $\varepsilon_0 = 8.854\times10^{-12}[F/m]$ is the free-space permittivity, and $\mu_0 = 4\pi\times10^{-7}[H/m]$ is the free-space permeability. The free-space wavenumber is $k_0 = \omega\sqrt{\mu_0\varepsilon_0} = 2\pi/\lambda_0$, with λ_0 being the free-space wavelength, and the free-space intrinsic impedance is $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$. The model is of infinite extent, and the radius of the dielectric cylinder is a, the thickness of the material layer is $b-a$. The analytical solution of the model could be obtained based on the eigenfunction-expansion method. As the length limit of the paper, they are not presented here.

3. Near field property of the metamaterial covered conductor cylinder

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In this subsection, the near-field property of the electromagnetic model is discussed. The electric field $E(\rho,\phi)$ in the material layer and outside the cylinder is calculated. Based on the theoretical prediction of the metamaterial which has the characteristics of negative refraction, there should be a "focus" in the metamaterial layer which does not exist in the conventional material layer. Comparing to other field, the "focus" should have a relative high value. Because of the different incident direction and the curvature of the cylinder, the "focus" is not a point but a small area. The quantity 20Log10 ($|E(\rho,\phi)|$) is calculated in figure 2 to figure 7 to give the electric fields of the electric model under different geometric and electromagnetic parameters. In these figures, the darkest circular area is the perfectly conductor cylinder and the electric field in it is zero. Between the free space and the conductor cylinders it is the covered lossless material layer. The relative magnitude of the electric field is in proportion to the lightness. Therefore, the distributions of the electric field under different parameters could be qualitatively obtained. Comparing the conventional material with the metamaterial, from the figures it has been obviously seen that in the metamaterial layer there is a peak value which does not exist in the conventional material layer, it is the so-called "focus". The "focus" is not a point but a small area. This phenomenon is consistent with the theory prediction. Based on these figures, it can be seen that when the thickness of the metamaterial layer decrease, the effect of the metamaterial decrease too.

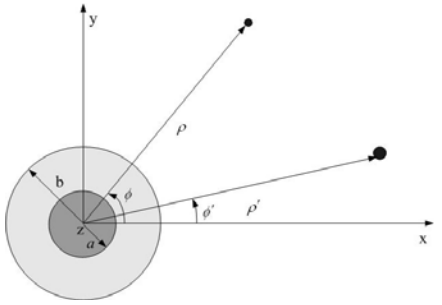

Figure 1: The model configuration

4. Near field property of the metamaterial covered air cylinder

Based on the theoretical prediction, as the metamaterial has the characteristic of negative refraction, the different conclusions should be obtained compared with the conventional material: If the "full focusing" occurs in the metamaterial layer, there should be a "focus" in the metamaterial layer and the other "focus" will appear in the inner air cylinder because of the "secondary focusing"; if the "full focusing" does not happen, there are not "focuses" in either the lossless metamaterial layer and the inner air cylinder. In the lossless conventional material covered air cylinder, there are not "focuses" at all. Comparing to other fields, the "focuses" should have relative high values. Because of the different incident direction and the curvature of the cylinder, the "focuses" are not isolated "points" but small domains. In these figures, the relative magnitudes of the electric field are also in proportion to the lightness. Therefore, the distributions of the electric field under different parameters could be qualitatively obtained. Comparing the conventional material with the metamaterial, from the figures it has been obviously seen that when the "full focusing" occurs in the metamaterial, there is a peak value in the metamaterial layer and the other peak value appears in the inner air cylinder because of the "secondary focusing"; In Figure 13, it can be seen that when the "full focusing" does not happen, there are not peak values in either the lossless metamaterial layer and the inner air cylinder. Figure 12 is the transition figure between "two focuses" and "no focus" and only one "focus" exists at the interface between the inner air cylinder and the covered lossless metamaterial. The "focuses" are not isolated points but small areas. This phenomenon is just consistent with the former analysis. Based on these figures, it can be seen that when the thickness of the metamaterial layer decreases, the effect of the metamaterial decreases too.

5. Conclusions

In this paper, the near field properties of the lossless metamaterial covered perfectly conductor and air cylinder are investigated. The quantity 20Log10 ($|E(\rho,\phi)|$) is calculated in figure 2 to figure 13 to give the electric fields of the electric model under different geometric and electromagnetic

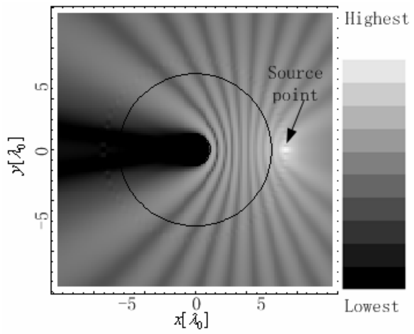

Figure 2: $\rho' = 6\lambda_0, a = \lambda_0, b = 5\lambda_0, 1\varepsilon_0 1\mu_0$
Conventional material

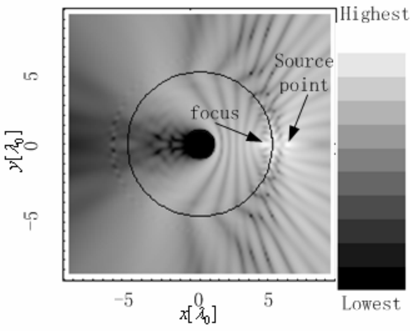

Figure 3: $\rho' = 6\lambda_0, a = \lambda_0, b = 5\lambda_0,$
$-1\varepsilon_0 -1\mu_0$ Metamaterial

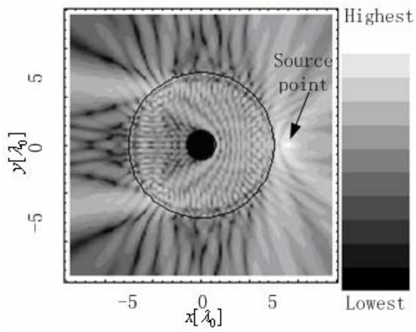

Figure 4: $\rho' = 6\lambda_0, a = \lambda_0, b = 5\lambda_0, 1\varepsilon_0 2\mu_0$
Conventional material

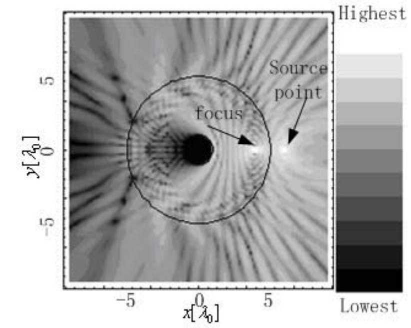

Figure 5: $\rho' = 6\lambda_0, a = \lambda_0, b = 5\lambda_0,$
$-1\varepsilon_0 - 2\mu_0$ Metamaterial

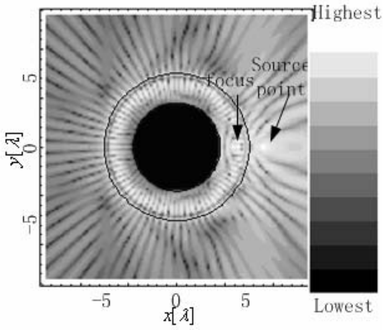

Figure 6: $\rho' = 6\lambda_0, a = 3\lambda_0, b = 5\lambda_0,$
$-2\varepsilon_0 -1\mu_0$ Metamaterial

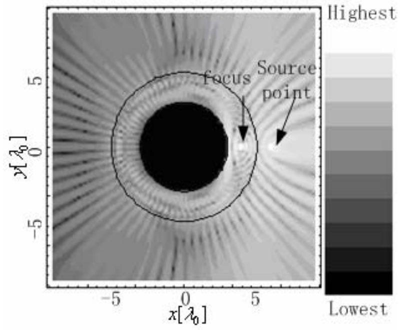

Figure 7: $\rho' = 6\lambda_0, a = 3\lambda_0, b = 5\lambda_0,$
$-1\varepsilon_0 - 2\mu_0$ Metamaterial

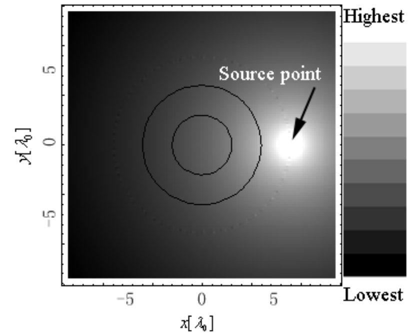

Figure 8: $\rho' = 6\lambda_0, a = 2\lambda_0, b = 4\lambda_0,$
$1\varepsilon_0 1\mu_0$ Conventional material

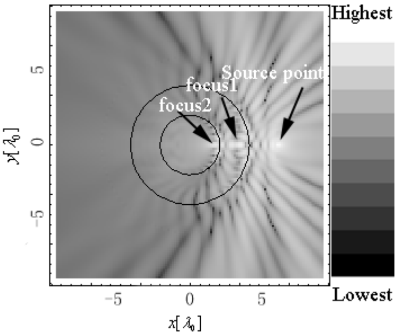

Figure 9: $\rho' = 6\lambda_0, a = 2\lambda_0, b = 4\lambda_0,$
$-1\varepsilon_0 -1\mu_0$ Metamaterial

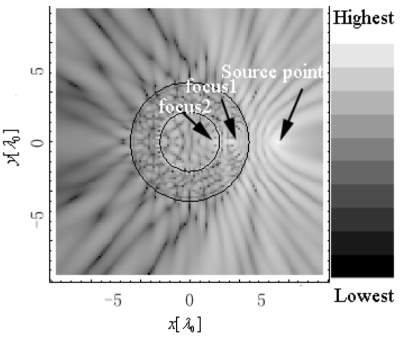

Figure 10: $\rho' = 6\lambda_0, a = 2\lambda_0, b = 4\lambda_0$, $-2\varepsilon_0 - 1\mu_0$ Metamaterial

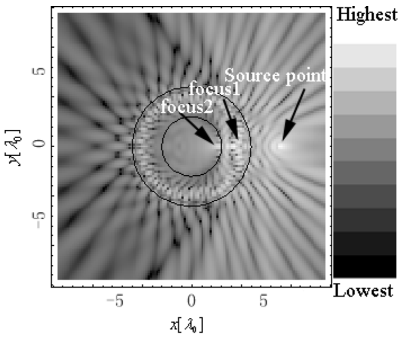

Figure 11: $\rho' = 6\lambda_0, a = 2\lambda_0, b = 4\lambda_0$, $-1\varepsilon_0 - 2\mu_0$ Metamaterial

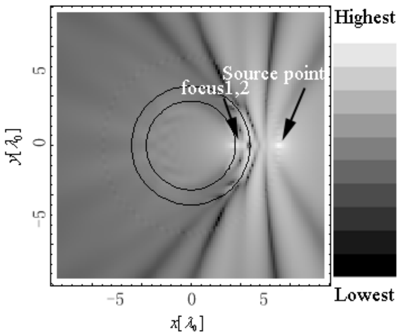

Figure 12: $\rho' = 6\lambda_0, a = 3\lambda_0, b = 4\lambda_0$, $-1\varepsilon_0 - 1\mu_0$ Metamaterial

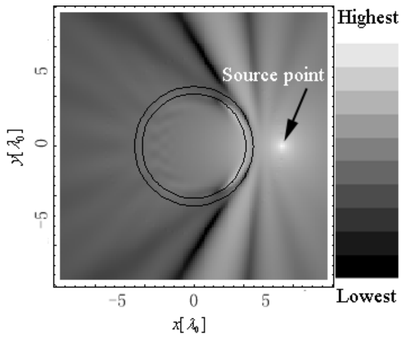

Figure 13: $\rho' = 6\lambda_0, a = 3.5\lambda_0, b = 4\lambda_0$, $-1\varepsilon_0 - 1\mu_0$ Metamaterial

parameters. For the inner perfectly conductor cylinder, comparing the metamaterial layer with the conventional material, layer it is obvious that in the metamaterial layer there is a peak value which does not exist in the conventional material layer, it is the so-called “focus”. For the inner air cylinder, comparing the lossless metamaterial layer with the lossless conventional material layer, it is obvious that if the “full focusing” occurs in the lossless metamaterial layer, there will be a “focus” in the lossless metamaterial layer and the other “focus” will appear in the inner air cylinder because of the “secondary focusing”; if the “full focusing” does not happen, there will not be “focuses” in either the lossless metamaterial layer and the inner air cylinder. In the lossless conventional material covered air cylinder, there are not “focuses” at all. The focuses mentioned above are not points but small areas because of the different incident direction and the curvature of the cylinder.

Acknowledgments

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