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Anisotropic Magnetic Metamaterial in Numerical Analysis for Electromagnetic-Wave Propagation around Cloaking Device

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Abstract- Anisotropic property of media is one function which metamaterials make possible for electromagnetic propagation. Hypothetical magnetic currents in the finite difference time domain (FDTD) method create such anisotropy in permeability in numerical models, in similar way to the modeling of Drude-type permitivity for plasma. Numerical results show clear effects of cloaking in which anisotropic permeability is conceivable by experiments.

I. Introduction

During the last decade, metamaterials were readily apparent as new artificial complex media, which have been offered subjects of great attention from the scientific communities [1–3]. Different kinds of metamaterials as passive media were picked out in agreement with macroscopic characteristics against electromagnetic waves [4]. Interest in metamaterials arosed from their intrinsic property whose both permittivity and permeability covers negative/ positive real values and/or anisotropic features. Manufacturing of a metamaterial as an array of electric or magnetic resonators requires conditions in which the size of the unit resonator is smaller than the wavelength of the wave. This array satisfies new values of permittivity and permeability in directions of the electric and magnetic fields, respectively [5]. By this reason, possibilities of metamaterials are greater than conventional isotropic materials which cannot realize the entire control of electromagnetic wave propagation. Therefore, one of the most required point for the anisotropic characteristic is the spacial arrangement of the resonators in a metamaterial.The possibility to realize anisotropy with a gradient characteristic was experimentally verified [6]. This spacial arrangement supports both possible anisotropic and gradient parameters which should be elaborately designed using theoretical approaches.

Previous efforts on metamaterials have encountered transformation optics to build up new devices, leading to the fact that its mathematical method reveals the real impact of anisotropic characteristics against electromagnetic wave propagation [7–9]. Our particular interest is the method on cloaking layers which are theoretically and experimentally based on the anisotropic media; to address this issue, we represent numerical results on differences between anisotropic and isotropic effects in wave media in this report.

Main focus so far was on the specific metamaterial which achieves the high control on permeability on the one hand and accessibility in terms of the fabrication on the other hand. This metamaterial is double split ring resonator (DSRRs) [5], which provides us possibilities for choosing the permeability in cloaking devices.

Smooth gradient of parameters is basically required in the ideal cloaking solution. When we form a cylindrical plasma, the profile of the electron density in the plasma follows the Bessel function in the radial direction [10], which is close to the theoretical prediction for cloaking phenomena. Based on this potential possible in experiments, the point we pursue in this report is a theoretical model predicting optimized solutions adequately [11].

This study of the design on anisotropic structure is based on solutions of electromagnetic-wave propagation solutions from a numerical code on finite-difference timedomain (FDTD) method [12]. We demarcate a two dimensional plane; an electromangetic-wave source is polarized on transverse magnetic (TM) mode in which the electric field is perpendicular to and the magnetic field is parallel to the plane. This numerical code is used here as a platform of measure in order to discuss the mechanism of anisotropic impacts from the best case to the worst case with comparable parameters [13]. The gradient permittivity formed, by plasma is in radial coordinate direction, and to compute such properties in the numerical code, the method introduced here is to implement a continuous electronic current. This current is derived from the equation for motions of charged particles [14], and its direction of gradient is easy to manage. In the same way, we introduced here the idea of hypothetical magnetic current and manage the anisotropic permeability in the radial and azimuth directions. In experimental circumstances, the magnetic currents will be achieved by DSRRs, whereas the electric current exist in plasma as spacial gradient. We note the difference between gradient of the perfect cloaking solution and the one made by the plasma, and this difference causes small amount of scattering waves

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from the target region. A simple coordinate transformation will finish our concrete construction for Cartesian coordinate used in (FDTD) method.

In Section 2, we describe our numerical model. In Section 3, we demonstrate numerical results with discussion. In Section 4, we conclude our results on our numerical method which achieves inclusion of anisotropic effects in the flexible way.

II. Numerical Model

a) Integration of permittivity/permeability by current densities

Let us consider the relation for motion conservation of charged particles, that is, electron momentum balance equation [10]:

$$mn_{\mathrm{e}}(r)\frac{\mathrm{d}\mathbf{v}_{\mathrm{e}}(r)}{\mathrm{d}t} = -n_{\mathrm{e}}(r)e\mathbf{E} - \bigtriangledown p_{\mathrm{e}}(r) - mn_{\mathrm{e}}(r)\mathbf{v}_{\mathrm{e}}(r)\nu_{\mathrm{E}}. \quad (1)$$

m is mass of electron, *e* charge of electron, $\mathbf{v}_{\mathrm{e}}$ electron fluid velocity, $\mathbf{E}$ electric field (V/m), n_{e} electron density and r radial position, t time, and ν_{E} electron elastic collision frequency with neutral particles. Admitting homogeneous electron pressure p_{e} and neglecting positive-ion contribution due to their huge mass in comparison with electrons, we found electric current density $\mathbf{J}_{\mathrm{E}}$ as a function of $\mathbf{E}$[15]:

$$\frac{\partial \mathbf{J}_{\mathrm{E}}}{\partial t} + \nu_{\mathrm{E}}\mathbf{J}_{\mathrm{E}} = \epsilon_0 \omega_{\mathrm{pe}}^2 \mathbf{E}. \quad (2)$$

Here ω_{pe} is electron plasma frequency, and ϵ_0 the permittivity in vacuum. To determine the solution of electromagnetic propagation, waves can be composed of the harmonic sinusoidal signals using Fourier transformation, which gives us, with ω the angular frequency and components at ω shown by the top arrow over variables;

$$(\mathrm{j}\omega + \nu_{\mathrm{E}})\vec{J}_{\mathrm{E}} = \epsilon_0 \omega_{\mathrm{pe}}^2 \vec{E}. \quad (3)$$

In the FDTD code we compute the Maxwell-Ampere equation, keeping the current density as:

$$\bigtriangledown \times \vec{H} = \mathrm{j}\omega\epsilon_0\vec{E} + \vec{J}_{\mathrm{E}}. \quad (4)$$

Substitution of current $\vec{J}_{\mathrm{E}}$ from Eq. (3) into Eq. (4) leads to:

$$\bigtriangledown \times \vec{H} = \mathrm{j}\omega\epsilon\vec{E}\left(1 - \frac{\omega_{\mathrm{pe}}^2}{\omega(\omega - \mathrm{j}\nu_{\mathrm{E}})}\right)$$

$$\equiv \mathrm{j}\omega\epsilon_0\epsilon\vec{E}. \quad (5)$$

In Eq. (5) the Drude model can be extracted for the permittivity ϵ, making large possible values of permittivity set through $\vec{J}_{\mathrm{E}}$. Formulation of Eqs. (1-5) shown in [15] is an alternative way to implement medium characteristics, and $\vec{E}$ is normal to the two-dimensional plane in our numerical code, as $\vec{J}_{\mathrm{E}}$. For further details, we take into account the distribution of n_{e} which is in the shape of the Bessel function in the radial direction, corresponding to the fact that it is the solution in correlation with real distribution of charged particle [10]. The permittivity with charge distribution is completed by the relation between n_{e} and ω_{pe}.

Throughout this report, we introduce several currents in our numerical code for control of electromagnetic-wave propagation. Since cloaking solutions require anisotropic permeability (or more precisely, refractive index), for this purpose, we introduce the magnetic current $\vec{J}_{\mathrm{M}}$ in the Maxwell-Faraday equation in the same manner to the permittivity of Maxwell-Ampere equation;

$$\bigtriangledown \times \vec{E} = -\mathrm{j}\omega\mu_0\vec{H} + \vec{J}_{\mathrm{M}}$$

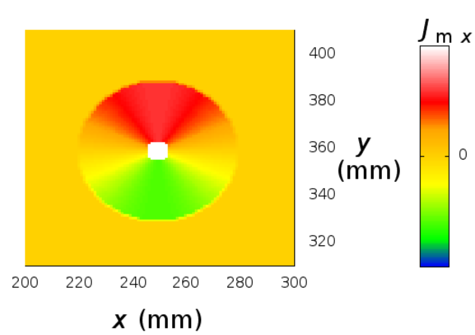
$$= -\mathrm{j}\omega\mu_0\vec{H}\left(1 + \mathrm{j}\frac{|\vec{J}_{\mathrm{M}}|}{|\vec{H}|}\right) \equiv -\mathrm{j}\omega\mu_0\mu\vec{H}. \quad (6)$$

This hypothetical current is the origin of any transformation of permeability μ in our numerical code. Directions of all preceding currents are designed for our media with adequate characteristics; the cloaking solution on cylindrical cloak has anisotropic permeability which is in radial (r) and azimuthal (θ) directions from the cylindrical coordinate. Our model for the FDTD method is discrete in the Cartesian coordinate, and vector transformation on currents back to the Cartesian characteristics is obtained by following transformation:

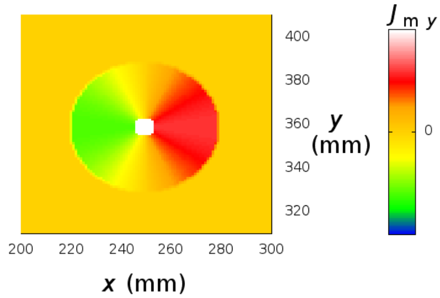
$$\vec{J}_{\mathrm{M}x} = \cos(\theta)\vec{J}_{\mathrm{M}r} - \sin(\theta)\vec{J}_{\mathrm{M}\theta}, \quad (7)$$

$$\vec{J}_{\mathrm{M}y} = \sin(\theta)\vec{J}_{\mathrm{M}r} + \cos(\theta)\vec{J}_{\mathrm{M}\theta}. \quad (8)$$

$\vec{J}_{\mathrm{M}r}$ is the magnetic radial current, $\vec{J}_{\mathrm{M}\theta}$ is the magnetic azimuthal current used in the cylindrical coordinate for radial and azimuthal anisotropic permeability; $\vec{J}_{\mathrm{M}x}$ and $\vec{J}_{\mathrm{M}y}$ are magnetic currents on the Cartesian coordinate.



(a)



(b)

Fig. 1: Current densities distribution in space (a) $\vec{J}_{Mx}$ and (b) $\vec{J}_{My}$. White area in center is for object which becomes invisible

We have degrees of freedom on permeability parameters from Eqs. (6-8). Figure 1 shows an anisotropic current of J_{Mx} and J_{My} derived from anisotropic cylindrical parameter used for the cloaking device shown in Fig. 2.

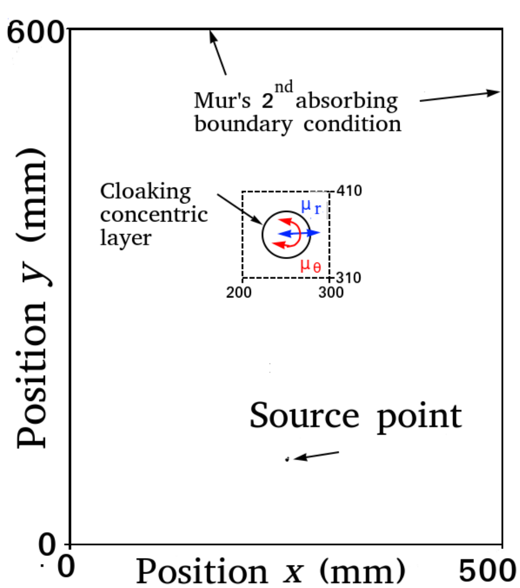


Fig. 2: Scheme of two dimensional plane implemented in the FDTD code

b) Model for finite-difference time-domain (FDTD) space

Electromagnetic-wave propagation which we solve by the numerical code is based on FDTD method. Our cloaking device has the outer boundary with 30-mm radius. Outside this region, a dielectric layer with permittivity 2.0 is located with 5-mm thickness, and this dielectric will confine in our experiment the plasma as a vacuum chamber. In the center, we place perfect conductor of 4-mm radius, and our aim is to manage to cloak this conductor. From the conductor region to the inner boundary of the dielectric layer, the metamaterial is assumed to be on the dielectric plates, and spatially-averaged permittivity of these plates is 2.0. Plasma is assumed to exist between the plates, and ϵ decreases spatially towards the center from 2.0. We develop a code on the two-dimensional space with the size of 500×600 mm^2 on x and y axis, respectively. Electromagnetic fields in the FDTD code are calculated in every 0.5-mm square grid. The FDTD code simulates current flows from Eqs. (4-6) as well as the fields in the Maxwell equations. Calculation of the propagation is made at every 0.5 ps on the purpose of propagation stability (the so-called Courant condition [12]). On the border of the two-dimensional space [10], we apply the second Mur's boundary [12], as shown in Fig. 2, which realizes almost perfect absorption. The source of the electromagnetic wave is a point one, at microwave frequency of 6 GHz, placed at $x = 250$ mm and $y = 100$ mm. We selected the TM mode, where **E** is normal to the two dimensional plane and **H** is parallel to the plane.

The device under test is composed of plasma and metamaterial to achieve invisibility of the perfect conductor located at x = 250 mm and y = 360 mm. Effects of $\vec{J}_{\mathrm{E}}$ and $\vec{J}_{\mathrm{M}}$ work with wave propagation expressed in the Maxwell's equation; $\vec{J}_{\mathrm{E}}$ is supported by n_{e} in the form of Bessel function in radial direction, which enables plasma to provide smooth gradient permittivity due to n_{e} profile in the ampibolar diffusion regime, shown as Fig. 3. We regulated μ in the radial (μ_{r}) and azimuthal (μ_θ) directions as shown in Fig. 1. Using Eqs. (7, 8), in fact, future experiments will be successfully performed by DSRRs as the metamaterial on a cylindrical shape where μ can reach any positive and negative values.

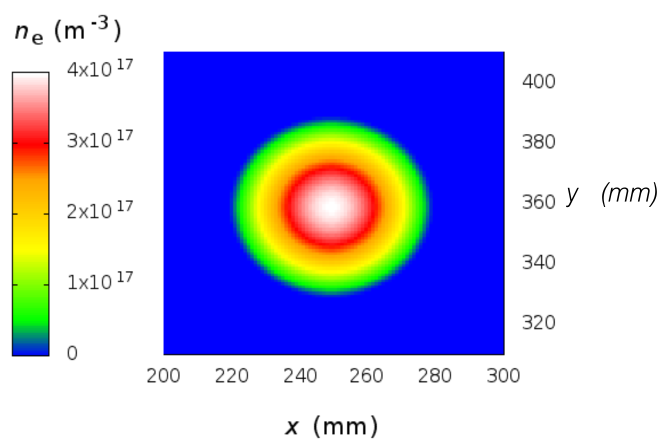


Fig. 3: Electron density distribution of plasma assumed in FDTD code

III. Numerical Results

Validation of the numerical code is shown in Fig. 5(a), which is a benchmark as waves in free-space propagation. Here, we see power propagation as $|\mathbf{E}|^2$ at fixed time. No scattering wave exists, and decremental power is a consequence of spacial profile of power spread as a function of r radius from the point source. In the case of anisotropic solution close to good cloaking in Fig. 5(b), we use parameter profiles shown in

Fig. 4. The two-dimensional plane including the magnetic field has anisotropic permeability $\mu_r = 0.27$ and $\mu_\theta = 1$. In addition to ϵ gradient of plasma, we add an effect of the dielectric from the metamaterial dielectric plates supporting metamaterial structure and boundary of the device. Thanks to anisotropy and gradient in Fig. 4, we observed cloaking in wave propagation in Fig. 5(b). In comparison with the result of free space propagation in Fig. 5(a), spacial profiles of wave power and phase behind the device is quite similar. This result indicates that suitable setting of parameters of μ and ϵ achieves cloaking phenomena.

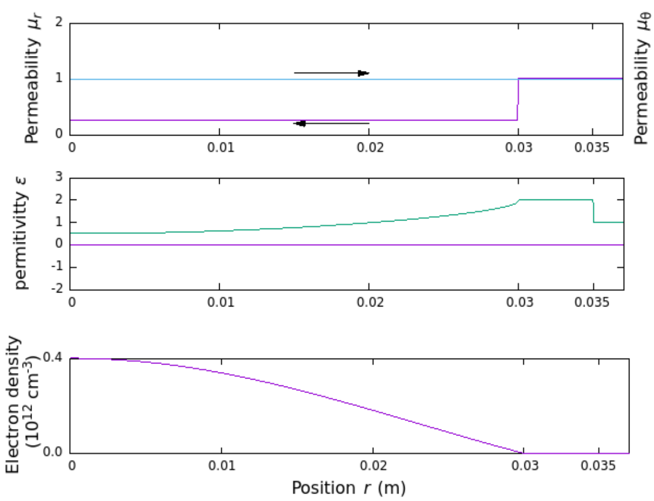
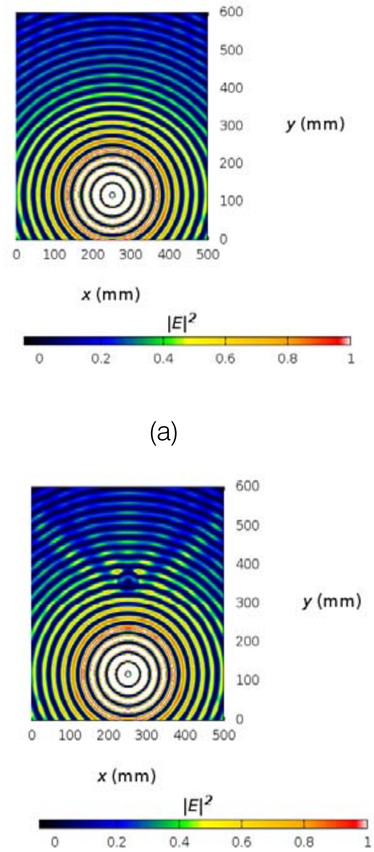


Fig. 4: Parameter distributions along *r* used in FDTD calculation

Imperfect point, observed in residue of scattering waves in Fig. 5(b), is due to the slight mismatch between theoretical prediction from transformation optics and possible parameters which is assumed in our numerical model. We apply the n_e profile similar to experimental observation but slightly different from the ideal case predicted by transformation optics. For reference of Fig. 5, we performed numerical calculation with comparable parameters equal to the values found in optimal parameters for cloaking except one of them, and the results are displayed in Fig. 6.

When we input isotropic permeability, the wave with fairly low power can pass through the device, and its large part is reflected or swerves into abnormal direction as shown in Figs. 6(a-d), which indicates that it induces consequent scattering wave. In case of the anisotropic characteristic in Fig. 6(e), the wave can propagate behind the antenna. However this anisotropic characteristic leads to a different one which is far from cloaking, and the anisotropic matrices are not reversible. These numerical results confirm the impact of anisotropic properties for media of electromagnetic waves. They show the validity of the FDTD method with addition of electric- and (hypothetical) magnetic-current densities to solve Maxwell's equations for any medium.



(a)

(b)

Fig. 5: Wave power, square of electric field in case (a) with free pace propagation and (b) case with solution for cloaking

IV. Conclusion

The numerical results shown in this report confirm that anisotropy opens possibilities for electromagnetic wave control, and they can be predicted using the FDTD method. Our numerical results are representations of the effects of anisotropic permeability as well as cloaking layers which can be realized in experiments using layers of magnetic metamaterials and plasma. Installation of hypothetical magnetic currents is a good imitation of anisotropic permeability which is realized in metamaterial experiments. Putting on light a new solution for electromagnetic wave, this report enlarges the possibility of media who could be designed by numerical methods.

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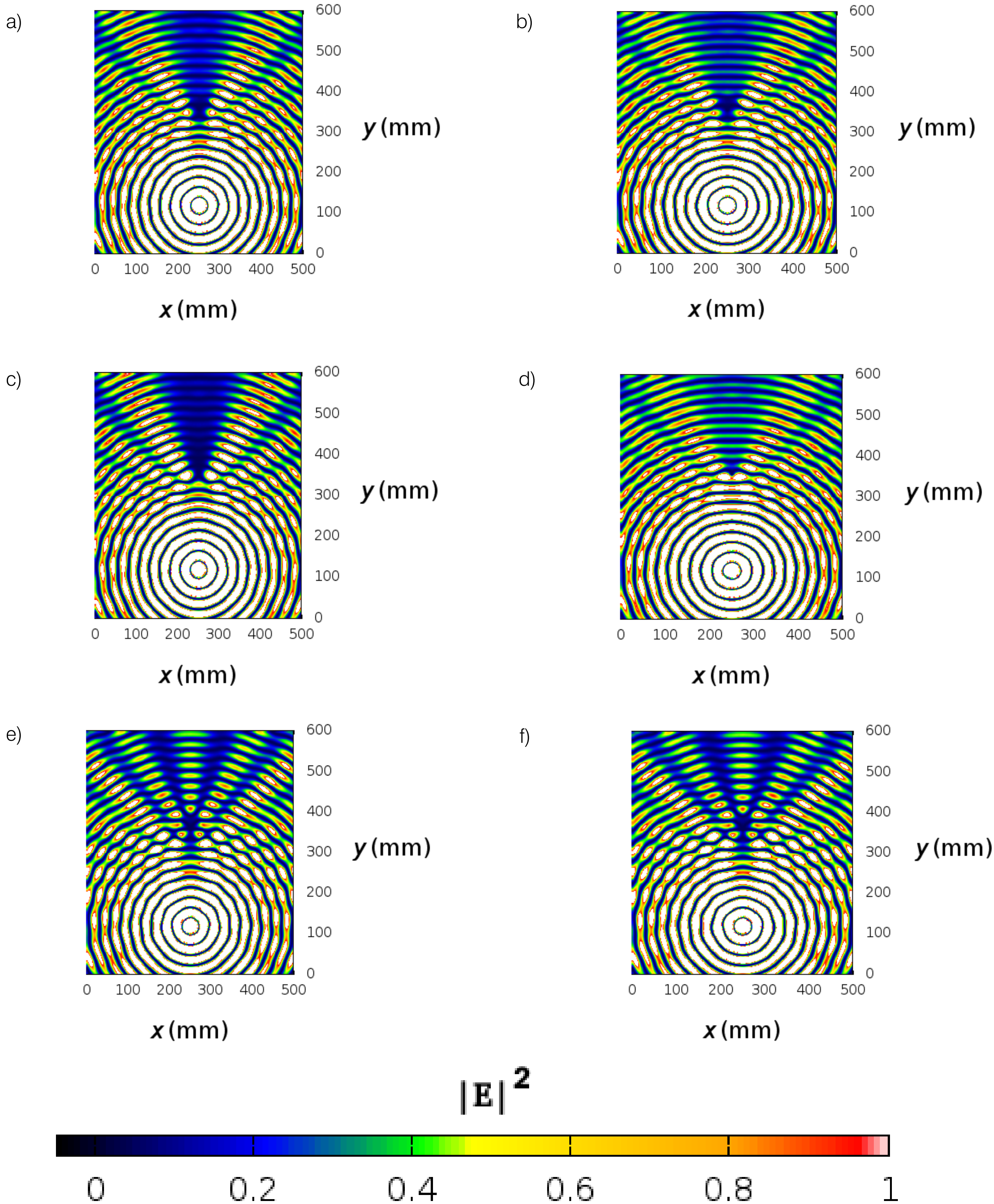

Fig. 6: Power propagation in FDTD at fixed time. In (a, c, e) plasma gradient is include and (b, d, f) only the metamaterial is keep for the result, (a & b) $\mu_r = \mu_\theta = 0.268$; (c & d) $\mu_r = \mu_\theta = 1$; (e & f) $\mu_r = 1$ and $\mu_\theta = 0.268$

References Références Referencias

1. S. A. Cummer, B. I. Popa, D. shuring, D. R. Smith, and J. Pendry. Full-wave simulations of electromagnetic cloaking structures. *Phys. Review E*, 74:036621, 2006.
2. A. Iwai, Y. Nakamura, A. Bambina, and O. Sakai. Experimental observation and model analysis of second-harmonic generation in a plasma-metamaterial composite. *Appl. Phys. Express*, 8, 2015.
3. J. Yi, A. de Lustrac, and S. N. Burokur. Metamaterial lens for beam steering. *2016 10th European Conference on Antennas and Propagation (EuCAP)*, June 2016. DOI: 10.1109/EuCAP.2016.7481899.
4. L. Solymar and E. Shamonina. *Waves in Metamaterials*. Oxford university press, Oxford, 2014.
5. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart. Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on microwaves theory and techniques*, 47:2075–2084, 1999.
6. D. Schurig and J. J. Mock and B. J. Justice and S. A. Cummer and J. B. Pendry and A. F. Starr and D. R. Smith. Metamaterial electromagnetic cloak at microwave frequencies. *Science*, 314:977–980, 2006.
7. M. Yan, Z. Ruan, and M. Qiu. Cylindrical invisibility cloak with simplified material parameters is inherently visible. *Phys. Review Lett.*, 99:233901, 2007.
8. W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev. Non-magnetic cloak with minimized scattering. *Appl. Physics Lett.*, 91:111105, 2007.
9. W. Yan, M. Yan, and M. Qiu. Non-magnetic simplified cylindrical cloak with suppressed zero*th*. *Appl. Phys. Lett.*, 93:021909, 2008.
10. M. A. Lieberman and A. J. Lichtenberg. *Principles of plasma discharges and materials processing*. WILEY, New Jersey, 2005.
11. O. Sakai, S. Yamaguchi, A. Bambina, A. Iwai, Y. Nakamura, Y. Tamayama, and S. Miyagi. Plasma metamaterials as cloaking and nonlinear media. *Plasma Phys. Control. Fusion*, 59:014042, 2017.
12. S. D. Gedney. *Introduction to the Finite-Difference Time-Domain (FDTD) Method for Electromagnetic*. Morgan & Claypool, USA, 2011.
13. A. Bambina, A. Iwai, S. Miyagi, and O. Sakai. Microwave propagation in plasma layer surrounding metallic monopole antenna. *2016 10th European Conference on Antennas and Propagation (EuCAP)*, June 2016. DOI: 10.1109/EuCAP.2016.7481510.
14. O. Sakai and S. Yamaguchi and A. Bambina and A. Iwai and Y. Nakamura, Y Tamayama and S Miyagi. Plasma metamaterials as cloaking and nonlinear media. *Plasma Phys. Control. Fusion*, 59:014042, 2016.
15. A. Petrin. *Wave Propagation*. InTech, Rijeka, 2011.