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Magnetized Plasma as a Versatile Platform for Switching

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Abstract—We study the magneto-permittivity effect in a magnetized plasma with appropriately designed parameters. We show that at frequencies near the plasma frequency, magneto-optical activity plays an important role to manipulate and control the wave propagations in the magnetized plasma. Such a unique feature can be utilized to establish sensitive magnetic field switching mechanism, which is confirmed by detailed numerical investigations. Switching by magnetic field based on magnetized plasma is flexible and compatible with other optical system; moreover it is applicable to any frequency by tuning the plasma density. For these reasons, our work shows the possibility for developing a new family of high frequency and ultrasensitive switching applications.

1. INTRODUCTION

Magnetic control has been one of the key drivers of basic science and of a whole wealth of technologies. Developments in this area follow closely scientific discovery and provide in turn tools for practical applications including material science, optical telecommunications, security control and laser applications [1–6]. Various technologies have been developed to achieve this task, among these, Hall devices and nonreciprocal devices [7–10] have attracted the most attention to date. Similar to the Hall effect based devices, there is another fascinating way to control the light propagation called giant magneto-resistance (GMR) or giant magneto-impedance (GMI) effect [11, 12], in which magnetic materials suffering a significant change of electrical resistance (or impedance) when subjected to an external magnetic field. The impedance change in GMI effect can be described using Maxwell equation for specific boundary conditions and is controlled by the changes of the material's permeability [13]. A traditional approach to design nonreciprocal devices is based on magneto-optical effect [14, 15] in which electromagnetic and optical waves through a medium may be manipulated and controlled by the presence of a quasi-static magnetic field. Magneto-optical mediums with a wide range of magneto-active responses have been utilized for achieving this task. It should be emphasized that magneto-optical effect usually involves changing the permittivity tensor of the medium, in sharp contrast to conventional scalar materials. Nevertheless, in conventional magneto-optical medium, this permittivity change is very weak and is insensitive to external magnetic field [14].

In recent years, in the case of naturally available magneto-optical materials, the concept of epsilon-near-zero materials design [16–20] combined with magneto-active response, has provided access to even a broader range of responses and give additional degrees of freedom for engineering novel nonreciprocal systems, such as optical isolation [21, 22] and one-way photonic surface plasmons [23–26]. These composites will provide an enhancement to change the balance between the parameter of magneto-optical activity and the dielectric parameters. Is it possible to establish a mechanism of permittivity change sensitive to magnetic field on use of these composites? Artificial metamaterials combined with epsilon-near-zero and magneto-active responses have been demonstrated recently in the form of metal-dielectric multilayers, and rectangular waveguide near its cut-off frequency [22]. However, these media

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require rather complicated and time-consuming microfabrication, and the epsilon-near-zero responses cannot be reproduced in real time.

In this paper, we propose to employ magnetized plasma to analyze this mechanism of sensitive permittivity change. We study propagation of the electromagnetic waves in this material and demonstrate that, in magnetized plasma, a conceptually new type of electromagnetic response emerges at frequencies near the plasma frequency, which can be classified as giant magneto-permittivity effect. Moreover, we design a magnetic field switch by utilizing the giant magneto-permittivity effect.

2. RESULTS AND DISCUSSION

We begin with the study of wave propagation in a magnetized plasma. For simplicity's sake and to highlight the main physical concepts, we assume that the magnetized plasma is collisionless, in the sense that the propagation frequencies greatly exceed collision frequencies. Consequently, the collision effect can be neglected and this magnetized plasma can be treated as a lossless medium. The electromagnetic properties of a lossless plasma are described by the Drude model

$$\varepsilon_p = 1 - \omega_p^2/\omega^2, \tag{1}$$

where $\omega_p = \sqrt{Ne^2/m\varepsilon_0}$ is the plasma frequency, N the electron concentration, and m the effective mass of electrons. In this case, plasma becomes anisotropic when an external magnetic field B is applied. Also, we assume that the magnetic field is in the z direction as it is shown in Figure 1. In this magnetized plasma, electrons circle around the direction of the magnetic field at the cyclotron frequency, given as $\omega_c = eB/m$. As a result, the dielectric response of magnetized plasma can be described by a Hermitian anti-symmetric relative permittivity tensor [27]

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon & -i\varepsilon_g & 0 \\ i\varepsilon_g & \varepsilon & 0 \\ 0 & 0 & \varepsilon_p \end{pmatrix}, \tag{2}$$

in which the constitutive parameters are given by

$$\varepsilon = \varepsilon_0 \left(1 + \frac{\omega_p^2}{\omega_c^2 - \omega^2}\right), \quad \varepsilon_g = \varepsilon_0 \frac{\omega_p^2 \omega_c}{\omega\left(\omega_c^2 - \omega^2\right)}, \quad \text{and} \quad \varepsilon_p = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2}\right).$$

ε_g is the off-diagonal component of the permittivity tensor. In the presence of an infinitely large magnetic field, ε_g disappears and permittivity tensor can be simplified as

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 - \omega_p^2/\omega^2 \end{pmatrix}. \tag{3}$$

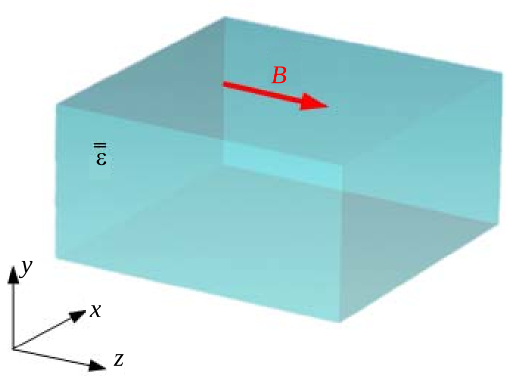

Figure 1. (Color online) Schematic of the bulk magnetized plasma. The red arrow represents the external magnetic field. The wave propagation is in the direction perpendicular to the magnetization direction.

According to Eq. (3), we find that the magnetized plasma under an infinitely strong magnetic field exhibits the same electromagnetic properties as a uniaxial anisotropic medium. It should be emphasized that no matter what frequency is, the essence of an infinitely strong magnetic field is to create an isotropic medium for wave propagation in the (x-y) plane. Thus, if the wave propagates from air to this plasma, total transmission can be obtained. Turning on and off the infinitely strong magnetic field is a way to achieve switching for wave propagation. However, such strong magnetic field switching is difficult to realize and is also a waste of energy. We ask whether the plasma has similar isotropy, but for ultra-weak magnetic field at specific condition. Here we are interested only in the case where the electromagnetic frequency is near the plasma frequency. In the following, we will explore the potential of magnetized plasma as a platform for sensitive switching. We consider that the wave propagation is in a direction perpendicular to the magnetization direction, thus the dispersion relation of magnetized plasma [28] can be simplified as

$$n^2 = \frac{\varepsilon^2 - \varepsilon_g^2}{\varepsilon}, \tag{4}$$

where n is the refractive index and can be described as

$$k_x^2 + k_y^2 = \left(\frac{2\pi}{\lambda}\right)^2 \frac{\varepsilon^2 - \varepsilon_g^2}{\varepsilon}. \tag{5}$$

According to the dispersion relation described in Eq. (5), we find that the wave propagation in the (x-y) plane is isotropic regardless of the anisotropic nature of the magnetized plasma. The effective permittivity can be deduced as

$$\varepsilon_{eff} = \frac{\varepsilon^2 - \varepsilon_g^2}{\varepsilon}. \tag{6}$$

It should be noted that when the electromagnetic frequency is far away from the plasma frequency, ε and ε_g will be almost invariable under a weak external magnetic field, and the plasma properties depend on the sign of the ε only, as expected. Only large magnetic field might significant change the ε and ε_g. When the electromagnetic frequency is near the plasma frequency, ε disappears and ε_g is expected to act the leading role under ultra-weak magnetic fields. From Eq. (6), we find that an emergence of a sharp electromagnetic response occurs during magnetization process.

We assume a realistic magnetized plasma system in which the plasma density is $1 \times 10^8\,\mathrm{cm}^{-3}$ (corresponding to $\omega_p = 5.64 \times 10^8\,\mathrm{rad/s}$) under an applied external magnetic field. Three cases are concerned: $\varepsilon = 0.001$, $\varepsilon = -0.005$, and $\varepsilon = -0.01$, for nonmagnetized plasma, which are correspond to three different frequencies: $\omega = 0.9995\omega_p$, $\omega = 0.9975\omega_p$, and $\omega = 0.9950\omega_p$, respectively. The variations of ε and ε_g versus the external magnetic fields are shown in Figure 2. It can be seen that the

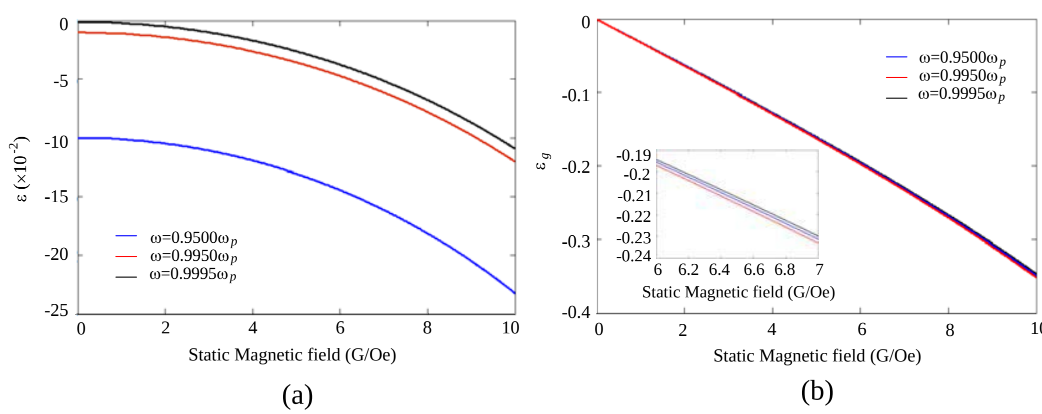

Figure 2. (Color online) ε and ε_g of magnetized plasma versus magnetic field at $\omega = 0.9995\omega_p$, $\omega = 0.9975\omega_p$, and $\omega = 0.9950\omega_p$. The variation of ε_g is greater than ε during the magnetization process which indicates that at frequencies near the plasma frequency, ε_g will play the dominant role to determine the electromagnetic properties of the magnetized plasma.

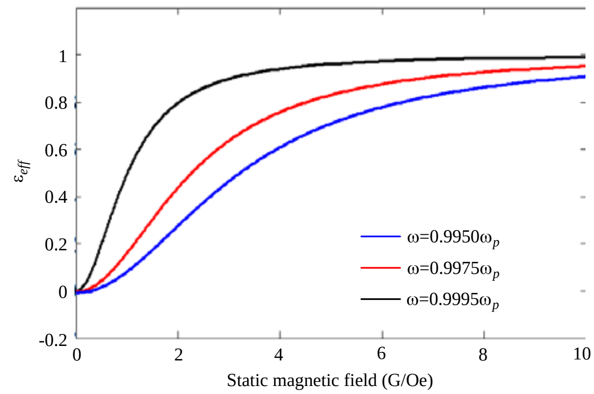

Figure 3. (Color online) Magneto-permittivity of the magnetized plasma at $\omega = 0.9995\omega_p$, $\omega = 0.9975\omega_p$, and $\omega = 0.9950\omega_p$. The effective permittivity increases during the magnetization process and becomes practically constant when the magnetization is saturated.

variation of ε_g is greater than ε during the magnetization process which indicates that at frequencies near the plasma frequency, magneto-optical activity ε_g will play the dominant role to determine the electromagnetic properties of the magnetized plasma. Figure 3 shows the effective permittivity versus the external magnetic fields, which can be classified as magneto-permittivity curves. The effective permittivities increase during the magnetization process and become practically constant ($\varepsilon_{eff} = 1$) when the magnetization is saturated. The saturation field can be considered as the field needs to be overcome and to saturate the magnetization during the electric polarization. The most dramatic result exhibited in Figure 3 is the tremendous value of the magneto-permittivity. For $\omega = 0.9995\omega_p$, there is almost a factor of 1000 between the permittivity at zero field and in the saturated state, respectively (in absolute value, the permittivity change is about 1). By drawing a comparison among these results for three different frequencies in Figure 3, it indicates that the saturation field is closely related to the electromagnetic frequency. That is to say, for frequency much closer to the plasma frequency, only a weaker saturation field is needed.

To summarize the computed results, we emphasize that giant magneto-permittivity effects are obtained in the magnetized plasma at frequencies near the plasma frequency. It should be noted that, due to the symmetry of the Maxwell equations, this giant magneto-permittivity effect predicted here can be easily extended to giant magneto-permeability via duality to the materials with the permeability tensor [29]. We proposed that this giant magneto-permittivity effect can be utilized to achieve switch function with ultra-weak magnetic field. To investigate the strength of the magnetized plasma in switching, we carried out analysis on wave propagation. The configuration is shown in Figure 4(a). Consider a plane wave incident normally on the interface of air and magnetized plasma. In the absence of magnetization, as we defined previously, $\varepsilon_{eff} = \varepsilon \to 0$, which indicates that this magnetized plasma can be considered as an epsilon-near-zero medium. As a result, total reflection occurs at the interface. Under the action of saturation magnetic field ($\approx 10\,\mathrm{G}$), $\varepsilon_{eff} \to 1$, this magnetized plasma can be treated as air, which means the waves could be totally transmitted through magnetized plasma without any difficulty. To be more intuitive, we also perform the numerical simulations of the lossless magnetized plasma at $0.9 \times 10^8\,\mathrm{Hz}$ with the use of Finite Element Method (COMSOL Multiphysics) as shown in Figures 4(b) and (c). Periodic boundary conditions are set on the upper and lower boundaries. For nonmagnetized plasma, the electromagnetic wave is totally reflected (Figure 4(b)), while for magnetized plasma with saturation magnetic field ($\approx 10\,\mathrm{G}$), the electromagnetic wave is totally transmitted through the magnetized plasma (Figure 4(c)). Therefore, the mechanism of weak magnetic field switching is established which can be utilized in optical circuit.

Also, we briefly discuss giant magneto-permittivity in loss case. The plasma frequency is kept the same as before ($\omega_p = 5.64 \times 10^8\,\mathrm{rad/s}$), whereas collision frequency reaches $\gamma = 3 \times 10^7\,\mathrm{sec}^{-1}$ (as indicated in Ref. [30]). Figure 5 illustrates the magneto-permittivity curves for magnetized plasma with loss at $\omega = 0.9950\omega_p$. From the curves, we find that the effective permittivity no longer varies monotonically during the magnetization process in contrast to the lossless case. Moreover, both real

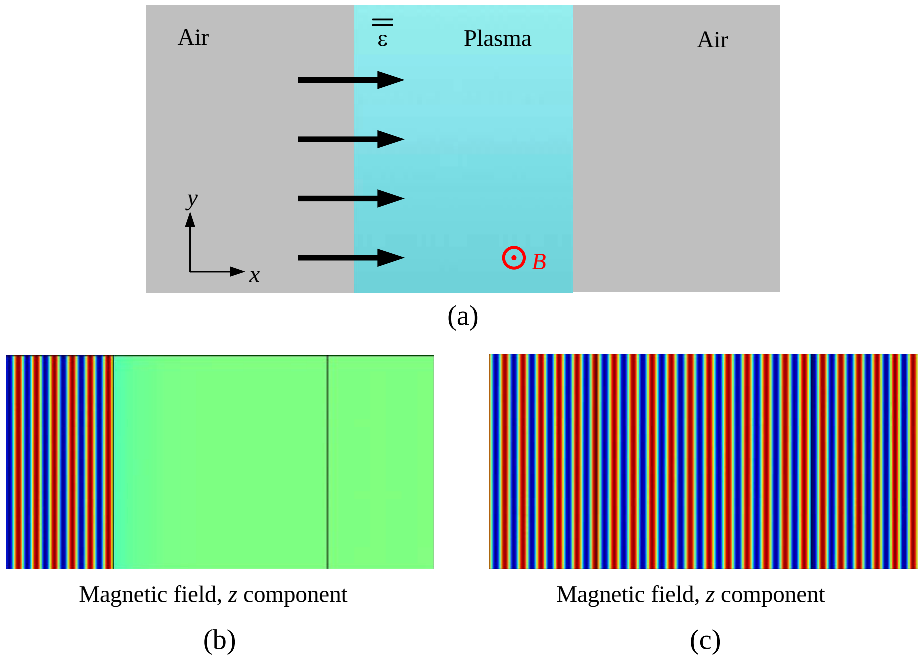

Figure 4. (Color online) (a) Schematic of a magnetic field switching system based on magnetized plasma. Electromagnetic wave (dark arrows) is normal incident from air to the magnetized plasma. (b)–(c) Numerical simulations of the lossless magnetized plasma at 0.9×10^8 Hz (b) for nonmagnetized plasma and (c) for magnetized plasma with saturation magnetic field (≈ 10 G).

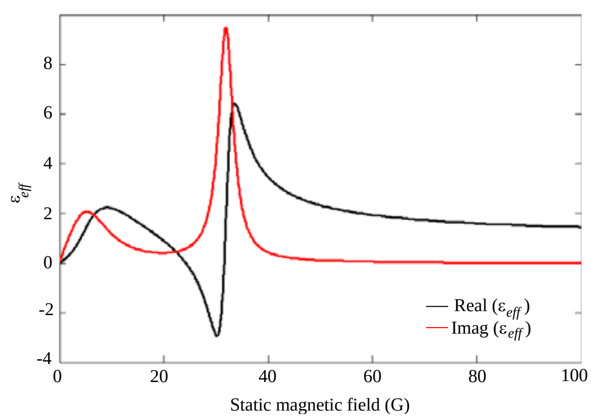

Figure 5. (Color online) Magneto-permittivity for loss magnetized plasma at $\omega = 0.9950\omega_p$. The effective permittivity no longer varies monotonically during the magnetization process.

part and imaginary part have the same variation trend. Loss will strongly restrict the transmission of wave propagation, thus, the mechanism of sensitive switching is invalid in this situation.

3. CONCLUSION

In conclusion, we have theoretically proposed a novel sensitive switching mechanism based on magnetized plasma. In lossless magnetized plasma, giant magneto-permittivity response emerges when the frequency approaches to the plasma frequency. Numerical simulations were performed validating this methodology for the magnetic field switching. We also show that in the loss case, this sensitive switching will be invalid. Particularly, in the system we have studied, the external magnetic fields are obviously very weak while the magneto-permittivity is large, and this enhances the function of ultra-weak magnetic field switching.

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