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Analog of giant magnetoimpedance in magnetized ϵ -near-zero plasma

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In this Letter we show that magnetized plasma with proper designed parameters at the plasma frequency suffers large magnetoimpedance change under a moderate external magnetic field. Such an interesting feature can be described as the analog of giant magnetoimpedance (GMI), which is confirmed by detailed calculation. GMI devices based on magnetized ϵ -near-zero plasma do not require microfabrication and they are capable of working at tunable frequency, even in terahertz frequency range; more importantly, they can be dynamically controlled by the environmental parameters such as temperature and pressure.

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The ability for the magnetic compounds to attain large magneto-response remains significant, yet fundamental property for the realization of various sensors and memory devices. One of the large magneto-response phenomena is the giant magnetoimpedance (GMI) [1, 2] which occurs in soft magnetic materials, such as fibers, wires, ribbons and films. For this GMI effect [3], the electrical impedance change is controlled by the changes of the soft ferromagnetic material's permeability with the application of a moderate magnetic field. Generally, the operation frequency range of the GMI effect can be realized by regulating the geometry and patterns of the materials accordingly. Most GMI devices with high sensitivity work at gigahertz or megahertz, because in this frequency range the skin effect and ferromagnetic resonance command the magnetoimpedance effect. Moreover, in order to reduce the size of GMI devices [4-8], electrical circuits need to be optimized by integrating amorphous and nanocrystalline materials in the form of films, wires or ribbons on electronic circuit boards. This also introduces additional design and fabrication complexities to the devices.

The fundamental purpose of this Letter is to introducing another platform of GMI effect, so that the operation frequency is able to extend into terahertz. In this mechanism, ϵ -near-zero (ENZ) materials [9-26] — continuous or artificial materials in which one or more of the constitutive parameters are near-zero — could be incorporated into the GMI. By combining the properties of ENZ with magnetoactive responses, we report an analog of GMI effect which is capable of working at tunable frequency, even in terahertz frequency range. To have a deeper understanding about the mechanism, the electromagnetic wave propagation in a homogeneous photonic material: a cold magnetized plasma under static bias magnetic field, described by an effective permittivity tensor at the plasma frequency is analyzed. As already known, the cold magnetized plasma can be utilized to achieve subdiffraction imaging [27] and magnetic field induced transparency [28]. We find that magnetoimpedance is highly dependent on the off-diagonal component of the permittivity tensor [24, 25] in proximity to ENZ region. Moreover, this analog of GMI holds the significant advantage of reconfigurable response in real time which can be controlled by the environmental parameters such as temperature and pressure. We also affirm that the proposed mechanism is general and could be applied to gyromagnetic materials such as graphene [29], yttrium-iron-garnet (YIG) [30] and bismuth iron garnet (BIG) [31] which have a general form of Hermitian relative permittivity tensor similar to magnetized plasma.

We start with a general physical picture to explain the wave propagation in a cold magnetized plasma, as shown in schematically in Figure 1a. The optical response of the cold magnetized plasma is considered local, as long as the mean spacing of the charged particles in the plasma is far less than the wavelength of the interest. In a magnetized plasma, electrons circle around the direction of the magnetic field at the cyclotron frequency, given as $\omega_c = eB/m$, where e is the elementary charge, B is the magnetic flux density and m is the effective mass of

electrons. The local dielectric response of the magnetized plasma taking into account the collision frequency γ can be described by a Hermitian anti-symmetric relative permittivity tensor [32]

$$\bar{\epsilon} = \begin{pmatrix} \epsilon_1 & -i\epsilon_g & 0 \\ i\epsilon_g & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_p \end{pmatrix}, \quad (1)$$

where $\epsilon_1 = 1 - \frac{\omega\omega_p^2 + i\omega_p^2\gamma}{\omega^3 - \omega\gamma^2 - \omega\omega_c + i2\omega^2\gamma}$ and $\epsilon_p = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$ are the diagonal components of relative dielectric permittivity, $\epsilon_g = \frac{\omega_c\omega_p^2}{\omega^3 - \omega\gamma^2 - \omega\omega_c + i2\omega^2\gamma}$ is the off-diagonal component of the permittivity tensor responsible for the “strength” of magneto-optical activity of the media, $\omega_p = \sqrt{Ne^2/m\epsilon_0}$ is the plasma frequency, ϵ_0 is the permittivity of the free space, and N is the electron concentration.

Fig. 1. (a) The schematic configuration of the magnetized plasma for the electromagnetic wave with frequency at the plasma frequency. The magnetic field is along the z -direction. The propagation vector of a plane wave lies in the xy plane. (b) Two critical parameters: ϵ_p and ϵ_1 , versus electromagnetic frequency without magnetization. (c) Two critical parameters: ϵ_L and ϵ_R , versus the magnetic field at the plasma frequency. The solid and dashed lines respectively represent the real and imaginary parts of the critical parameters.

Due to the weak magnetic field that is often applied to the wide range of magnetic sensors and non-volatile memories, the influence of the external magnetic field on the impedance of the magnetized plasma is studied. In order to fully discern the electromagnetic properties of the magnetized plasma, the dispersion relation of the system depicted in Figure 1a is needed. The dispersion relation is deduced as

$$\tan^2 \theta = [\epsilon_p(n^2 - \epsilon_L)(n^2 - \epsilon_R)] / [(n^2 - \epsilon_p)(\epsilon_L\epsilon_R - n^2\epsilon_1)], \quad (2)$$

where the wave is considered to be propagating at an angle θ , to the ambient magnetic field. From equation (2), n is the refractive index, $\epsilon_L = \epsilon_1 - \epsilon_g$, and $\epsilon_R = \epsilon_1 + \epsilon_g$. The electromagnetic properties of the magnetized plasma can be flexibly designed by choosing the relative values of ω , ω_p , and ω_c . The magnetized plasma system in which the plasma frequency is at terahertz is chosen, which is $\omega_p = 2\pi \times 10^{12}$ rad/s, and with a relatively low collision frequency $\gamma = 3 \times 10^8$ Hz (one order of the magnitude larger than that in Ref.[33]).

For the sake of discussion, the plasma frequency response along the two major magnetization directions is chosen, i.e. parallel to the magnetization direction ($\theta = 0^\circ$), and perpendicular to the magnetization direction ($\theta = 90^\circ$). For the parallel magnetization, i.e. the Faraday configuration, the nature of the wave could be described by the following equations

$$\begin{aligned} (\epsilon_1 - n^2)E_x - i\epsilon_g E_y &= 0 \\ i\epsilon_g E_x + (\epsilon_1 - n^2)E_y &= 0. \\ \epsilon_p E_z &= 0 \end{aligned} \quad (3)$$

At plasma frequency, it is worth to mention that, without magnetization, ϵ_p is close but not equal to zero for a realistic magnetized plasma system, which is shown in Figure 1b. From

equation (3), since $\epsilon_p \neq 0$, then $E_z = 0$. In other words, propagation mode must be transverse electric. The ratio of E_x and E_y is obtained as $E_x/E_y = (n^2 - \epsilon_1)/i\epsilon_g = i\epsilon_g/(n^2 - \epsilon_1)$, and the dispersion relation (3) decomposes into two separate equations, $n^2 = \epsilon_L$ and $n^2 = \epsilon_R$ for the left-handed (LH) and right-handed (RH) circularly polarized waves respectively. In spite of the anisotropic nature of the permittivity tensor, the wave propagations can still be defined by the effective permittivities $\epsilon_{\text{eff}} = \epsilon_L$ and $\epsilon_{\text{eff}} = \epsilon_R$. The LH and RH circularly polarized wave propagations in the magnetized plasma now depend on the value of ϵ_{eff} , which is similar to conventional materials with the scalar dielectric response. Without magnetization, $\epsilon_g = 0$, and $\epsilon_{\text{eff}} = \epsilon_1$, the effective material property depends on the value of ϵ_1 only, and the magnetized plasma can be classified as a usual isotropic material. With the presence of magnetization, ϵ_g becomes nonzero and crucial to the effective material property of the magnetized plasma. Coincidentally, at plasma frequency, ϵ_1 approaches zero, and the system resembles non-magnetized case above. These phenomena are respectively illustrated in Figures 1b and 1c.

Fig. 2. (a) Analog of GMI curves [i.e., $\Delta Z/Z$ (%)] of a cold magnetized plasma for LH and RH circularly polarized wave propagations at the plasma frequency. (b,c) Analog of GMI curves of two other cases having different frequencies, (b) $\omega = 0.99995\omega_p$ and (c) $\omega = 1.00005\omega_p$. The blue (red) curve denotes the analog of GMI measurements made while increasing (decreasing) magnetic field. (d) Analog of GMI curves [i.e., $\Delta Z/Z$ (%)] of a cold magnetized plasma for extraordinary wave propagations at the plasma frequency. (e) Analog of GMI curves of two other cases having different frequencies, $\omega = (1 \pm 0.00005)\omega_p$.

Fig. 3. Analog of GMI curves [i.e., $\Delta Z/Z$ (%)] of a cold magnetized plasma versus plasma frequency $\omega_p(T, P)$ under different strengths/directions of the magnetic field: (a) $H=0\text{Oe}$; (b) $H=3\text{kOe}$; (c) $H=-3\text{kOe}$. The $\omega_p(T_o, P_o)$ represents plasma frequency at an initial state with a given temperature (T_o) and pressure (P_o).

Figure 2a shows the magnetoimpedance curves obtained in a magnetized plasma for the electromagnetic wave with frequency at the plasma frequency. The impedance of the magnetized plasma is expressed as $Z = \sqrt{1/\epsilon_{\text{eff}}}$ due to nonmagnetic magnetized plasma. The magnetoimpedance response [7] for the plasma is calculated as the ratio of the change in the impedance due to the external magnetic field (H), which is expressed as $\Delta Z/Z$ (%) = $[Z(H) - 1] \times 100\%$ since the impedance of plasma under saturated magnetic field approaches to unity. For convenient comparison, we replace the magnetic flux density

B by the magnetic field strength H , since the value of B measured in teslas in SI units is equal to the value of H measured in oersteds (Oe) in Gaussian-cgs units. Thus, the analog of GMI response $\Delta Z/Z$ (%) of 14372% can be observed at the plasma frequency. In this case, the field sensitivity to the magnetic field [i.e., $\xi = 2(\Delta Z/Z)_{\max}/\Delta H$, where ΔH is equal to the full width at half maximum of GMI curve] is found to be 220%/Oe. For comparison, the magnetoimpedance curves of two other cases having different frequencies, $\omega = 0.99995\omega_p$ and $\omega = 1.00005\omega_p$, are also shown in Figures 2b and 2c. An optical equivalent of spin valve [34], whose impedance (or GMI) depends on the spin state of photons (LH or RH circularly polarized waves) passing through a magnetized plasma is demonstrated.

When the propagation direction is perpendicular to the magnetization direction, i.e. the Voigt configuration, the nature of the wave could be described by the following equations

$$\begin{aligned} \varepsilon_1 E_x - i\varepsilon_g E_y &= 0 \\ i\varepsilon_g E_x + (\varepsilon_1 - n^2)E_y &= 0, \\ (\varepsilon_p - n^2)E_z &= 0 \end{aligned} \quad (4)$$

For the ordinary mode, $(\varepsilon_p - n^2)E_z = 0$ requiring $E_z \neq 0$ for a non-trivial solution. The wave field E_z is parallel to the magnetic field so that electron motions are unimpeded by the magnetic Lorentz force. This dispersion relation is thus the same as for an unmagnetized plasma. For the extraordinary wave, the ratio of E_x and E_y is obtained as $E_x/E_y = i\varepsilon_g/\varepsilon_1 = (n^2 - \varepsilon_1)/i\varepsilon_g$, and the dispersion relation becomes $n^2 = \varepsilon_L \varepsilon_R / \varepsilon_1$. Akin to the parallel case, the extraordinary wave propagation is isotropic and can be defined by the effective permittivity $\varepsilon_{\text{eff}} = \varepsilon_L \varepsilon_R / \varepsilon_1$. Similarly, when the electromagnetic frequency approaches the plasma frequency, the contribution of the off-diagonal component ε_g becomes increasingly important and further affects the impedance of the magnetized plasma. Figure 2d depicts the magnetoimpedance curve for the extraordinary wave with frequency at the plasma frequency. For comparison also, the magnetoimpedance curves with different frequencies, $\omega = 0.99995\omega_p$ and $\omega = 1.00005\omega_p$, are shown in Figure 2e. The magnetoimpedance curve has a single peak with the response $\Delta Z/Z$ (%) of 14372% at zero fields and this behavior changes to a symmetrical split double-peaked curve by drifting away from plasma frequency. Interestingly, the field sensitivity can reach as high as 450%/Oe compared with 110%/Oe for the previous case. Due to a split in the photonic density of states in the magnetized plasma, there is a net spin polarization, therefore, an equal number of spin states (LH and RH circularly polarized waves) will be generated that lead to a symmetrical double-peaked characteristic.

From the calculation results, it is proven that the proposed magnetized ENZ plasma can achieve an analog of GMI effect with high field sensitivity at terahertz frequencies. As mentioned earlier, the system can be reconfigured in real time by varying the plasma density as well as the strength or direction of the magnetic field. Generally, the density of plasma can be varied over a wide range by varying the pressure. Moreover, the temperature deviations are due to the changing effective mass, reducing plasma density and increasing electron-electron interactions. Since the temperature and pressure could influence the plasma frequency which can be expressed as $\omega_p(T, P)$, they can be utilized to control the analog of GMI as shown in Figure 3. Note that the operation and collision frequencies remain constants. Intuitively, without magnetization, the magnetoimpedance curves for circularly polarized and

extraordinary wave propagations coincide perfectly with each other. From Figure 3a, it is shown that any slight change of the plasma frequency caused by the temperature or pressure strongly reduces the value of the analog of GMI. This high sensitivity to the environmental parameters may pave the way for the possible development of thermal or pressure sensors. When the external magnetic field is applied, i.e., $H = \pm 3\text{kOe}$, the magnetoimpedance curves split for different polarized waves, as shown in Figures 3b and 3c. For extraordinary wave propagation, we could consider that an equal number of spin states is generated and resulted into a double-peak curve. We reveal that $\omega_p(T, P)$ at the two peaks are the same for circularly polarized and extraordinary wave propagations.

Since the system is reconfigurable in real time, it is possible to tune the plasma frequency and control the analog of GMI when the operating frequencies always satisfy the condition, $\omega = \omega_p$. In Figures 4a and 4b, the contour plots of the analog of GMI for circularly polarized and extraordinary wave propagations as a function of the magnetic field and plasma frequency are respectively shown. The collision frequency remains constant. From these two figures, we could find that analog of GMI can be continuously tuned by varying plasma frequency and magnetic field. Without magnetization, the field sensitivity increases when it is tuned to work at higher frequencies, as shown in Figure 4c. This better performance of the analog of GMI at higher frequencies can be attributed to the higher reflection properties possessed by magnetized plasma, which becomes “thicker” than the corresponding operating frequency.

Moving to a higher frequency is usually accompanied with increasing losses in the system. For the magnetized ENZ plasma, the loss effect which increases due to increase in electron collision probability at higher frequency is analyzed. For demonstration, the operating frequencies satisfy the condition, $\omega = \omega_p$ and the ratio between the plasma frequency and collision frequency are assumed to be constant, $\omega_p/\gamma = (2\pi \times 10^4)/3$. Figure 4d shows that, by reducing the collision frequencies from $4 \times 10^8\text{Hz}$ to $1 \times 10^8\text{Hz}$, the field sensitivity increases from 165%/Oe to 662%/Oe for circularly polarized and 368%/Oe to 1466%/Oe for extraordinary wave propagations. It is interesting to note that, by fixing the ratio of ω_p/γ , the peaks for different frequencies coincided at the same point. Remarkably, the ratio ω_p/γ is unconstrained, any change of ω_p or γ caused by the temperature and pressure affects the variation of the analog of GMI as shown in Figures 4a and 4b. Since the ratio ω_p/γ defines the operating point, it gives us the flexible freedom to select the appropriate ratio so that it coincided with the highly sensitive operation point by using real-life magnetized plasma in our system.

Generally, studies of transport properties of materials via magnetic field response are of broad importance in both science and applications. The capability to convert the magnetic field into impedance provides a route to design magnetic sensors, which is an essential part of magnetic storage disks and tape drives in modern computers [35]. However, the geometry and dimensions of the samples limit their applications for higher frequencies and on-chip electronic integration. Here, we propose an analog of GMI

effect by utilizing a cold magnetized plasma, which is capable of working at tunable frequency, even in terahertz frequency range. Since the plasma is reconfigurable in real time, this analog of GMI is tunable and can be controlled by the environmental parameters such as temperature and pressure. We also notice the fact that in certain doped semiconductors such as indium antimonide (InSb), the effective mass of electrons is almost 2 orders of magnitude less than its free space mass; therefore, the cyclotron frequency can easily reach terahertz. Additionally, magnetized plasma can be produced by using a standing helicon wave [36, 37]. These have demonstrated that the technology of such an analog of GMI design is really mature. We expect that the analog of GMI put forward here may open up new avenues for future research in the field of the magnetic sensor.

In summary, all calculated results for circularly polarized and extraordinary wave propagations in the magnetized ENZ plasma reveal interesting analog of GMI performance. This also ascertains the validity of the proposed design to be utilized as GMI sensors. The proposed design procedure is general and can be employed as an innovative approach to achieving robust sensors.

Fig. 4. The contour plots of the analog of GMI [i.e., $\Delta Z/Z$ (%)] for (a) circularly polarized and (b) extraordinary wave propagations as a function of the magnetic field and plasma frequency. (c) Field sensitivity [i.e., $\xi = 2(\Delta Z/Z)_{\max}/\Delta H$] versus plasma frequencies for circularly polarized and extraordinary wave propagations at plasma frequency. (d) Analog of GMI curves [i.e., $\Delta Z/Z$ (%)] of a cold magnetized plasma at different collision frequencies for circularly polarized and extraordinary wave propagations at the plasma frequency under different strengths/directions of the magnetic field. The ratio between the plasma frequency and collision frequency is assumed to be constant, which is $\omega_p/\gamma = (2\pi \times 10^4)/3$.

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