Emerging Aspects in a Plasma-Metamaterial Composite

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Abstract

When plasmas are immersed in a metamaterial structure, such a composite shows various properties which are not expected in an ordinary metamaterial. Plasmas are either generated by external powers or present in nature as a space plasma, and composites of metamaterials and such plasmas serve as elements of electromagnetic wave controllers as well as negative-refractive-index materials. This report describes the fundamental properties of the composites with specific examples, and some fields of potential applications for human space activities are surveyed.

1. Introduction

Propagation of electromagnetic waves in plasmas have been well investigated for several decades [1,2], and several categories of plasmas are present in the ionosphere layer on the earth and in the outer space, in which electromagnetic waves propagate in a way mainly described in the linear dispersion relations shown in the literature [3]. Even if we consider the effects of an external magnetic field on plasmas, fundamental understanding of electromagnetic wave propagation have been well explored, although the frontiers of the research fields still exist with huge scientific interests and technical requirements.

At the late 90's, there emerged concepts of "metamaterials" which drastically deform a well-known wave propagation [4]. For instance, in a metamaterial structure, the permeability μ can be macroscopically negative when we install an array of magnetic resonators [4], and refractive index N suffers phase shift up to $\pi/2$ rad. in its complex-value plane. With the addition of the negative-μ component, when an array of thin metal wires that works as a negative-ε component is included in the structure, N becomes negative, leading to inverse bending of the wavenumber on its surface [5]. Their research interests mainly focused on extraordinary effects such as super lens by a negative-N effect [5] and cloaking phenomena by spatially-distributed μ and ε profiles [6].

If a metamaterial is set in plasmas existing in advance, the propagation of electromagnetic waves will vary drastically. In another situation, if plasmas are generated in a metamaterial structure, electromagnetic waves propagating in advance suffer significant deformation. At this point of view, we recently proposed "plasma metamaterials" or plasma-metamaterial composites [7-10]. In comparison with ordinary metamaterials composed of solid materials, they include plasmas as a component of the entire structure with solid materials. One of the outstanding features of plasmas affecting on metamaterials is negative ε. That is, if we combine plasmas with a negative-μ material, we will obtain a negative-N material. Another significant feature is nonlinearity for field amplitude of electromagnetic waves. This feature will be important for plasma generation for material processing as well as control of microwaves.

In this report, we demonstrate fundamentals and applications of plasma-metamaterial composites. In Section 2, their theoretical backgrounds are briefly reviewed; in particular, ε in a plasma can be controlled as a complex value by changing external parameters at $\mathrm{Re}(\varepsilon) < 0$, and consequently N shows unique features that have been abnormal in ordinary metamaterials. In Section 3, the specific examples of plasma-metamaterial composites are listed up, which are relevant to an achievement of a negative-N material by a plasma-metamaterial composite and nonlinear effects originating from plasma properties. Finally, in Section 4, this report is summarized, and we survey future perspectives of plasma-metamaterial composites for human space activities.

2. Theoretical Backgrounds of Plasma-Metamaterial Composites

An ordinary metamaterial has a functional periodic micro structure which has a periodic length smaller than a wavelength of a given electromagnetic wave. Electric and magnetic fields of the wave exhibit local responses to the micro structure, and spatially integrated and macroscopic responses determine μ and ε for the wave. As mentioned

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earlier, in an ordinary metamaterial, ε as a macroscopic value is controlled by an array of metal wires. On the other hand, in a plasma-metamaterial composite, we use *microscopic* ε purely determined by an exiting plasma, shown as

$$\varepsilon_{\mathrm{p}} = 1 - \frac{\omega_{\mathrm{pe}}^{2}}{\omega(\omega + j\nu_{\mathrm{m}})} = \left(1 - \frac{\omega_{\mathrm{pe}}^{2}}{\omega^{2} + \nu_{\mathrm{m}}^{2}}\right) + j\frac{\nu_{\mathrm{m}}\omega_{\mathrm{pe}}^{2}}{\omega(\omega^{2} + \nu_{\mathrm{m}}^{2})}, \quad (1)$$

where $\omega/2\pi$ is the wave frequency, ω_{pe} is the electron plasma frequency, and ν_{m} is the electron elastic collision frequency against neutral particles. Combined with a macroscopic structure for control of μ such as an array of double split ring resonators [1], N is expressed as

$$N = \sqrt{\varepsilon_{\mathrm{p}}}\sqrt{\mu}\,. \quad (2)$$

Note that both $\varepsilon(=\varepsilon_{\mathrm{p}})$ and μ are usually complex values in our case. If $\nu_{\mathrm{m}} << \omega_{\mathrm{pe}}$, ε is almost a pure real number. On the contrary, if $\nu_{\mathrm{m}} >> \omega_{\mathrm{pe}}$, ε is nealy a pure imaginary number with $\mathrm{Re}(\varepsilon) \sim 1$. ν_{m} or gas pressure determines $\arg(\varepsilon - 1)$, and ω_{pe} or electron density determines $|\varepsilon - 1|$ [11]. That is, if we generate plasmas in this composite, ε of a plasma-metamaterial composite is completely controllable by external parameters such as output of power supply for plasma generation and gas pressure.

When a plasma is not generated but present in advance, ω is an important parameter to secure propagation of an electromagnetic wave. Although controllability of ε is not perfect, with adjustment of resonance frequency of magnetic resonators for μ expressed in an approximate Lorentz model, N can be controlled to a certain extent.

In a plasma-metamaterial composite, N is also a complex value. For instance, a negative-N state is achieved in a condition of $\arg(\sqrt{\varepsilon}) + \arg(\sqrt{\mu}) > \pi/2$ [10], instead of a state with both negative values (ε and μ) in the real number case.

3. Specific Examples of Plasma-Metamaterial Composites

When we generated plasmas in a plasma-metamaterial composite using another wave (i.e., low-frequency waves at kHz) whereas the metamaterial is effective in the microwave range, we have to carefully design a discharge electrode configuration; a structure for control of μ, which usually has magnetic resonance by a series pair of inductance and capacitance, might be affected by metallic components of the discharge electrodes. To remove this concern, we proposed a double-helix metal-wire structure which work both as a magnetic resonator and a pair of discharge electrodes [9,10]. Rough estimation of N using a simple interference method indicated that such a plasma metamaterial composite exhibits a negative-N state [9]. Currently, more precise measurement on parameter retrieval is being performed.

If the power of a propagating microwave is so high with large electric field E, plasmas in the composite may be generated by a propagating microwave itself. In this case, the composite shows an extreme nonlinear property. Nonlinearity in ε is generally shown as

$$\varepsilon^{\mathrm{NL}} = \varepsilon^{\mathrm{L}} + \varepsilon_0 f(E(\boldsymbol{r})), \quad (3)$$

where the superscripts NL and L indicate nonlinear and linear parts, respectively, ε_0 is the permittivity in vacuum, and $\boldsymbol{r}$ is the local position vector. In a nonlinear Kerr effect, the function f includes an E^2 term, which is usually assumed in a case of nonlinear crystals in the infrared photon range. However, if E contributes to plasma generation, f includes an $\exp(E)$ term via an ionization coefficient, which is extremely nonlinear. As a brief review of Ref. [12], the $\varepsilon - E$ bifurcation diagram exhibits bistability in a case of negative μ, with wave propagation in a plasma with unlimited high electron density.

4. Conclusion and Future Perspectives

In conclusion, we report fundamentals and examples of plasma-metamaterial composites. Unlike the ordinary metamaterials in which ε is determined macroscopically, ε in this composite is equal to that of a plasma itself. This indicates that ε is almost completely controlled by external parameters if plasmas are generated in a structure whose μ is controlled macroscopically. When a plasma is present in advance and a material for control of μ is inserted, the wave frequency for propagation is carefully selected with synchronized resonance frequency of the magnetic resonators. If a propagating microwave has a so high E to generate plasmas, nonlinear properties of the composite emerges clearly.

Now, we survey future perspectives of plasma-metamaterial composites for human activities in the (outer) space. One of the important application fields of electromagnetic waves is information carrier in communication between spacecrafts and the base on the earth. One of the crucial problems in this area is blackout in spacecrafts reentering the earth atmosphere [13]. When a spacecraft reenters the earth atmosphere, its kinetic energy loses through friction against low-pressure air gases, and a plasma is created beyond the threshold condition determined by the energy balance and the air pressure. The parameters of a plasma surrounding a spacecraft depend on specific conditions such as the outer shape of the spacecraft and reentering speed. One report indicates that electron density is on the order of 10^{12} cm^{-3}, and the corresponding plasma frequency which is also the wave cutoff frequency is at the microwave range. That is, if we set a negative-μ material on or just beneath the surface of the space craft, microwaves can penetrate through the plasma region with negative ε since N becomes real and negative.

Another important application fields of electromagnetic waves is power transmission, and the future electric power generated in a space solar power station [14] may be transmitted by microwaves [15,16]. If such a high-power microwave suffers effects of plasmas with negative-ε, triggers by negative-μ materials on its paths might make the area transparent for microwaves, although such effects are required to be investigated theoretically at a first stage.

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