Final report of AOARD-10-4038

“**Plasma metamaterials for arbitrary complex-amplitude wave filters**”

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14. ABSTRACT
In this project, we investigated arbitrary complex functions for electromagnetic waves by using a plasma array reinforced by metallic components and changing a pattern of series switches, external power for plasma generation, and pressure of discharge gases. In Section II., we describe the theoretical part of this project, where plasma metamaterials were predicted for the purpose of potential complex wave filters for the first time. In Section III, we show the experimental part of this project, and verified flexible complex function filters composed of plasma metamaterials, using newly-developed microwave analytical circuit.

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"Plasma metamaterials for arbitrary complex-amplitude wave filters"
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Goal of this project

Investigations of arbitrary complex functions for electromagnetic waves by using a plasma array reinforced by metallic components and changing a pattern of series switches, external power for plasma generation, and pressure of discharge gases.

I. Introduction

A metamaterial, which has a functional microstructure leading to an extraordinary macroscopic property, is composed of metals and dielectrics in general.[1-3] Specific and careful design of its spatial structure is required before it works, for instance, as a negative-refractive-index (negative-N) material.[4-6] To secure flexibility of its design and parameters, here we propose *plasmas* as materials composing metamaterials. Microplasmas, which have sizes ranging from millimeter to micrometer scale and work near and at atmospheric pressure, have electron densities $n_e = 10^{12} - 10^{16}\ \mathrm{cm}^{-3}$ that correspond to electron plasma frequencies $\omega_{pe}/2\pi$ at 10 GHz-1 THz. They are equivalent dielectrics with permittivity ε between unity and zero above ω_{pe}, and equivalent metals with negative ε below ω_{pe}. n_e and the gas pressure that determine ε are controllable by adjusting input of electric power and gas inlet for plasma generation, and their spatial profiles can be altered to a certain extent.

We have reported plasma photonic crystals that exhibit significant functions of an array of microplasmas for control of electromagnetic waves.[7-10] In a plasma photonic crystal, a 1-dimensional or 2-dimensional array of spatially periodic plasmas is formed, and topical features such as photonic band gaps and surface-plasmon-like chains were predicted theoretically and observed experimentally. We also pointed out the importance of complex ε, which can be controlled in a discharge plasma and makes a band gap around which wave attenuation changes drastically. In such a structure, ε was elaborately controlled in a homogeneous array, although permeability μ was constant at unity.

Here, we extend these results to metamaterials composed of plasmas,[11-13] referred to as "plasma metamaterials" hereafter. The concept of plasma metamaterials was proposed in Ref. 11. One type of plasma metamaterial was shown in Ref. 12, which verified that spoof surface plasmons propagating on a perforated metal plate can be controlled dynamically by microplasma generation in the holes of the plate. Another type, possibly with the most significant role that plasma metamaterials may play, is a dynamic negative-refractive-index material composed of negative-ε plasmas and negative-μ (metallic) structure; our brief previous report[13] demonstrated experimental results of plasma metamaterials with negative refractive index, although theoretical background has not been clarified thus far. Theoretical design of plasma metamaterials is required for further extension of plasma metamaterials in industrial applications as well as for scientific purposes.

Before we describe plasma metamaterials specifically, we take a close look at their performance requirements. When we generate plasmas, metallic discharge electrodes are usually required. If we design metallic wires as electrodes to generate microplasmas with negative ε and simultaneously as resonators to make macroscopic μ negative due to magnetic resonance, the synthesized structure with spatial periodicity is expected to be a state with negative N as a double-negative system. We note that the state with negative ε arises from microscopic parameters in plasmas, which differs substantially from macroscopic permittivity emerging in an array of thin metal wires.[14,15]

Another important characteristic of plasma metamaterials is the role of the imaginary part of ε,[10] ε_{i}, given as

$$\varepsilon = 1 - \frac{\omega_{\mathrm{pe}}{}^2}{\omega^2} \frac{1}{1 + \mathrm{j}(\nu_{\mathrm{m}} / \omega)} \equiv \varepsilon_{\mathrm{r}} + \mathrm{j}\varepsilon_{\mathrm{i}} \ . \tag{1}$$

This is mainly associated with the electron elastic collision frequency with neutral particles ν_{m}, which directly depends on gas pressure. ε_{i} is estimated as a loss source for propagating electromagnetic waves, and we usually tend to minimize its value to

avoid wave attenuation. Figure 1 shows complex values of (ε_r, ε_i) in various gas species and pressures with several levels of n_e, which indicates that we can control (ε_r, ε_i) freely by changing gas conditions and energy input for generation.
However, when we consider the refractive index $N = N_r + jN_i$ as a product of ε and μ, say,[16]

$$N = \sqrt{\varepsilon}\sqrt{\mu}, \tag{2}$$

we recognize that wave attenuation expressed by N_i is not directly connected to ε_i. To understand wave propagation more rigorously, calculation of a dispersion relation in the periodic structure with complex N is required, where, in the dispersion relation, wavenumber $k = k_r + jk_i$ is as a function of electromagnetic wave frequency $\omega/2\pi$. In our previous report where we mentioned a specific plasma metamaterial with non-one μ using experimental results, we assumed that both ε and μ are real numbers for simplicity,[13] which is not sufficient for understanding the importance of ε_i.

In this project, we investigated arbitrary complex functions for electromagnetic waves by using a plasma array reinforced by metallic components and changing a pattern of series switches, external power for plasma generation, and pressure of discharge gases. In Section II., we describe the theoretical part of this project, where plasma metamaterials were predicted for the purpose of potential complex wave filters for the first time. In Section III, we show the experimental part of this project, and verified flexible complex function filters composed of plasma metamaterials, using newly-developed microwave analytical circuit.

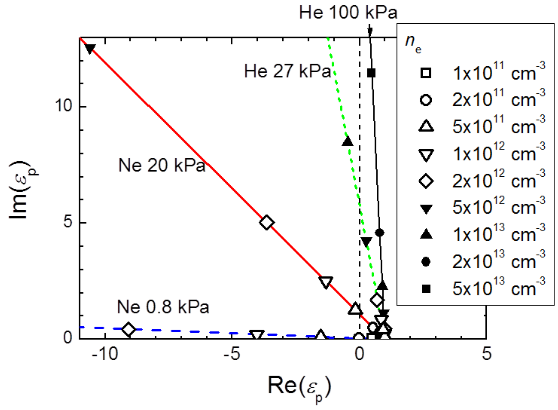

Fig. 1. Complex *e* as functions of gas species, pressure and n_e deduced from Eq. (1).

II. Theoretical prediction of flexible plasma metamaterials

Detailed formulation of the theoretical model was described in Ref. 17. In short, Faraday's law and Ampere's law are applied to calculate an equivalent μ. Relationship between induced voltage and current is deduced from Foster's theorem. And effects of micro-periodicity whose length is much less than a wavelength is included with the knowledge of the Bloch modes.

In the following results, we used Eq. (2) for derivation of N where $\varepsilon(=\varepsilon_{\mathrm{p}})$ is expressed by Eq. (1) and displayed in Fig. 1, and $\mu(=\mu_{\mathrm{eff}})$, which is a pure real number, is displayed in Fig. 2. k is derived by solving Eq. (8), where k_{r}, the real part of k, has the maximum value of 12.57, which corresponds to the end of the first Brillouin zone.

Figure 3 shows frequency dependence of N and dispersion relation when collisionless plasmas with $\varepsilon_{\mathrm{pi}}=0$ are generated. Here we set $n_{\mathrm{e}}=4\times10^{12}\,\mathrm{cm}^{-3}$ to derive ε_{p}; in the following calculation, we use this n_{e} value. $\varepsilon_{\mathrm{pr}}$ is always negative at frequencies of less than 18 GHz where $\omega=\omega_{\mathrm{pe}}$, and so N becomes imaginary at most frequencies outside the resonance-vicinity bands and wave propagation is prohibited. However, since both ε_{p} and μ_{eff} are negative in the resonance-vicinity bands, N becomes real and negative. As a result, k_{r} has a finite value while k_{i} is

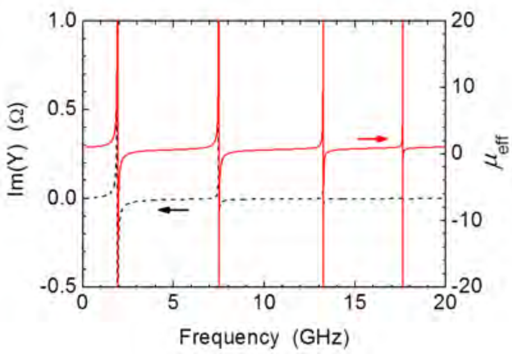

Fig. 2. Macroscopic m for double-helix metal wires with calculated admittance Y for structure in Fig. 2. 1D plasma

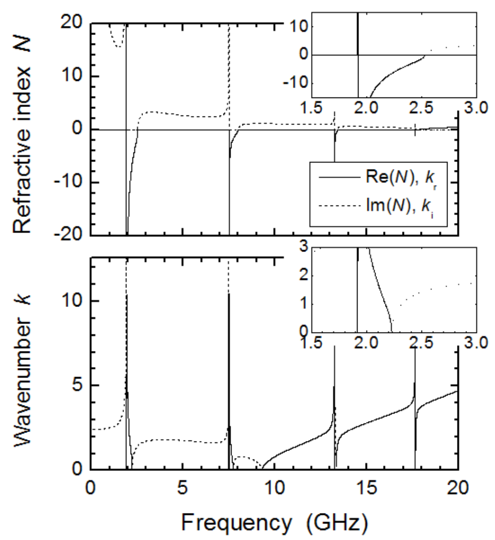

Fig. 3. Frequency dependence of N and k of 1D collisonless plasma metamaterial with $n_{\mathrm{e}}=4\mathrm{x}10^{12}\,\mathrm{cm}^{-3}$.

zero in these bands, and waves can propagate with negative phase velocity. Arising from the fact that $N < 0$, several extraordinary phenomena are expected, such as performance as a perfect lens.[5]

Now, we proceed further to look at the effects of finite $\varepsilon_{\mathrm{pi}}$. Figure 4 shows frequency dependence of N and dispersion relation when plasmas are slightly collisional at 50 Torr of Ne. In the resonance-vicinity bands, N_{r} is negative, similar to the value in Fig. 3, but N_{i} is not zero. Consequently, k_{i} is a certain value while k_{r} is still larger; the waves propagate with slight attenuation. We note that $\varepsilon_{\mathrm{pr}}$ is so negative that we easily recognize that N_{r} is negative from Equation (1). Figure 5 shows frequency dependence of N and dispersion relation when plasmas are more collisional, at 150 Torr of Ne. In the resonance-vicinity bands, N_{r} is still negative, but N_{i} is large with its amplitude comparable to N_{r}. Consequently, k_{i} is almost similar to k_{r}. In this case, $\varepsilon_{\mathrm{pr}}$ is negative with larger $\varepsilon_{\mathrm{pi}}$ value.

Figure 6 shows frequency dependence of N and dispersion relation when plasmas are highly collisional at 760 Torr of He. In the resonance-vicinity bands, N_{r} is still negative as well, but now N_{i} is much larger than that in Fig. 5. Consequently, k_{i} is quite large, although k_{r} is still finite. We have to point out that, in this case, $\varepsilon_{\mathrm{pr}}$ is *not* negative, but N_{r} is certainly negative. This phenomenon is unique to a plasma metamaterial, in which $\varepsilon_{\mathrm{pi}}$ plays an important role. When we take a careful look at Eq.

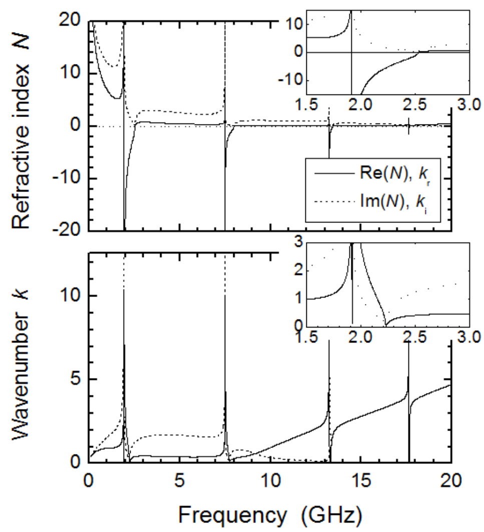

Fig. 4. Frequency dependence of N and k of 1D lossy plasma metamaterial with n_{e} = 4x10^{12} cm^{-3} at 50 Torr of Ne.

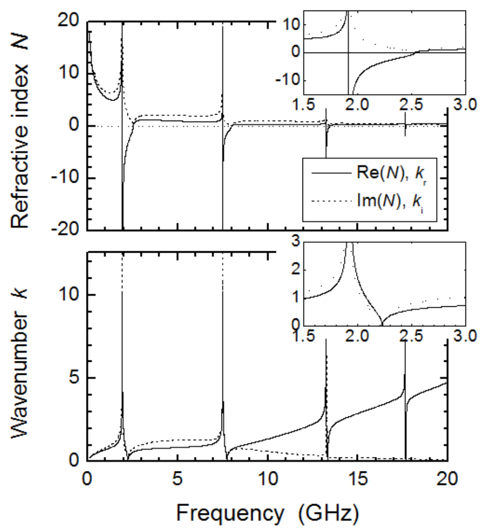

Fig. 5. Frequency dependence of N and k of 1D lossy plasma metamaterial with n_{e} = 4x10^{12} cm^{-3} at 150 Torr of Ne.

(1) again with possibilities of complex ε and μ, we recognize a possibility that large ε_{pi} with respect to small ε_{pr} may contribute to yielding negative N_r with large N_i.

From these results, we can recognize that k_i and N_i can be set to different k_r and N_r values by changing gas conditions. As we mentioned earlier, N_r and N_i affect phase shift and amplitude attenuation of waves, and so we can predict potentials for complex value filters by plasma metamaterials.

III. Experimental verification of flexible plasma metamaterials

We briefly reported a controllable-N material in preliminary experiments.[13] Double-helix metal wires and generated plasmas formed this metamaterial.[17] In the double-helix structure, inductance L is expected to be along a wire, and capacitance C is present between the wires. L and C form a ladder-like equivalent circuit, showing a series resonance when two of its ends are connected. Consequently, the entire structure has multi resonance frequencies above which macroscopic μ of its array becomes negative. As shown in Fig. 7, the array of the double-helix metal wires was set in a capillary tube, and the tubes were installed on a coplanar microwave waveguide to investigate the entire structure as a device under test (DUT). Interference measurement indicated that the DUT became negative-N material, although the results obtained in this measurement include large error bars.[13]

To confirm negative N in this metamaterial configuration in a more precise

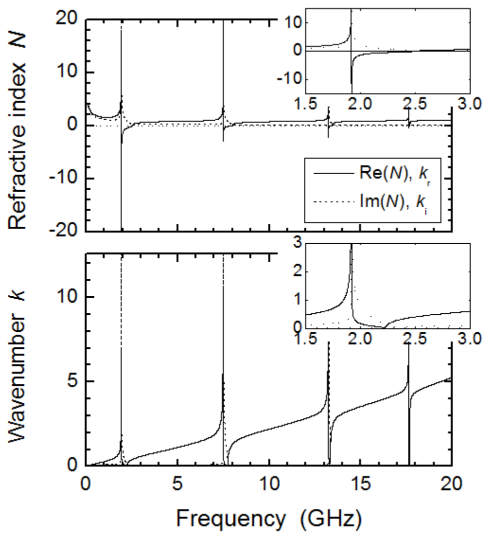

Fig. 6. Frequency dependence of N and k of 1D lossy plasma metamaterial with n_e = 4×10^{12} cm^{-3} at 760 Torr of He.

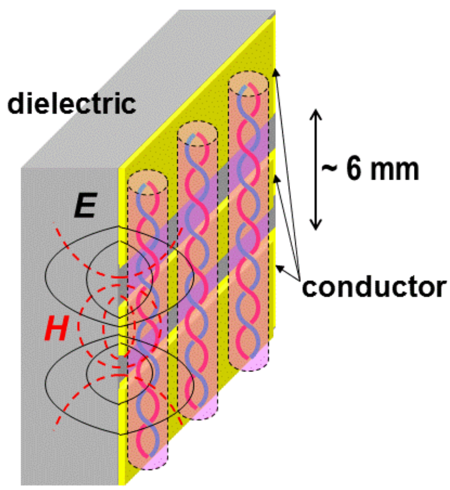

Fig. 7. Schematic view of device under test composed of double-helix metal wires and generated microplasmas.

diagnostics, we developed a microwave lumped-element circuit for a parameter retrieval method[18] using the two-port twelve-term error model,[19] which in displayed in Fig. 8.[20] In short, signals are analyzed by splitting into in-phase and quad-phase parts, and precise phase information is deduced in the assumption of sinusoidal wave forms, where quad-phase signals have phase difference of 90 degrees from the initial one. The measured microwave properties through the DUT are partly shown in Figs. 9 and 10, where various gas conditions were set to see the effects of complex ε shown in Fig. 1. First, the time evolutions of S_{21} were very different from those of transmitted signals in the 2D plasma photonic crystal.[13] The composites of plasmas and metallic resonators make the microwave transmitted signals vary more drastically in both amplitude and phase.

Here we estimate values of N in a typical case shown in Fig. 9 where metamaterial effects are dominant. Without plasmas, the resonance frequency of the array of the double-helix wires was around 4.25 GHz, where $\mathrm{Re}(N) \sim 1.8$ with the length of the structure = 3.8 mm and the corresponding phase shift through the structure ~ 6.1 rad. At 4.27 GHz, which was very close to the resonance frequency, and for Ne at 20 kPa, the change of $\arg(S_{21})$ by plasma generation was more than 2π rad, which indicates that $\mathrm{Re}(N)$ of the DUT decreased down to negative values. From calculation of the filling factor of the double-helix wires (~0.32) in the entire DUT structure,[21]

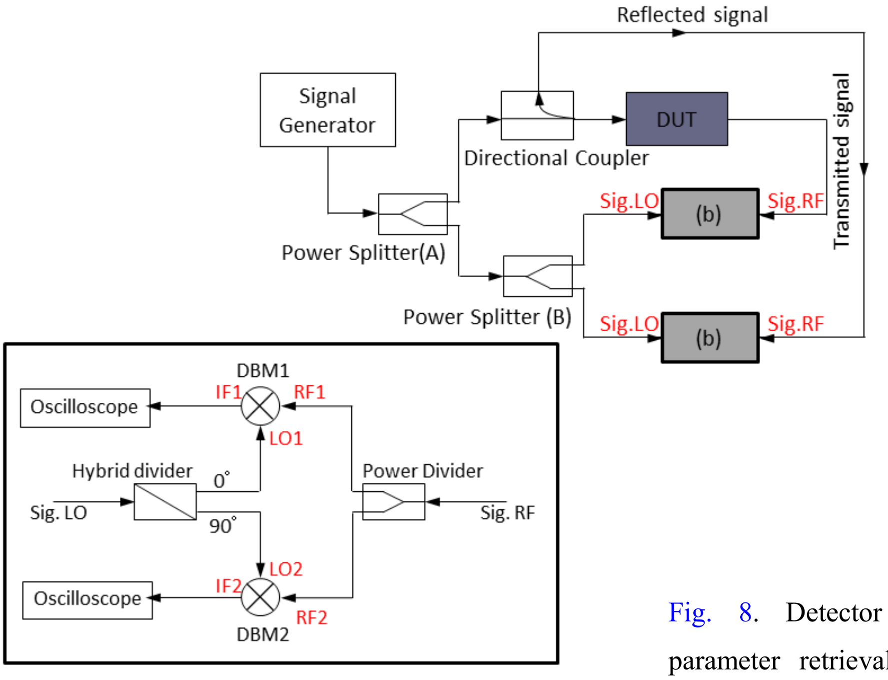

Fig. 8. Detector circuit for parameter retrieval method of dynamic metamaterials.

$\mathrm{Re}(N)$ in the metamaterial layer composed of the microplasmas and the double-helix metal wires was estimated to be -1.5 – -3.0.

If the discharge gas conditions are different, corresponding transmitted microwave signals are along different contours in the complex S_{21} plane, as shown in Fig. 11. For instance, in the case of Ne at 20 kPa in Fig. 9, the phasor of S_{21} rotated at more than 2π rad since complex ε changes in both real and imaginary components, as shown in Fig. 1. We also note that this gas condition roughly corresponds to the case in Fig. 5. On the other hand, in the case of He at 100 kPa in Fig. 10, the phasor of S_{21} swung along one straight line which implies no substantial change of the phase component. The corresponding ε might change only in its imaginary component with almost no change of $\mathrm{Re}(\varepsilon)$, which roughly corresponds to the case in Fig. 6. These facts verify that the complex components in ε and N are key factors and distinguish the plasma metamaterials from the ordinary solid metamaterials.

IV. Summary and future perspectives

We theoretically and experimentally verify complex electromagnetic-wave

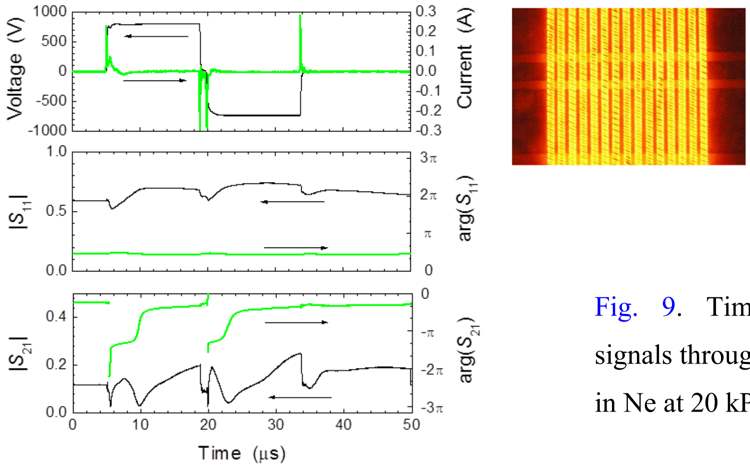

Fig. 9. Time evolution of microwave signals through DUT with discharge signals in Ne at 20 kPa.

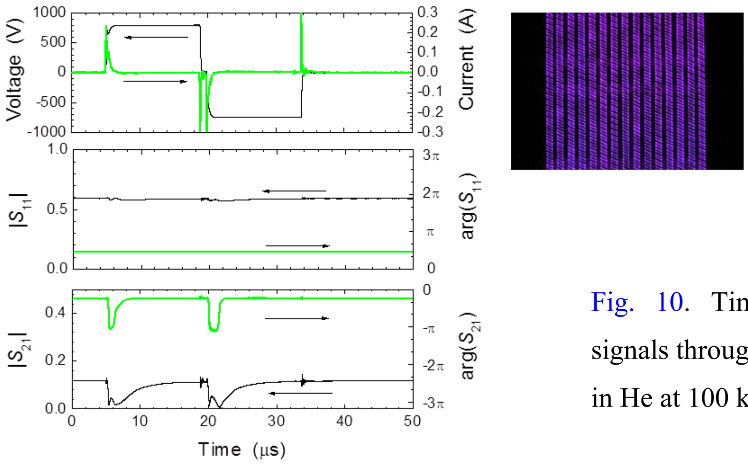

Fig. 10. Time evolution of microwave signals through DUT with discharge signals in He at 100 kPa.

filters achieved by plasma metamaterials. In addition to the previous results in which number of turn-on plasma columns was controlled,[13] we can control electromagnetic waves with adjustable phase shift and attenuation by changing gas pressures and external power supply for plasma generation. Although such a concept and verified technology are applicable for alternatives of conventional solid-state microwave devices, we cannot recognize certain advantages to replace them by novel devices based on plasma metamaterials. Instead, when we apply plasma metamaterials to controllable media for high-power microwaves working as electric energy carriers, they will be superior to other conventional devices since plasmas do not deteriorate by microwave with high energy density.

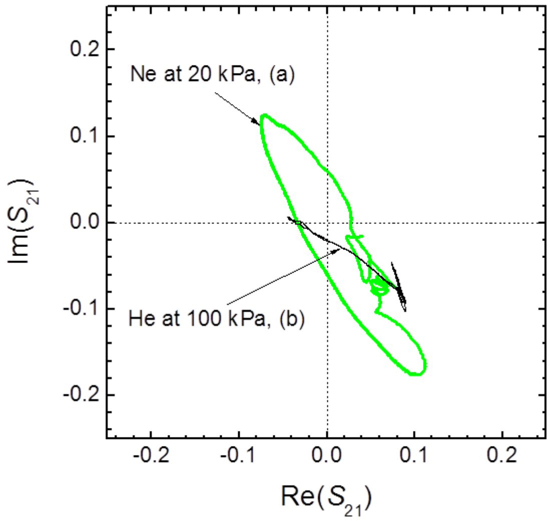

Fig. 11. Time trajectories of complex phasor S_{21} in two corresponding cases in Fig. 9 as (a) and Fig. 10 as (b).

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VI. Publication of results in this project

(a) Scientific papers

1. O. Sakai, T. Naito and K. Tachibana,
   "Experimental and numerical verification of microplasma assembly for novel electromagnetic media,"
   Physics of Plasmas, vol. 17 (2010), pp. 057102-1-9.
2. O. Sakai, T. Shimomura and K. Tachibana,
   "Negative refractive index designed in a periodic composite of lossy microplasmas and microresonators,"
   Physics of Plasmas, vol. 17 (2010), pp. 123504-1-9.
3. O. Sakai, S. Iio, T. Shimomura and K. Tachibana,
   "Experimental and theoretical characterization of plasma metamaterials,"
   Transactions of the Materials Research Society of Japan (in Press).
4. O. Sakai and K. Tachibana,

"Plasmas as metamaterials: a review,"
Plasma Sources Science and Technology (invited paper, in Press).

5. O. Sakai, T. Shimomura and K. Urabe,
"Detector design for a parameter retrieval method applicable to dynamic metamaterials,"
Review of scientific instruments (in preparation).

(b) Conference papers

1. O. Sakai, T. Shimomura,
"Anomalous response of lossy plasmas immersed in metamaterial structure in the microwave range,"
Proceedings of The 63th Gaseous Electronic Conference and 7th International Conference on Reactive Plasmas (Paris, France, October 4-8, 2010) p. 45.
2. Osamu Sakai, Satoshi Iio and Takuya Shimomura
"Experimental and Theoretical Characterization of Plasma Metamaterials,"
Proceedings of 20th Academic Symposium of The Materials Research Society of Japan (Yokohama, Japan, December 20-22, 2010) p. 4.

(c) Patent submission

(None)