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Simultaneous formation of microwave plasma and negative refractive index state with metamaterial effects

メタマテリアル効果による
マイクロ波プラズマと負屈折率状態の同時形成現象

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Microwave plasmas with high electron density can be generated in a metamaterial structure with negative permeability. In a conventional scheme in which the permeability is unintentionally positive, the cutoff phenomenon against propagating microwaves restricts electron density which represents positive permittivity in the discahrge space; when the electron density exceeds the cutoff density, the refractive index becomes imaginary, and the waves cannot propagate furthermore. However, since the concept of "metamaterials" allows us to obtain a negative-permeability state, the refractive index becomes real and negative when a plasma has high electron density, leading to negative permittivity, and with negative permeabity. In this study, we predict bifuration of solutions in a nonlinear system where a high-density microwave plasma is geenrated wimultaneously with negative refractive index, and demonstrated experimentals results which cannot be comprehended using previous understandings.

1. Introduction

Plasma reactors in which plasmas are generated by high-power microwaves are one of the main processing tools in the industrial fabrication for semiconductor devices. In a reactor without an external magnetic field, electron density is limited up to the so-called cutoff density since refractive index becomes imaginary in an overdense plasma and microwaves for plasma generation cannot propagate inside it. To overcome this difficulty to obtain high-density microwave plasmas, one solution is to excite surface waves which can support plasma generation with higher density than the cutoff density, and surface wave reactors are suitable for a large-area plasma processing such as thin film deposition and surface treatment of flat substrates [1]. In such plasma reactors, electron density usually depends on the frequency of the excited surface wave, and is not a direct function of input microwave power.

In our recent report, we proposed another scheme for high-density microwave plasmas in which the concept of metamaterials [2,3] are applied [4]. In ordinary materials, permeability is positive and unity except some materials such as ferrites in microwave regions. However, using metamaterials which contains much smaller periodic length of microstructure than a given electromagnetic wave, a volumetric metamaterial becomes a negative-permeability (negative-μ) space which includes free spaces with small volume fraction of metallic components. In such a space without a plasma, microwave cannot propagate since permittivity ε is positive and the refractive index N is imaginary, according to the relation:

$$N = \sqrt{\varepsilon}\sqrt{\mu}. \qquad (1)$$

When there is an overdense plasma whose ε is negative, N becomes real and *negative*, and microwave can propagate to sustain a high-density plasma. Interesting point is that electron density is unlimited, unlike the cases of the surface wave excitation.

One missing point in the above argument is that a state should pass through an imaginary-N state when a microwave starts to propagate and ignite plasma with fairly low density. In this report, we briefly overview a process underlying this scheme using theoretical predictions. We also demonstrate extraordinary phenomena observed in experiments; transmitted microwave *increased* when plasmas were generated, which cannot be explained with our usual experimentalist's knowledge saying that microwaves should decrease due to power absorption after plasma generation.

2. Theoretical Prediction

The detailed prediction based on numerical and analytical approaches is found in our recent report [JAP2011], and here we describe the points associated with experimental results.

We performed numerical calculation of propagating microwaves at 2.45 GHz using a finite-difference time-domain (FDTD) method. When we set negative μ in a certain area, the waves cannot propagate in cases of positive ε; electric fields inside the structure is extremely low. On the other hand, they can propagate in cases of negative ε with large electric field though the calculated region, and their properties indicate negative-N state such as reversed phase velocity and negative refraction angle on the interface.

In contrast, when we see a formula of ε in a plasma expressed in the Drude model, given as

$$\begin{aligned}\varepsilon &= 1 - \frac{{\omega_{\mathrm{pe}}}^2}{\omega^2(1+\mathrm{j}\nu_{\mathrm{m}}/\omega)} \\ &= 1 - \frac{e^2 n_{\mathrm{e}}}{\varepsilon_0 m_{\mathrm{e}}\omega^2(1+\mathrm{j}\nu_{\mathrm{m}}/\omega)},\end{aligned} \qquad (2)$$

where is the wave frequency, the electron plasma frequency, the electron elastic collision frequency, n_{e} is the electron density, the elementary charge, the vacuum permittivity, and the electron mass. Because ε does not include a step-wise function of n_{e} around zero, the electric fields inside the structure varies smoothly, unlike the step-wise function. This discrepancy between two facts yields bifurcations of solution of ε.

3. Experimental Results

We installed a rectangle waveguide inside a vacuum chamber, and double split ring resonators (DSRRs)[3] with a resonance frequency around 2.45 GHz occupied the inside of the waveguide for about 10 cm along the axis, which indicate that μ in the region of the DSRRs may become negative. Before and after this region, we set directional couplers to detect input and output microwave power at 2.45 GHz. Ar gas at 0.5 kPa occupied the entire volume of the chamber.

DSRRs work as wave energy “condenser” due to its resonant property as well as a component of a negative-μ material, leading to enhancement of the electric field near the structure. Microwaves with several tens of watts ignited plasmas around the DSRRS, and the microwave

When plasmas were ignited around the DSRRs, we observed *increase* of transmitted microwaves; this is an abnormal phenomenon for plasma generation, since input energy is consumed in the plasma region. However, according to the prediction shown in Section 2, this increase is quite reasonable for possible generation of the negative-N state with an overdense plasma. Further experiments will verify detailed space parameters and their features in the region around the DSRRs.

4. Conclusion

A negative-μ state induces quite different phenomena which have not been observed in conventional discharge spaces. The concept of this new scheme is based on the recent progress of researches on metamaterials, and leads to high-density microwave plasma generation. Experimental results were partly predicted by theoretical approaches.

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