Microwave plasma generation in negative-permeability space

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1. Introduction

Plasma metamaterials which were recently reported [1,2] have advantages over ordinary metamaterials; a dynamic change of permittivity and tunable amplitude on the complex plane can be manipulated by external power supply for plasma generation and adjustable gas pressure. Not only negative refractive index with both negative permittivity and permeability but also elaborated control of propagating microwaves with large phase shift were performed so far. Now, if the power of the propagating microwave is beyond ignition threshold of microwave plasmas, electron density will be enhanced and lead to additional plasma generation which modifies permittivity in space and the wave propagation itself; this is a feedback phenomenon, and will lead to a nonlinear dynamic system.

In this report, we describe microwave plasma generated in a negative-permeability space; when electron density in the plasma is sufficiently high, we can expect simultaneous generation of a negative-refractive-index state. After numerical predication of this phenomenon, experimental results will be demonstrated.

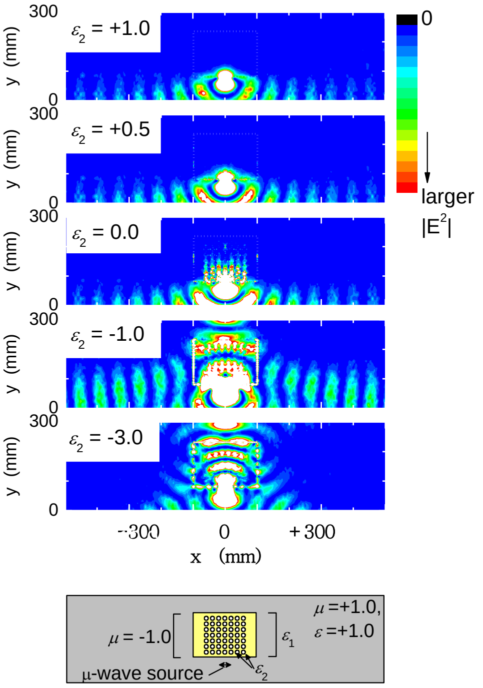

Fig. 1: Numerical results of electric fields of propagating waves in a negative-permeability material.

2. Numerical results

Figure 1 shows numerical results on propagating waves at 2.45 GHz in a negative-permeability material which may be an array of double split ring resonators. The calculation method is similar to the one used in Ref. [3]. Unlike a case with positive permeability, electromagnetic waves can propagate in a high-density plasma whose density is *beyond* the so-called cutoff density (7×10^{10} cm^{-3} at 2.45 GHz). Simultaneously, permittivity becomes negative, and the refractive index becomes negative, which is confirmed by negative phase velocity and bending wave trajectories on the surface. Details of the results indicate a kind of nonlinear dynamics in which permittivity shows a saddle-node bifurcation phenomenon.

3. Experimental results

We made an array of double split ring resonators on dielectric substrates as a negative-permeability material, and set the array at the center of a waveguide for 2.45 GHz (WRJ-2) (Fig. 2). Then, we measured frequency dependence of a scattering matrix *S* of the array installed in the waveguide by Vector Network Analyzer (VNA), and calculated a frequency spectrum of the imaginary part of refractive index from *S* (Fig. 3). Figure 3 shows that the imaginary part of refractive index increases at around 2.45 GHz, and because there is no negative-permittivity material, this means that around this frequency, the array becomes a negative-permeability material. In this setup, at 0.5 kPa, we made Ar flow into the waveguide that we installed the array into, and launched microwaves (< 500

W) at 2.45 GHz which propagate inside the waveguide. Then we successfully observed generated plasmas, and Fig. 4 shows their visible emission images. The emission intensity was enhanced by the resonators, in comparison with the case without resonators. So far we did not recognize negative refractive index in this result. Further experiments on microwave power dependence and parameter retrieval will specify refractive index as well as permittivity and electron density.

4. Summary

In this report, we performed calculations and experiments about the effects of negative permeability on microwaves and plasma generation, where the power of the microwaves is sufficiently high for plasma generation. From numerical results, we recognized that as electron density in plasmas increased beyond the cutoff density, microwave could propagate into the negative-permeability space. In the experiment, we launched microwaves to negative-permeability space composed of double split ring resonators. Then we successfully observed plasma generation, but high electron density, which makes the permittivity negative, has not been confirmed, although plasma emissions were enhanced by installation of the resonators.

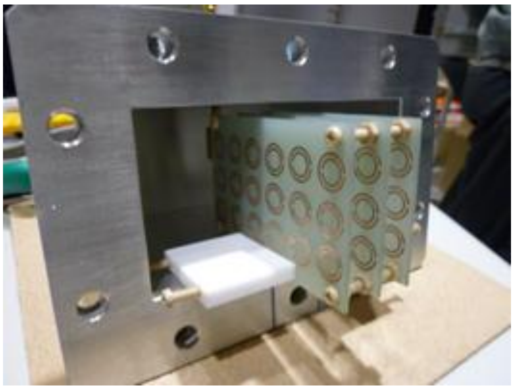

Fig. 2: An array of double split ring resonators.

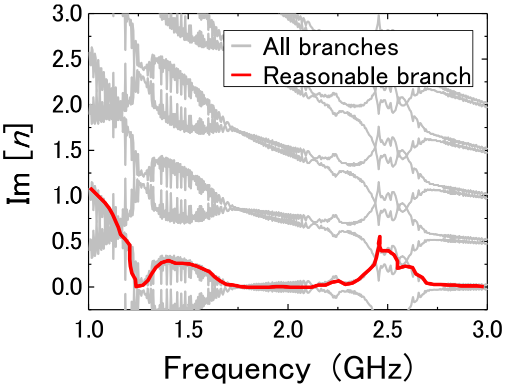

Fig. 3: Frequency dependency of imaginary part of refractive index on both the array and the waveguide.

References

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2. O. Sakai, T. Shimomura, and K. Tachibana, Phys. Plasmas **17**, 123504 (2010).
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(a). Without plasma (b). 27 W (c). 53 W (d). 109 W

Fig. 4: Visible emission images of plasmas on the array.