Efficient microwave injection into overdense plasma supported by negative-permeability resonant metamaterial

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1. Background

A 2.45-GHz microwave has been widely selected as a power source for generation of high-density plasma which conventionally has negative permittivity ε and reflects the incident microwave. We have studied efficient generation of microwave plasma with using double-split-ring resonators (DSRRs) which are typical metamaterials whose permeability μ becomes negative since negative ε of overdense plasmas and negative μ of the DSRRs can achieve a negative index state [1]. We reported negative-index propagation in this composite by numerical simulations [2], and confirmed that negative-ε plasmas were actually generated in our system [3]. In this report, we show efficient microwave propagation into this composite.

2. Experimental setup

An experimental system is shown in Fig. 1. Microwaves (2.45 GHz) enter the vacuum chamber filled with 100-Pa Ar gas via the waveguide (WR-430). A DSRRs' array (μ=-2.6-0.3j for 2.45 GHz) is set to achieve negative-index plasma metamaterial composite. We detect signal intensities of the microwaves $V_{2.45\mathrm{GHz}}$ at position P in Fig. 1 with tuning distance from the entrance to a monopole antenna z and input power.

3. Experimental results

Figure 2(a) shows $V_{2.45\mathrm{GHz}}$ as a function of z in cases without and with DSRRs when the input power is 170 W. Though $V_{2.45\mathrm{GHz}}$ is perfectly attenuated in the overdnense plasma without DSRRs up to z ~ 10 mm, in the composite, $V_{2.45\mathrm{GHz}}$ gently decrease as the increment of z and quite stronger than that without DSRRs in z > 10 mm. The values of $V_{2.45\mathrm{GHz}}$ at z = 14 mm as a function of the input power is shown in Fig. 2(b). As the increment of the input power, $V_{2.45\mathrm{GHz}}$ largely increases and decreases in cases with and without DSRRs, respectively. Moreover, $V_{2.45\mathrm{GHz}}$ in the composite is quite larger than that in the simple overdense plasma. These results strongly suggest that the efficient propagation of the microwaves occurs in the composite of the negative-permittivity plasma and the negative-permeability DSRRs' array.

Reference [1] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett., **84**, (2000) 4184. [2] A. Iwai, O. Sakai, and Y. Omura, Phys. Plasmas, **24**, 122112 (2017). [3] O. Sakai, Y. Nakamura, A. Iwai, and S. Iio, Plasma Sources Sci. Technol., **25**, 055019 (2016).

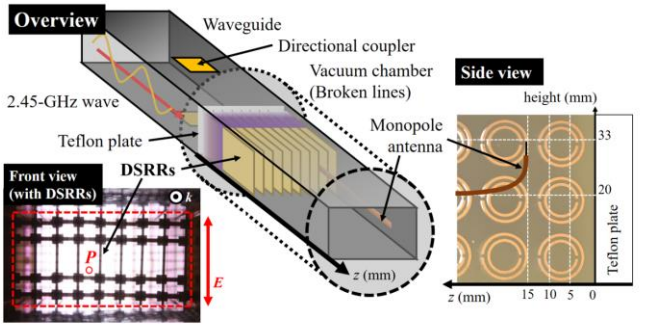

Fig. 1 Experimental system. A monopole antenna is installed at position P, and distance from the tip of the antenna and a Teflon plate z is tuned.

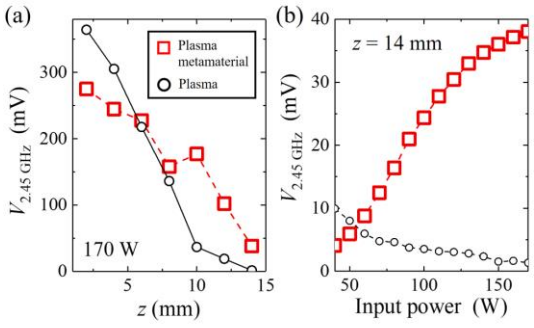

Fig. 2 Detected signal intensities $V_{2.45\,\mathrm{GHz}}$ as a function of (a) z and (b) input power.