Efficient second-harmonic generation by microwave plasma with metamaterial effect (Ⅳ)

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1. Introduction

Frequency conversion is one of the topics which has been focused on in general science and engineering. Plasma has the dynamic relative permittivity ε_r from a varying electron density, and a number of researches about harmonic-wave generation, one of the nonlinear optical phenomena, have been performed using plasma [1]. In general condition with relative permeability μ_r equal to unity, electromagnetic wave cannot propagate into high-density plasma space (overdense plasma) because of negative ε_r. On the other hand, electron density is one of the important factors about efficient harmonic-wave generation in plasma [2]. We combined negative-μ_r metamaterial [3] and negative-ε_r plasma, and showed the efficiently enhanced second-harmonic-wave generation in this composite [4,5]. In this address, we introduce the second-harmonic wave generation with different metamaterials.

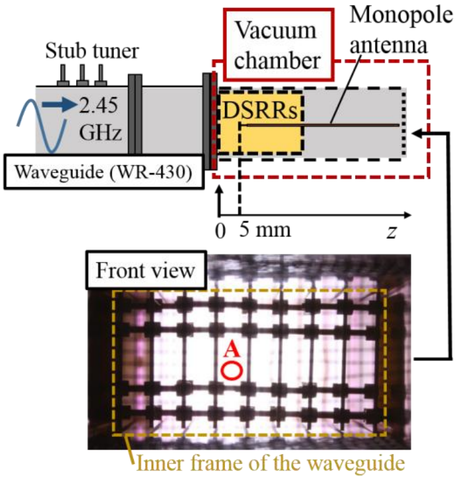

Fig.1 Overview of experimental setup. Front view is a photo of excited plasma and DSRRs.

2. Experimental setup

We installed double-split-ring resonators (DSRRs: the conventional negative-μ metamaterial) [3] in the rectangular waveguide (Fig. 1). We used negative-μ_r (-2.6-0.3j) and positive-μ_r (~1) DSRRs for 2.45 GHz, the input power frequency, and both of them had unity μ_r for double frequency 4.9 GHz. Both frequencies signals were detected at position A when plasma was excited by the input 2.45-GHz microwave (< 500 W).

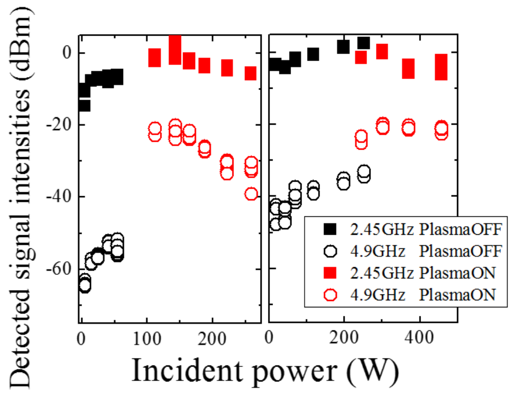

Fig. 2 2.45- and 4.9-GHz signals in negative- (left) and positive-μ_r (right) cases.

3. Experimental results

Figure 2 shows the comparison of two cases with the different DSRRs. In both cases, 4.9-GHz signals are increased after plasma excitation, which indicates the enhanced nonlinearity in this system depends on plasma. However, the threshold input levels for plasma generation are largely different because the negative μ_r helps energy incidence into high density plasma. The intensities of 4.9-GHz signals are relatively higher than that of the case without DSRRs [4] and it is possible that they are induced by local energy concentration and plasma sheathes on inserting DSRRs.

References [1] P. Gibbon, IEEE J. Quantum Electron., **33** (1997) 1915. [2] E. Takahashi, M. Mori, N. Yugami, Y. Nishida, and K. Kondo, Phys. Rev. E, **65** (2001) 016402. [3] J. B. Pendry, A. J. Holden, D. J. Robbins and W. J. Stewart, IEEE Trans. Microw. Theory Tech., **47** (1999) 2075. [4] A. Iwai, Y. Nakamura, and O. Sakai, Phys. Rev. E, **92** (2015) 033105. [5] A. Iwai, Y. Nakamura, A. Bambina, and O. Sakai, Appl. Phys. Express, **8** (2015) 056201.