18aE-3

Metamaterial Properties of Microwave Media Based on Plasma Components
プラズマを構成要素とするマイクロ波媒質のメタマテリアル特性

Osamu Sakai[1,2], Akinori Iwai[2] and Atsushi Sanada[3]
酒井道[1,2], 岩井憲亮[2]，真田篤志[3]

[1]*The University of Shiga Prefecture, 2500, Hassaka-cho, Hikone, Shiga 522-8533, Japan*
[1]滋賀県立大学　〒522-8533　滋賀県彦根市八坂町2500
[2]*Kyoto University, Kyoto-daigaku Katsura, Nishikyo-ku, Kyoto 615-8510, Japan*
[2]京都大学　〒615-8510　京都市西京区京都大学桂
[3]*Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi 755-8611, Japan*
[2]山口大学　〒755-8611　山口県宇部市常盤台2-16-1

When a metamaterial includes plasmas inside its structure, its property varies significantly. If the metamaterial determines macroscopic permeability and the embedded plasmas yield tunable permittivity, we can expect dynamic media of negative refractive index via magnetic resonance in the metamaterial and high-density overdense states in the plasmas. Furthermore, its tunability leads to nonlinearlity which is enhanced by inherent features in plasmas, leading to a nonlinear metamaterial. Theoretical prediction and experimental results clarify their properties, which are quite unique and cannot be achieved by conventional metamaterials.

1. Introduction

For media of electromagnetic waves whose frequency ranges from microwaves to optical light, microstructures that have a much smaller size than the wavelength of the corresponding electromagnetic wave have been reported to show extraordinary properties that cannot be realized in bulk materials [1]. This topic has attracted much attenions during these 10-20 years in a concept of a “metamaterial,” [2,3] which can be a media of negative refractive index [4] and cloaking devices [5]; these two topics were so epoch-making, and verified in experiments [6].

When we insert plasmas into metamaterial structures, what can we expect? One simple and important point is to serve as negative-permittivity media. Since the refractive index is a product of square of permittivity and that of permeability, both of them should be negative to make the refractive index negative [7]. Plasmas easily show negative permittivity in overdense states in which the electron plasma frequency is higher than the wave frequency, the insertion of the plasmas is so effective to realize negative-refractive-index states. Furthermore, since this negative value of the permittivity is variable by changing electric power for plasma generation, we can expect dynamic negative refractive index in a plasma-metamaterial composite “plasma metamaterial” in which solid metamaterials are assumed to control permeability. Another novel point that cannot be realized in conventional solid metamaterials is nonlinearity; plasmas have been investigated as nonlinear materials for decades, and we can expect nonlinear metamaterials based on this heritage.

Here we overview our researches on plasma metamaterials [7], and report some recent results on achievements of negative refractive index with nonlinear effects [8].

2. Example of Plasma Metamaterials with Negative Refractive Index

So far we confirmed achievements of negative-refractive-index sates in microwave range in two different plasma metamaterial configurations. One of them was detected in phase shift measurement of transmitted microwaves through the plasma metamaterial in the array of double-helix metallic structures and microplasmas on a coplanar waveguide [9]. In this experiment, we also pointed out dynamic features of negative refractive index in plasma metamaterials.

Another was achieved in an array structure of double split ring resonators (DSRRs) embedded in a microwave-generated plasma [8,10,11], as shown in Fig. 1 [8]. First, we measured scattering (S) parameters of a DSRR array using a microwave network analyzer when plasmas were not generated. The parameter retrieval method [12] revealed that the macroscopic permeability was -5.8+2.8j at 2.45 GHz, whose real part was completely negative. Then, we injected the high-power (< 500 W) microwave at 2.45 GHz into the region of the DSRR installed in the rectangular waveguide at 100

Pa of Ar. Using a single Langmuir probe, we detected significantly high electron density (2-3x10^{11} cm^{-3}), which was well beyond the cutoff density in the waveguide (~ 5x10^{10} cm^{-3}), as shown in Fig. 1. The corresponding permittivity was ~ -2, leading to negative refractive index.

3. Nonlinear Properties

Since the electron density or the permittivity of plasmas is tunable by changing the generation power, plasma metamaterials are inherently reconfigurable. Furthermore, since time evolution of the permittivity or the local electron density depends on that in the past (as a kind of memory)

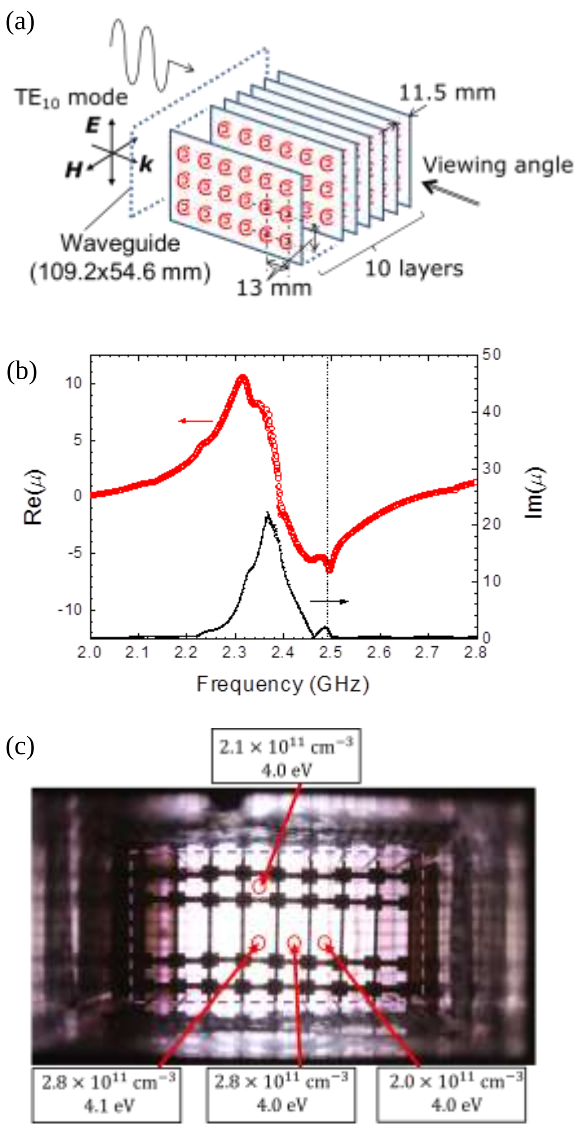

Fig.1. Experimental setup and results [8]. (a) Solid metamaterial structure for negative permeability, installed in rectangular waveguide. (b) Measured macroscopic permeability of solid metamaterial. (c) Emission of generated microwave (2.45 GHz) plasma embedded in metamaterial, and profiles of electron density and temperature monitored by single probe.

and that at other positions (nonlocal property), plasma metamaterials are nonlinear [8]. So far, as predicted theoretically, we observed saddle-node bifurcations of the permittivity in the plasma metamaterials [8], leading to transition of refractive index from imaginary to negative values. Another phenomenon we observed recently is second harmonic wave generation (SHG) at microwave frequencies, which can be optimized by controllable frequency dispersion.

4. Summary

Plasma metamaterials composed of negative-permittivity plasma and negative-permeability metamaterials are novel media for electromagnetic waves at microwave frequencies. We observed dynamic negative refractive index states, and nonlinear phenomena like bifurcations and SHG.

Acknowledgments

This work is supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, and by Strategic Information and Communications R&D Promotion Programme (SCOPE) from the Ministry of Internal Affairs and Communications, Japan.

References

[1] I. Awai: IEEE Microw. Mag. **9** (2008) 55.
[2] J. B. Pendry, A. J. Holden, D. J. Robbins and W. J. Stewart: IEEE Trans. Microw. Theory Techniq. **47** (1999) 2075.
[3] A. Sihvola (ed.), *Advances in Electromagnetics of Complex Media and Metamaterials* (Dordrecht, Kulwer Academic Publishers, 2002).
[4] J. B. Pendry: Phys. Rev. Lett. **85** (2000) 3966-3969.
[5] J. B. Pendry, D. Schurig, and D. R. Smith: Science **312** (2006) 1780.
[6] L. Solymar and E. Shamonina, *Waves in Metamaterials* (Oxford, Oxford University Press, 2009).
[7] O. Sakai and K. Tachibana: Plasma Sources Sci. Technol. **21** (2012) 013001.
[8] Y. Nakamura, A. Iwai and O. Sakai: "Nonlinear properties of negative-permittivity microwave plasmas embedded in metamaterial of macroscopic negative permeability," Plasma Sources Sci. Technol., **23** (2014) in press.
[9] O. Sakai, J. Maeda, T. Shimomura and K. Urabe: Phys. Plasmas **20** (2013) 073506.
[10] O. Sakai, S. Iio and Y. Nakamura: Plasma Fusion Res. **8** (2013) 1406167.
[11] Y. Nakamura and O. Sakai: Jpn. J. Appl. Phys. **53** (2014) 03DB04.
[12] D. R. Smith, S. Schultz, P. Markos, and C. M. Soukoulis: Phys. Rev. B **65** (2002) 195104.