Time-varying magnetic metamaterials

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The most typical metamaterials are those with a negative index of refraction and for invisible cloaks. These are referred to as space-varying metamaterials because the wavevectors of light are changed at the spatial boundary. Recently, a new paradigm for light generation and steering has emerged -- time-varying metamaterials, in which refractive indices are temporally modulated [1]. Time-varying metamaterials would bring about promising applications to frequency converters, nonreciprocal devices, and anti-reflection temporal coatings as well as exotic phenomena, for example, time refraction and reflection, analogue of continuous time crystal, and temporal aiming.

The temporal modulation of refractive indices has been achieved experimentally using time modulated electric permittivity (ε). However, time modulation of magnetic permeability (μ) is possible because μ is the counterpart of ε in the refractive index [2]. The space-time modulation of both ε and μ is essential for investigating Fresnel drag for light in optically moving media [3], spatio-temporal four-dimensional control of wave-matter interactions [4], quantum electrodynamics phenomena, and Doppler cloaks. In any case, the key is the realization of μ time-varying metamaterials. Nevertheless, experimental demonstration of μ time modulation is lacking.

In this invited talk, we introduce magnetic metamaterials including a ferromagnetic-metal (permalloy (Py), $Ni_{80}Fe_{20}$) layer together with microwave carrier and modulation lines for μ time-varying metamaterials. Ferromagnetic Py shows frequency dispersion of μ in the vicinity of ferromagnetic resonance (FMR) frequencies in the microwave region. A time-periodic Oersted magnetic field generated by microwaves through the modulation line alters the effective magnetic field for FMR temporally at GHz frequencies, realizing temporal modulation of μ. We observe frequency conversion of the carrier microwaves and verify that the conversion is caused by the temporal modulation of μ in the Py layer [5]. A magnetic counterpart of the EO modulator is realized at microwave frequencies.

The most striking feature of the μ time-varying metamaterials in this study is that the up-conversion efficiency is much larger than the down-conversion efficiency. The numerical calculation indicates that the significant up-conversion efficiency is traced back to nonlinear magnetization dynamics in the μ time-varying metamaterials [5]. This would be advantageous to study Floquet engineering of light-matter interaction [6,7].

We acknowledge T. Kodama, N. Kikuchi, T. Chiba, S. Ohno, S. Okamoto, and Y. Kanamori for valuable contributions. This work is financially supported by JST- CREST (JPMJCR2102).

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