In-situ generation of THz electromagnetic waves for studies of effective continuous properties of magnonic metamaterials

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Abstract

We propose a novel technique of metamaterials characterization at THz frequencies based on the use of combined structures consisting of nonlinear crystals and metamaterials. The femtosecond optical pulses induce transient pulses of either nonlinear polarization or nonlinear magnetization that emit THz waves as well as have their own near fields. Both of the latter can be used to probe metamaterials adjacent to nonlinear crystals. In particular, we study the possibility to employ the inverse Faraday effect as a mechanism to generate transient pulses of magnetic field at THz frequencies. The field can be coupled to spins in magnonic metamaterials.

1. Introduction

The study of magnonic metamaterials, represented by nano-structured naturally magnetic materials, is an emerging field in the physics of metamaterials. These materials gain their properties from the magnetic or spin wave resonances. Spin waves can have frequencies of hundreds GHz (in the exchange dominated regime) and have already been shown to play role in the high frequency magnetic response of composites containing magnetic inclusions. At the same time, magnetic hysteresis offers an efficient means of controlling and programming useful properties of metamaterials that contain magnetic constituents.

To study electromagnetic properties of magnonic metamaterials at THz frequencies one has to use THz electromagnetic pulses to excite spins. However, standard magnonic metamaterials usually exhibit relatively weak coupling to the THz light. It comes from the great mismatch between the wavelengths of the light and spin waves at the same frequency. Also, the magnetic effects are generally weaker than their electric counterparts. Recently, it was suggested that one could use the spin pinning at interfaces of thin magnetic films to provide “artificial” coupling between light and standing spin waves [1]. However, the experimental prove of the properties is still missing.

In this work we would like to propose a way of magnonic metamaterials characterization based on the use of near fields of transient electric and magnetic polarizations optically induced in nonlinear crystals [2]. Thus, we further develop ideas of Ref. [3] and Ref. [4]. In the Ref. 3 scheme for optically induced and photo-magnetic field assisted magnetization reversal on nanomagnetic elements was proposed. The key feature of the scheme was an employment of near field of the magnetic dipole induced in nonlinear crystal. In Ref. 4 authors proposed a scheme for experimental verification of the reversed Cherenkov effect. This scheme uses emission of terahertz waves by optical rectification of the femtosecond laser pulse propagating in a sandwich like structure with nonlinear core and left-handed cladding (i.e. made from a metamaterial).

Since we are interested in magnonic metamaterials characterization, we consider inverse Faraday Effect as a source of high magnetic field in THz frequency range. We experimentally show that this field can be in order of kOe.

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2. Results and discussion

We performed quantitative measurements of the strength of both the direct and inverse Faraday effects in Terbium Gallium Garnet (TGG) within the same pump-probe experiment. We studied the spatial profile of the magneto-optical signal representing the near field pattern inside the crystal. Indeed, the spatial profile of the magneto-optical signal is not simply the convolution between the pump and probe optical pulses. It follows the magnetic field generated by the optically induced nonlinear magnetization in its vicinity.

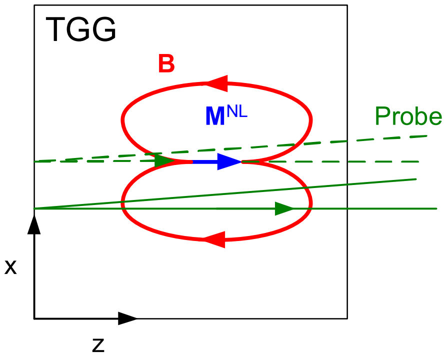

Fig. 1: Geometry of experiment (horizontal cross-section).

The measurements were performed on a 10×10×1 mm^3 single crystal of TGG, which was chosen due to its high Verdet constant at room temperature. The experimental geometry is schematically shown in Fig. 1. The Ti:Sapphire laser generated 800 nm pulses with duration of 100 femtoseconds at repetition rate of 1050 Hz. Each pulse was split into two parts – a pump pulse (90 % of power) and a probe pulse (10 % of power). The helicity of the pump pulse was controlled by a quarter wave plate. The pump and probe beams illuminated the sample from the opposite sides with a minor deviation from the normal incidence. The pump pulse is focused to a vertical line using a cylindrical lens. The nonlinear magnetization associated with the pulse produces the magnetic field in the surrounding space. A beam profiler was used to carefully measure the width of the close to parallel pump beam at the sample position to be about 50 μm at half maximum. The probe spot was somewhat smaller than 100 μm in diameter. The part of the probe pulse reflected from the rare surface of the sample was directed into a balanced optical bridge detector to measure the polarization rotation acquired in the sample. When the pump and probe pulses inside the TGG crystal were overlapped in time and space, the pump induced nonlinear magnetization rotated the probe polarization. Changing the time delay between the pump and the probe, we recorded the time evolution of the polarization signal, given by the convolution of the induced magnetization and the probe pulse. Changing the relative transverse position of the pump line and the probe beam we traced the transverse distribution of the Faraday signal. Relative position of the pump line and the probe beam determines which point of the field pattern is measured.

Fig. 2 shows the transverse distribution of the Faraday signal for the pump focused to a line by the lens with 10 cm focal length. The signal is not Gaussian-like and have negative lobes at both sides. From the Fig. 2 one can easily see that the probe beam suffers the polarization rotation even when there is no overlap between the probe spot and the pump line. It is clear that the form of the signal cannot be explained in terms of convolution between the probe pulse (Gaussian) with neither effective field nor nonlinear magnetization since both just follow the profile of the pump intensity (Gaussian). However, the result is explicable if we assume that the convolution between the magnetic field generated by the nonlinear magnetization and the probe pulse profile was traced. We found exact solution of Maxwell equations with the given source – nonlinear magnetization with Gaussian transverse profile and Gaussian time envelope. Since the pump line is very long compared with the wavelengths of interest (in order of 100 μm) we considered two dimensional problem with the infinite line of nonlinear magnetization. Our theoretical model accounts all essential factors such as finite width of the laser beam, nonlinear magnetization motion, and the presence of the crystal boundaries. We calculated the magnetic field using parameters representing experimental situation. On the Fig. 2 the curve resulting from the convolution between the calculated near field transverse profile and Gaussian profile of the probe pulse is shown as a red line. One can see a good agreement with experimental data.

The amplitude of magnetic field inferred from the Faraday signal was estimated to be about 1500 Gauss. The field could be used to study the effectively continuous properties of magnonic metamaterials formed in the vicinity of the illuminated part of the nonlinear crystal (e.g. TGG as here) in the THz range. Importantly, the (presumably metallic) magnonic metamaterial would not be directly illuminated by the infrared optical pulse, and hence it would experience any direct thermal effects due to the optical pulse.

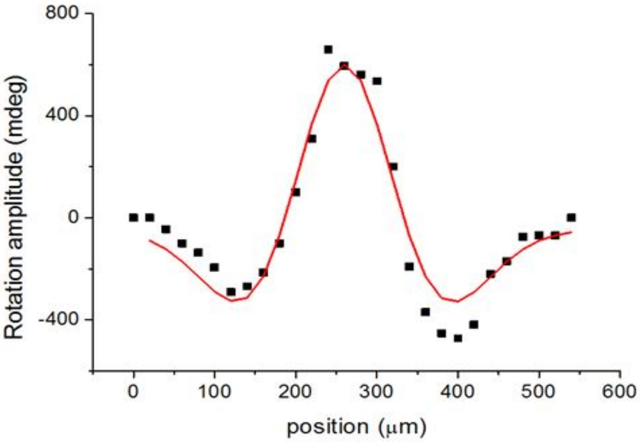

Fig. 2: Transverse profile of the Faraday signal – experimental points and theoretical curve.

3. Conclusion

To conclude, we presented experimental verification of in-situ generation of THz electromagnetic waves in TGG crystal. There is an excellent outlook for implementation of the observed high magnetic fields the area of magnonic metamaterials.

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