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Magnetic field-controlled femtosecond pulse shaping by magnetoplasmonic crystals

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Femtosecond-scale magnetic field-controlled shaping of 200 fs laser pulses reflected from a one-dimensional magnetoplasmonic crystal is experimentally demonstrated. Magnetic field-induced modification of the pulse shape is revealed by measuring the second-order intensity correlation function (CF) of femtosecond pulses reflected from the sample. The sign of the magnetic contribution to the CF is reversed within the pulse. Such temporal shaping of the pulses is attributed to modification of the Fano-type surface plasmon spectral response function under magnetization of the sample in the Voigt configuration. © *2013 AIP Publishing LLC* [http://dx.doi.org/10.1063/1.4801640]

I. INTRODUCTION

Surface plasmon-polaritons (SPPs) are quasi-planar electromagnetic waves coupled to free-electron plasma, which can be excited at the boundary between metal and dielectric. These waves are believed to be the candidate for everyday-use information units as opposed to diffraction-limited photons and bandwidth-limited electrons.[1] However, for plasmon-based technologies to be realized, efficient techniques for active manipulation of SPP signals are required. Considerable effort was afforded to actively control plasmonic devices by external DC electric field,[2,3] AC electromagnetic field,[4–6] and DC magnetic field.[7–12] The latter works describe how CW light beams interacting with a magnetic plasmonic medium are affected by magnetization.

On the other hand, one of the most prominent opportunities of using SPP nanostructures is to shape femtosecond laser pulses. The mean lifetime of SPPs in nanostructures varies from several femtoseconds to several hundreds of femtoseconds. A femtosecond laser pulse interacting with such a short-living excitation gets coherently modified as indicated in many preceding works. Temporal shaping of femtosecond laser pulses by plasmonic nanostructures was observed both for the intensity[13,14] and polarization state.[15] However, the active control of the laser pulse shaping effect with plasmonic nanostructures has not been demonstrated yet.

In this work, we experimentally demonstrate the magnetic field-controlled shaping of femtosecond laser pulses reflected from a one-dimensional (1D) magnetoplasmonic crystal, which is a nickel diffraction grating supporting the SPP excitation via the ± 1st diffraction orders. External magnetization of the magnetoplasmonic crystal induces temporal modulation of 200 fs laser pulses when the SPP resonance is tuned across the spectral range of the femtosecond pulse being used. The switching of the pulse shape is attributed to modification of the surface magnetoplasmon dispersion law under magnetization applied in the Voigt configuration with respect to the SPP wavevector.

II. THEORY

The wavevector of surface plasmon-polariton propagating along the boundary between dielectric and metallic media with permittivities of ε_0 and ε_1, respectively, is written as

$$k_{\mathrm{SPP}} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_0}{\varepsilon_1+\varepsilon_0}}, \tag{1}$$

where ω is the light frequency and c is the light speed. Consider the Voigt configuration when external magnetic field is oriented along the boundary perpendicular to the SPP wavevector. Magnetization of the metallic film brings about non-diagonal components of ε_1 tensor, which influences the value of wavevectors of surface magnetoplasmons propagating in opposite directions in the plane of incidence

$$\Delta k^{\pm}_{\mathrm{SPP}} = \pm k_{\mathrm{SPP}}\frac{g\varepsilon_0}{\sqrt{-\varepsilon_0\varepsilon_1}(\varepsilon_1^2-\varepsilon_0^2)}, \tag{2}$$

where g is the magnitude of the gyration vector. This fact is revealed as a pronounced feature in the transverse magneto-optical Kerr effect (TKE) spectrum obtained in specular reflection from magnetoplasmonic crystals from which the magnetic field-induced shift of the central SPP resonance wavelength is estimated to be $\Delta\lambda \approx 0.4$ nm.

Reflection spectrum of the 1D magnetoplasmonic crystal can be described by the Fano resonance model[16]

$$R(\omega) = C_0 + \frac{f\Gamma e^{i\phi}}{\omega-\omega_0(H)+i\Gamma}, \tag{3}$$

where $\omega_0(H)$ is the magnetic filed-dependent central frequency of the SPP resonance, C_0 is the non-resonant contribution rising due to specularly reflected light, f and ϕ are the strength and relative phase of the oscillator, and Γ is the

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damping constant. The decay time of the SPP is defined as $\tau_{SPP} = 1/\Gamma$.

If a Gaussian pulse with amplitude $E_G(t)$ is reflected from a magnetoplasmonic crystal with a Fano-type reflection spectrum $R(\omega)$, its evolution upon reflection $E(t,H)$ is described as follows:[14]

$$E(t,H) = \int_{-\infty}^{+\infty} E_G(t') \times \left(f\Gamma e^{i\phi-(i\omega_0(H)+\Gamma)(t-t')} h(t-t') + C_0\delta(t-t') \right) dt', \quad (4)$$

where $h(t)$ is the Heaviside step function and $\delta(t)$ is the Dirac delta function. The pulse envelope (4) is governed by SPP resonance parameters. In numerical calculations, SPP lifetime of $\tau_{SPP} = 30$ fs and resonance wavelength of $\lambda_0 = 1.54\,\mu$m are used. The Fano resonance parameters are picked to be $\phi = -0.3\pi$, $C_0 = 0.7$, and $f = 0.3$; under these conditions, the reflection spectrum shown in Fig. 1(a) takes the form of a dip indicating the energy flux redistribution into SPP propagating along the magnetoplasmonic crystal surface. Laser pulse shaping upon reflection from the magnetoplasmonic crystal is modeled for pulse duration $t_0 = 200$ fs and carrier wavelength $\lambda = 1.56\,\mu$m describing a realistic experimental situation. Normalized intensity $I(t,0) = |E(t,0)|^2$ of a pulse reflected from the non-magnetized magnetoplasmonic crystal is shown in Fig. 1(b). As the magnetic field is applied, the SPP resonance is shifted by $\Delta\lambda \approx 0.4$ nm and the electric field $E(t, H)$ is modified. The intensity difference $\Delta I(t) = |E(t,0)|^2 - |E(t,H)|^2$ shown in Fig. 1(b) represents the plasmon-induced femtosecond pulse switching under magnetization.

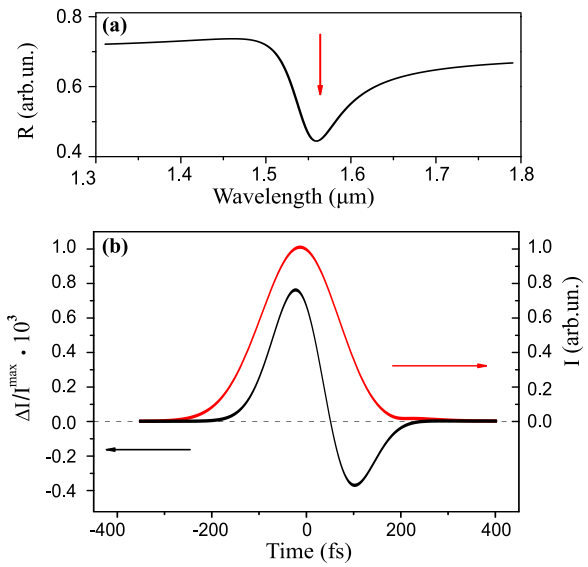

FIG. 1. (a) Calculated reflection coefficient spectra of magnetoplasmonic crystal with an asymmetric Fano resonance lineshape. Arrow indicates the central wavelength $\lambda = 1.56\,\mu$m of a Gaussian laser pulse used in numerical calculations. (b) Red curve stands for calculated normalized intensity $I(t, 0)$ of the pulse reflected from an unmagnetized magnetoplasmonic crystal. Black curve stands for calculated magnetic field-induced difference in the shape of a femtosecond laser pulse $\Delta I(t)$ normalized to the maximal value of $I(t, 0)$.

III. EXPERIMENTAL RESULTS

Samples of magnetoplasmonic crystals were nickel 1D gratings with a period of 1.5 μm fabricated by nanoimprint lithography and metal thermal evaporation. Reflection spectra of the sample measured for the p-polarized light near normal incidence are shown in Fig. 2(a). Plasmonic band gap is seen at $\lambda \approx 1.53\,\mu$m, two parabolic-like stripes visualize two plasmonic branches in magnetoplasmonic band structure. For time-resolved measurements, the angle incidence $\theta \approx 2^\circ$ was chosen. The cross-section of reflection spectra for this angle of incidence shown in Fig. 2(b) has two dips indicating the spectral region of SPP phase-matching involving -1st and $+1$st diffraction orders.

Plasmon-induced pulse shape switching under magnetization was observed by using a second-order intensity

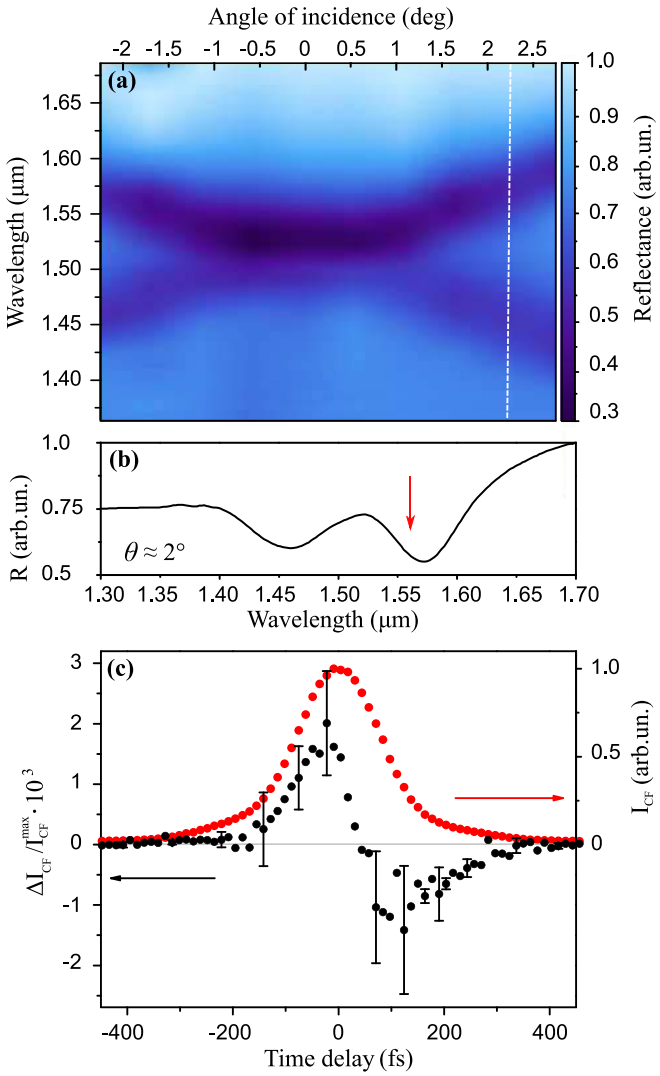

FIG. 2. (a) Reflection coefficient of the magnetoplasmonic crystal sample measured as a function of wavelength λ and angle of incidence θ for the p-polarized incident light. (b) Reflection spectra for $\theta \approx 2^\circ$. Arrow indicates the central wavelength $\lambda \approx 1.56\,\mu$m of the laser pulse used in time-resolved measurements. (c) Red circles denote the measured normalized correlation function I_{CF} for the p-polarized incident laser pulse with duration $t_0 \approx 200$ fs reflected from magnetoplasmonic crystal. Black circles denote the correlation function measured at the frequency of external magnetic field, $\Delta I_{CF}(t)$, normalized to the maximal value of I_{CF}.

correlation measurement setup based on a 130 mW Er^{3+} fiber laser generating 200 fs pulses, for details see Ref. 14. The laser intensity was small enough to neglect nonlinear processes such as laser-induced demagnetization in nickel. The laser beam was split into a signal channel, where the pulse was modified by the sample and a reference channel with an optical delay line. Both beams were co-focused at a nonlinear BBO crystal, where the noncollinear second harmonic was generated.

To determine the surface plasmon impact on the femtosecond pulse shape, the second-order correlation function (CF) $I_{CF}(\tau)$ was measured, τ is the time delay between the laser pulses: one coming from the sample with the envelope $I(t, 0)$ and another one being the reference pulse with the envelope $I_G(t)$

$$I_{CF}(\tau) = \int_{-\infty}^{+\infty} I_G(\tau - t')I(t', 0)dt'. \quad (5)$$

The correlation function $I_{CF}(\tau)$ measured for the *p*-polarized light is shown in Fig. 2(c). No visible difference from the autocorrelation function of the laser was detected since the SPP lifetime in nickel is significantly smaller than the laser pulse duration.

To impose magnetic field-controlled femtosecond pulse shaping, magnetic field of the strength up to 300 Oe was applied to the sample perpendicularly to the plane of incidence, corresponding to TKE configuration for specularly reflected light and to the Voigt configuration for SPP propagation. The photodetector signal locked-in to the frequency of the external magnetic field of 115 Hz represented the changes in the correlation function brought by magnetization of the sample

$$\Delta I_{CF}(\tau) = \int_{-\infty}^{+\infty} I_G(\tau - t')\Delta I(t')dt'. \quad (6)$$

An experimental dependence $\Delta I_{CF}(\tau)$ is shown in Fig. 2(c). The sign of the difference (6) reverses within pulse duration. $\Delta I_{CF}(\tau)$ is positive with the maximum at −50 fs within the interval from −200 fs to 20 fs, and negative between 20 fs and 300 fs with the minimum at 100 fs and the amplitude smaller than in the positive part. This behavior of CF is similar to the numerical calculations shown in Fig. 1(b). Temporal shaping of the femtosecond pulse measured at the frequency of the external magnetic field is attributed to modification of the surface plasmon spectral response function under magnetization. The resonance wavelength shift leads to the fs-scale shaping of the pulses reflected from the sample, $\Delta I(t)$, which results in the correlation function modification $\Delta I_{CF}(\tau)$. Plasmon-induced dynamics of the transversal Kerr can be obtained by dividing $\Delta I_{CF}(\tau)$ by the correlation function $I_{CF}(\tau)$ measured without magnetic field.

In the experiment, pulse shape switching does not exceed 2×10^{-3}, and there are several ways to its increase. One option is the SPP resonance shape control. At the slopes of the Fano resonance, only positive or negative difference $\Delta I(t)$ can be detected with absolute values approximately three times greater than ones measured. Second, other metals, such as iron or cobalt, and sample design alternatives[17–19] may be useful to consider.

To conclude, ultrafast magnetic field-controlled shaping of femtosecond laser pulses reflected from magnetoplasmonic crystal is experimentally demonstrated. SPP-induced temporal modulation of femtosecond laser pulses, which depends on the external magnetization of nickel magnetoplasmonic crystal is detected. The modification of the surface plasmon spectral response function under magnetization leads to switching of the femtosecond pulse shape reflected from the magnetoplasmonic crystal.

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