

Sub-picosecond polarization conversion with plasmonic crystals

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Abstract

Ultrafast polarization state alteration is observed in optical response of a plasmonic nanograting by means of sub-picosecond time-resolved polarimetry. Simultaneous measurement of Stokes parameters as a function of time with a time-gate of 130 fs reveals a significant conversion of polarization state in a single pulse when the incident polarization is oriented at 45° to the sample's optical axis. The effect is attributed to the excitation of the long-living surface plasmon-polaritons under the plasmonic bandgap condition.

1. Introduction

Polarization properties of the surface plasmon (SPP)-active media are studied for a long time [1, 2]. High coupling of CW radiation to the SPP modes under the phase-matching conditions allows one to use plasmonic nanostructures as polarizers [3], waveplates [4] as well as handedness-sensitive chiral media [5] of submicron thickness. In this paper we use surface plasmons to induce a remarkable state of polarization (SoP) alteration inside a single sub-picosecond telecom laser pulse reflected from a plasmonic nanograting. Time-resolved femtosecond-resolution full Stokes parameters measurement demonstrates the variation of the SoP from the horizontal one to the vertical one along with the non-coherent mixing of horizontally and vertically polarizations in between.

2. Results

The samples of plasmonic nanogratings were fabricated by thermal sputtering of 50-nm gold layer onto a polymer diffraction grating with the period of $1.6 \mu\text{m}$ made by means of nanoimprint lithography. The period of the structure was chosen to match the SP resonances to the central wavelength of $\lambda = 1.56 \mu\text{m}$ of the femtosecond laser source. The reflection spectra of the sample under different angles of incidence reveal the minima associated with the band structure of SPs coupled onto the surface of the film via the 1st and -1 st diffraction orders. The plasmonic bandgap is seen at the intersection between the plasmonic modes. The bandgap width is $\Delta\lambda = 67 \text{ nm}$, $\Delta\lambda/\lambda \simeq 0.04$ which is comparable with previous results on linear spectroscopy of plasmonic crystals.

The CW polarization properties of the plasmonic crystal under study were measured using the spectrally-resolved ellipsometry setup based on a photoelastic modulator. The ellipsometric measurements provide two quantities: $\rho(\lambda)$ and $\varphi(\lambda)$. Here, $\rho(\lambda)$ stands for the ratio between the field reflection coefficients of p-polarized and s-polarized light or linear dichroism; $\varphi(\lambda)$ is the phase delay introduced into one of these states or linear birefringence. The dichroism spectrum $\rho(\lambda)$ demonstrates two minima corresponding to

the reflection minima at the bandgap edges. The birefringence spectrum $\varphi(\lambda)$ experiences a jump from 0 to 1.8π at the long-wave edge of the bandgap while the short-wave edge provides only 0.2π deviation which is a direct consequence of the coupling between the plasmonic modes.

To determine the plasmonic impact on the femtosecond pulse shape time-resolved response of the plasmonic crystal in s- and p-polarized light was studied. A Er^{3+} -doped fiber laser produced a 130 fs pulse train at a telecom wavelength of $\lambda = 1.56 \mu\text{m}$. The beam was split into two channels one being a signal channel with the sample in it and the second being the reference channel with a delay line. Beams of the channels were co-focused onto a BBO crystal under different angles where the non-collinear second harmonic was generated. The non-collinear geometry was chosen to get rid of the collinear second harmonic and to observe low intensities at the pulse tails. Correlation functions (CFs) were measured by varying the time delay between pulses in two channels. The results of the CF measurements for p- and s-polarized incident SoP shown in Fig. 1 demonstrate a considerable alteration of the femtosecond pulse shape by the SPs. A delay of about 150 fs is seen between the CFs measured for orthogonal input SoPs which is a previously attained result [6].

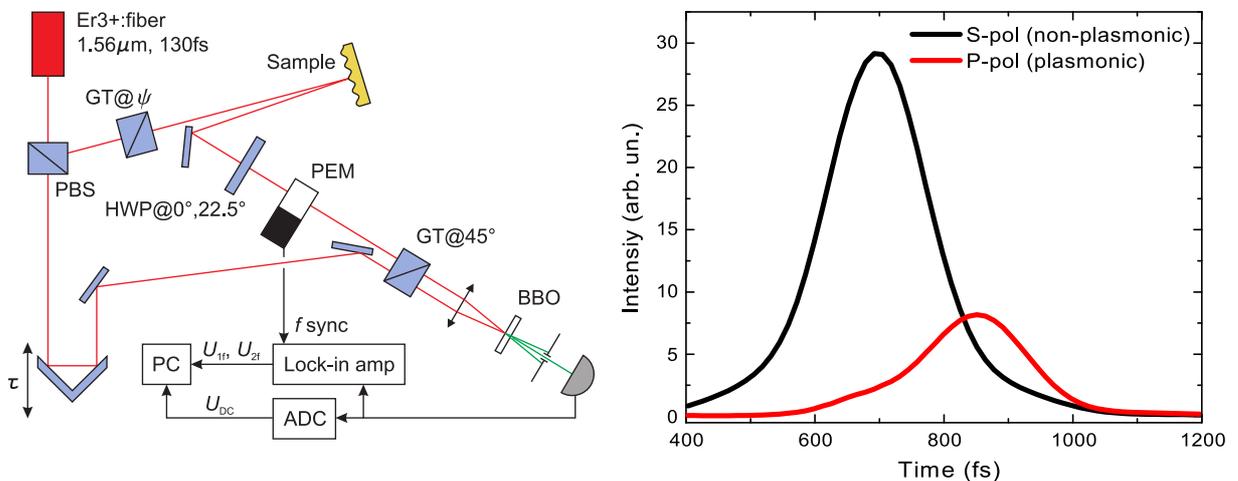


Fig. 1: Left: experimental setup for time-resolved Stokes parameters measurement. PBS – polarizing beam splitter, $\text{GT}@\psi$ – Glan-Taylor polarizer oriented at an angle ψ with respect to the Oy axis, HWP – half-wave plate, PEM – photoelastic modulator, $\text{GT}@45^\circ$ – Glan-Taylor polarizer oriented at an angle of 45° with respect to the Oy axis. Right: intensity correlation functions measured for p- and s- polarized incident SoP depicted in red and black lines, respectively.

Symmetry considerations lead $|H\rangle$ and $|V\rangle$ to be the eigenstates of the system under study. The SoP of the incident $|H\rangle$ or $|V\rangle$ femtosecond laser pulse retains all along the pulse as it will be shown below. However, if one sends a linear combination of these states onto a plasmonic crystal the evolution of the SoP inside a single pulse becomes complicated. To experimentally observe the temporal SoP conversion, a time-resolved Stokes parameter measurement setup was built. The sketch of the setup is provided in Fig. 1. The input SoP is prepared by a Glan-Taylor prism. The beam of the signal channel is transformed by a half-wave plate (HWP), a PEM and analyzed by a Glan-Taylor prism. The pulse after the analyzer contains the temporal distribution of a particular Stokes' vector coordinate at different harmonics of the PEM operating frequency. The pulse containing the information about the Stokes vector components is gated with the reference pulse and detected. Measured CFs provide the 130 fs-averaged temporal distribution of the Stokes parameters. This technique allows one to measure the evolution of all the Stokes vector components of the beam reflected from the sample in two delay line scans.

Fig. 2 shows the evolution of the polarization of light pulse reflected from the sample for different input linearly polarized SoPs oriented at an angle ψ with respect to the Oy axis. For $\psi = 0^\circ$ the SoP is

a linearly polarized $|V\rangle$ state for any moment of time within the uncertainty of the method which is equal to 0.1 on the scale of Stokes parameters. If $\psi = 45^\circ$ the beginning and the end of the pulse are polarized vertically and horizontally, respectively. It is seen that the degree of polarization defined as $D = \sqrt{Q^2 + U^2 + V^2}$ is less than unity around time delays of 750 fs in the right panel of Fig. 2. This means that the SoP consists of a non-coherent sum of two pulses shown in Fig. 1. To our knowledge, this is the first observation of the time-resolved depolarization of light reflected from a plasmon-active media.

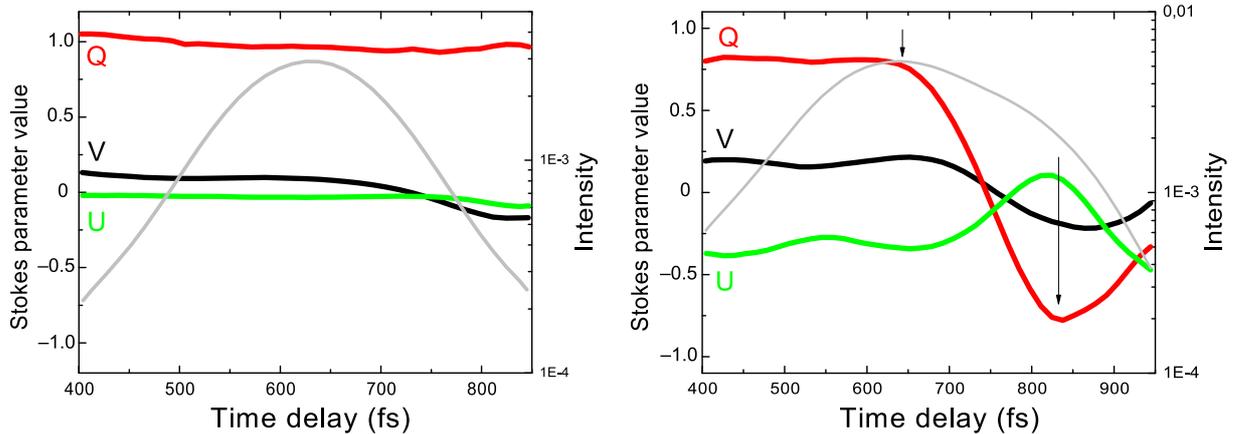


Fig. 2: The evolution of the stokes parameters inside a single femtosecond pulse. Left: the incident light is vertically polarized. Right: the incident light is diagonally polarized. Grey curves indicate the intensity profile of the pulse in the log scale.

4. Conclusion

In conclusion, sub-picosecond polarization conversion is experimentally found in the ultrafast optical response from a plasmonic grating under plasmonic bandgap made excitation condition. The time-resolved Stokes parameters measurement revealed complicated behavior of the polarization inside a single pulse including switching from the vertically polarized state to the horizontally polarized state as well as time-dependent depolarization.

References

- [1] G. P. Bryan-Brown et al., Polarisation conversion through the excitation of surface plasmons on a metallic grating, *Journal of Modern Optics*, vol. 37, p. 1227, 1990.
- [2] R. Gordon et al., Strong polarization in the optical transmission through elliptical nanohole arrays *Physical Review Letters*, vol. 92, p. 037401, 2004.
- [3] N. Yu et al., Semiconductor lasers with integrated plasmonic polarizers, *Applied Physics Letters*, vol. 94, p. 151101, 2009.
- [4] M. R. Shcherbakov et al., Full Poincaré sphere coverage with plasmonic nanoslit metamaterials at Fano resonance, *Physical Review B*, vol. 82, p. 193402, 2010.
- [5] A. Drezet et al., Miniature plasmonic wave plates, *Physical Review Letters*, vol. 101, p. 043902, 2008.
- [6] P. P. Vabishchevich et al., Femtosecond Relaxation Dynamics of Surface PlasmonPolaritons in the Vicinity of Fano-Type Resonance, *JETP Letters*, vol. 92, p. 575, 2010.