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Coherent Polarization Spectroscopy of Metamaterials

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***Abstract* – We demonstrate control of light polarization with light, without nonlinearity. The manifestation of optical activity in a metasurface is dynamically controlled using the coherent interaction of light waves on the nanostructure to enhance and suppress the light-matter interaction. This enables ultrafast polarization modulation and highly sensitive detection of optical activity.**

I. INTRODUCTION

Control of light with light is at the heart of optical information processing. Here we demonstrate for the first time optical control of the polarization of light with light without nonlinearity through the exploitation of coherent interactions between light waves on optically active metasurfaces. This polarization effect is ultrafast, compatible with arbitrarily low intensities and opens new opportunities for established polarization spectroscopy and sensing techniques.

Interference between coherent electromagnetic waves forms a standing wave pattern of nodes and anti-nodes in space. A functional medium of sub-wavelength thickness, such as a planar photonic metasurface, may be placed at a node or anti-node of the standing wave pattern, respectively resulting in suppressed or enhanced light-matter interactions and the associated expression of the metasurface's effect on the incident waves. Recently, it has been shown that this coherent control paradigm allows for high-contrast modulation of absorption in ultra-thin films [1, 2], manipulation of the coupling efficiency to extraordinary diffraction orders from phase-gradient metasurfaces [3], and selective electric/magnetic excitation in spectroscopic analyses of thin film media [4]. Here we study coherently-controlled polarization effects in a freestanding metasurface consisting of a gold film ~50 nm thick perforated with an array of asymmetrically split ring apertures with a period of 310 nm, see Fig. 1. The metasurface exhibits optical activity (circular birefringence and circular dichroism) at oblique incidence, i.e. when the experimental arrangement becomes different from its mirror image – an asymmetry known as extrinsic 3D chirality [5-6].

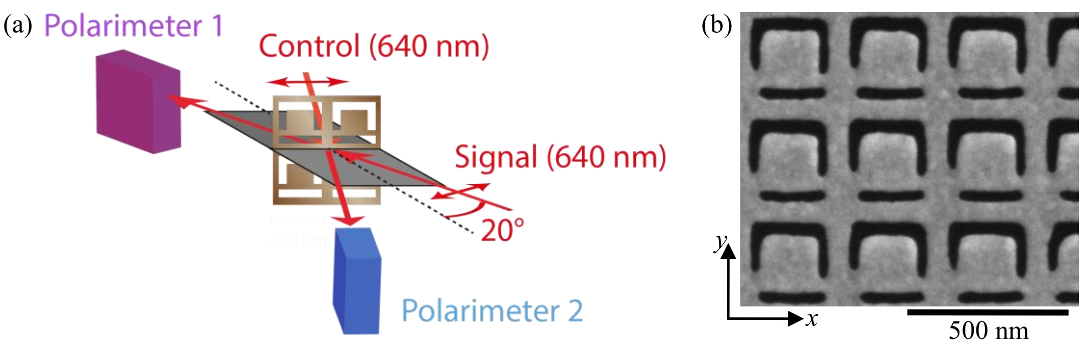

Fig.1 (a) Schematic of the extrinsically 3D-chiral experimental arrangement (not superimposable with its mirror image) for coherent polarization spectroscopy, comprising a metasurface and oblique incident beams. (b) SEM image of a section of the free-standing gold asymmetric split ring metasurface (310 nm unit cell size).

II. COHERENT CONTROL OF OPTICAL ACTIVITY

Coherent control of optical activity is demonstrated in the visible part of the spectrum via the interaction of coherent light waves on a metasurface in an extrinsically chiral experiment, illustrated schematically in Fig. 1. A CW laser beam at a wavelength of 640 nm is divided into two beams, which are referred to as "signal" and "control" beams. These are incident on opposite sides of the freestanding metasurface at an angle of 20° and co-polarized in the x-direction perpendicular to the metamaterial's symmetry axis, so any observed polarization change in the output beams must be due to optical activity. The sample position is finely controlled with a piezoelectric translation stage in order to modulate the phase of the control beam relative to that of the signal beam at the sample position. The output beams are monitored by an identical pair of polarimeters, which detect power, ellipticity angle and azimuth rotation of each beam simultaneously.

We observe that the polarizations of the output beams depend strongly on the relative phase of the incident beams. In Fig. 2(a), the total power in both output beams and the fraction of the output power that has been converted from *x* to *y*-polarization are plotted as functions of the relative phase of the input beams. In-phase excitation of the metasurface by the two input beams (multiples of 360° phase – the antinodes of the illuminating standing wave) enhances the light-matter interaction, leading to pronounced optical activity and coherent absorption, which are seen as maxima of *x*-to-*y* polarization conversion and minima of total output power, respectively. In contrast, out-of-phase excitation of the metasurface by the incident beams (±180° phase – nodes

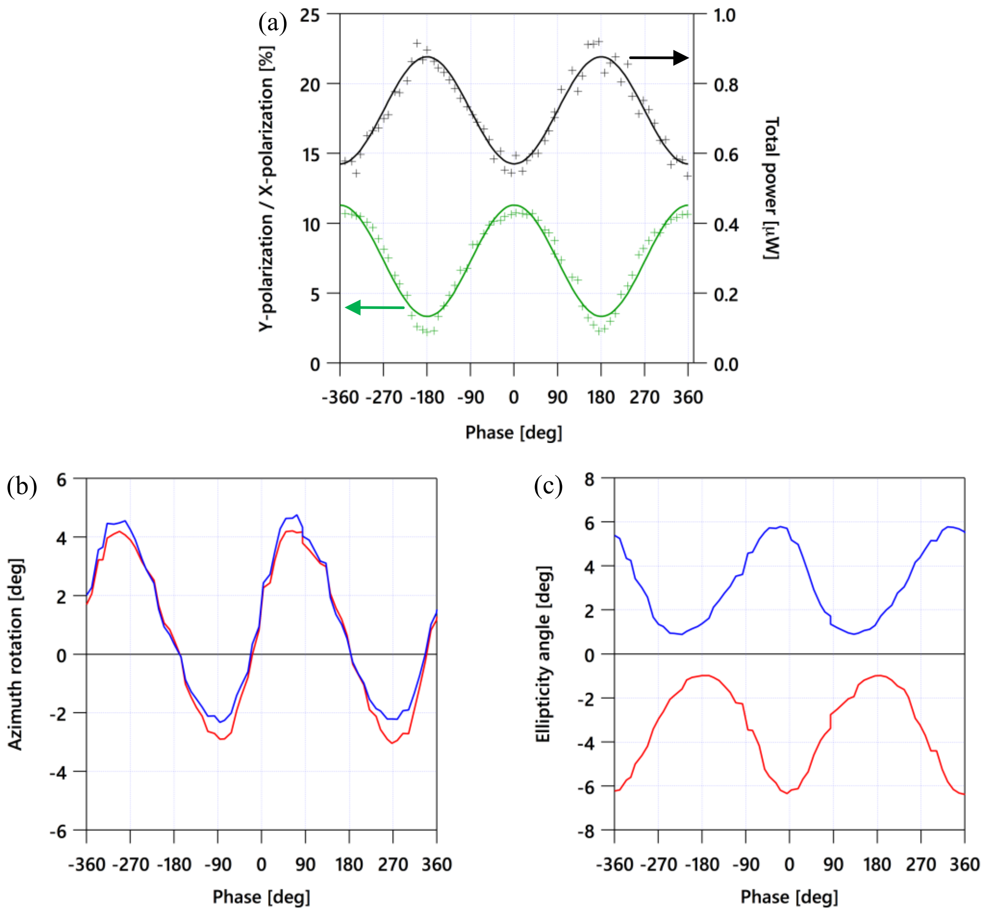

Fig. 2. Coherent control of light polarization with light. (a) Total (combined) power in both output beams (black) and percentage of linear polarization conversion (green) with sinusoidal fits. (b) Polarization azimuth rotation and (c) ellipticity angle of the output beams at polarimeters 1 (red) and 2 (blue) as functions of the phase difference between the input beams at the sample position.

of the standing wave) suppresses the light-matter interaction, i.e. produces minima of optical activity and thus polarization conversion and maxima of total output power.

Figs. 2(b) and (c) show the measured polarization change in terms of azimuth rotation and ellipticity angle of the output beams respectively, again as functions of the relative input phase. All polarization effects become small when the incident beams interfere destructively at the metasurface (±180° phase), while the ellipticity of the output beams is maximized for constructive interference of the incident waves (multiples of 360° phase). Furthermore, phase control allows both the complete suppression and sign reversal of polarization azimuth rotation.

VI. Conclusion

We demonstrate for the first time that the expression of metasurface optical activity can be controlled by the interaction of two coherent light waves on the metasurface. The coherent control paradigm can be implemented on ultrafast (femtosecond) timescales and at arbitrarily low (even single photon) power levels, making it a versatile solution for controlling the polarization of light with light in optical signal processing and spectroscopic applications. For example, coherent polarization modulation can enable highly sensitive detection of optical activity via measurements of ellipticity angle and azimuth rotation using a lock-in amplifier synchronized with the modulated phase difference between the input beams.

Acknowledgement

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