# Near-field polarization control with plasmonic metamaterials

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**Abstract**

Polarization properties of planar optical metamaterials are studied by means of far-field optical spectroscopy and near-field optical microscopy. It is shown that resonances of local and surface plasmon-polaritons along with specific symmetry of the structure give rise to enormous polarization conversion effects allowing one to cover the whole Poincare sphere with the output light polarization. Local field maps of linear and circular dichroism measured with near-field optical microscope (NSOM) and calculated using finite-difference time-domain (FDTD) method demonstrate strong polarization in the nanoscale regime which make polarization-sensitive metamaterials a notable candidate for subwavelength polarization control.

## 1. Introduction

The progress of contemporary nanolithography techniques allowed one to structure media on submicron scale. Varying the geometry of the structuring makes the media acquire different optical properties which are not specific to the host media. Among the most remarkable properties are magnetic response of nanostructures at optical frequencies and negative refraction [1], extraordinary optical transmission [2], light nanofocusing with nanostructured metallic films [3], artificial optical anisotropy [4] and chirality [5]. The latter two became possible with thin metallic films structured with patterns of certain types of asymmetry. Nevertheless the thicknesses of the films are much less than the wavelength of the visible light, these metamaterials are capable of competing with the conventional bulk polarization optics in specific linear birefringence and dichroism and chirality. In this work different types of anisotropic metamaterials are shown to manifest strong polarization in far field in the spectral vicinity of local and surface plasmon-polariton resonances using which an arbitrary polarization state could be achieved at the output of the metamaterial. Moreover, local-field analogues of the linear dichroism and circular dichroism effects are numerically and experimentally found in these metamaterials. High in-plane spatial variation of these effects indicates the key role of plasmons in establishing of the polarization-sensitive response of metamaterials.

## 2. Results

The samples of polarization-sensitive optical metamaterials were prepared using the electron beam lithography and ion beam lithography methods out of thin opaque noble metal films. Nanowire array, nanoslit array and elliptical nanohole array samples formed the anisotropic metamaterial sample group. All of the anisotropic samples demonstrated high optical anisotropy, e.g., input linearly polarized light could

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be transformed to almost arbitrary polarization state by varying samples principal axis orientation as a consequence of enormous specific birefringence and dichroism. The phase delay between the ordinary and extraordinary rays is changing from $0.35\pi$ to $0.85\pi$ over the narrow spectral range of 40 nm which is determined by the spectral width of the Fano-type surface plasmon-polariton resonance in the nanoslit array. The maximum specific value of the refraction index difference is reported to be $\Delta n \sim 10$.

A polarization modulation technique was applied to the near-field optical microscopy (NSOM) to obtain the local values of the linear dichroism effect. Two-dimensional map of the linear dichroism measured for the nanowire array sample in the local-plasmon resonance is presented in Fig. 1. The map displays the distribution of the ratio of the field transmission coefficients for the light polarized along and perpendicularly to the wires $\rho_{nf} = T_H/T_V$ . The image shows the inhomogenious distribution of the said effect with the maxima situated above the nanowires. The mean maximum value of the $\rho_{nf}$ equals $2.5 \pm 0.3$ which is approximately twice the corresponding far-field value $\rho_{ff} = 1.2$. This indicates the enhancement of the optical anisotropy with plasmon-active media on the local subwavelength level.

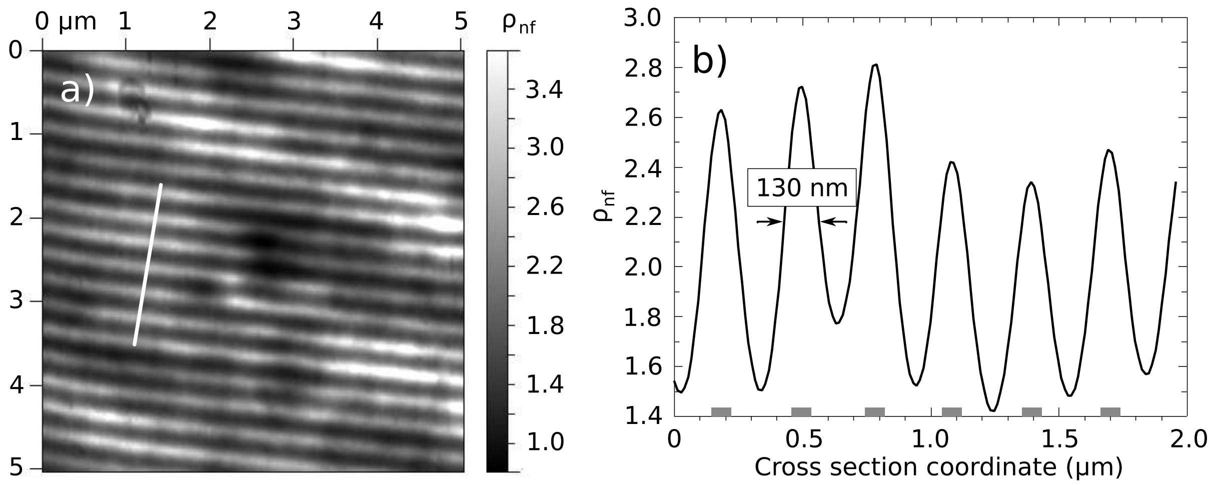


Fig. 1: a) The distribution of linear dichroism in the $\lambda/25$ vicinity of the sample. b) The cross-section of the map to the left. Grey rectangles denote the position of the nanowires.

Using the finite-difference time-domain simulations we show that achiral, i.e. having the mirror symmetry in its plane, ensemble of elliptical nanoholes with planar 3-fold rotational symmetry made in an opaque thin golden film exhibits mirror symmetry breaking in the near-field zone when illuminated with either right- or left-handed circularly polarized light. Fig. 2 shows the distribution of the electromagnetic field intensity collected at a fixed subwavelength distance from the film. The surface plasmon modes are seen to be launched in three directions away from the nanoholes position which is a consequence of interference between three point-like polarization-sensitive plasmon emitters. The phase between the emitted plasmons is controlled by the handedness of the impinging circularly polarized light. As a result, the direction of the plasmon propagation is handedness-sensitive in spite of the structure being handedness-insensitive in the zeroth transmission order. This makes a near-field circular polarization filter—a near-field probe placed in a particular place in the of the sample would detect light only if it is polarized with a certain way of handedness. The maximum local-field diattenuation between the right-hand circularly polarized (RCP) and the left-hand one (LCP) is estimated as high as 35 dB.

## 4. Conclusion

In conclusion, by means of far-field and near-field studies giant specific values of optical anisotropy are found in polarization-sensitive metamaterials. The polarization sensitivity arising from various high-Q

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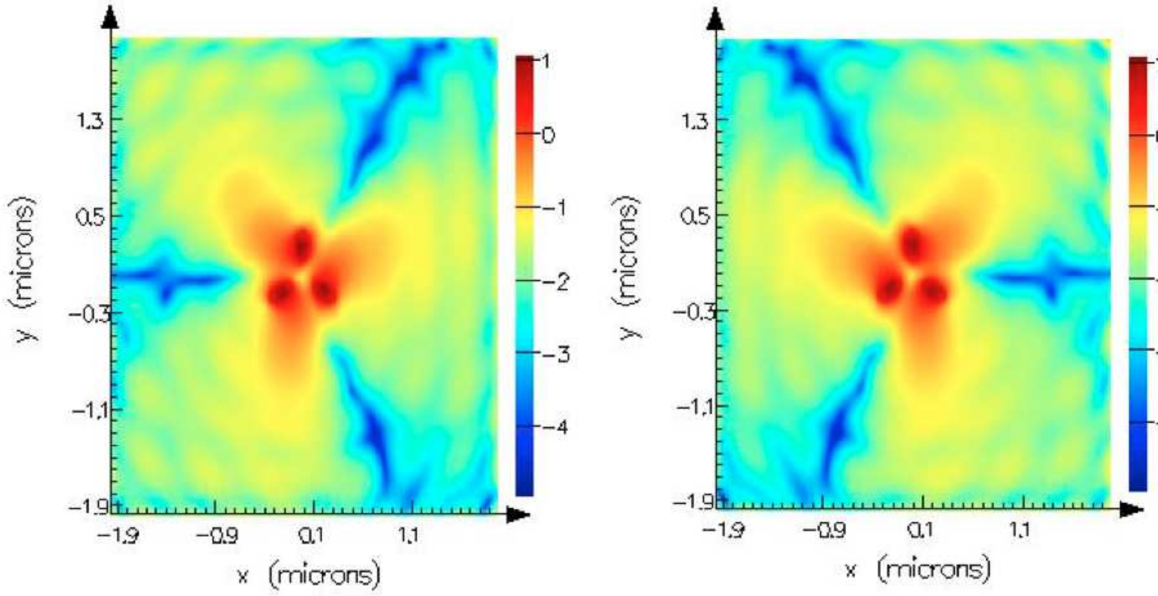


Fig. 2: The distribution of the electromagnetic field intensity near the surface of the 300 nm-thick golden film with three elliptic nanoholes illuminated with right-hand (left panel) and left-hand (right panel) circularly polarized light. The interference fringes occur due to the finite computational volume.

plasmonic modes also manifests itself in the optical near-field in the form of plasmon-enhanced diattenuation. A nanowire array exhibits two-fold enhancement of the local-plasmon-induced linear dichroism as viewed by the polarization-sensitive modification of the scanning near-field optical microscope with the $\lambda/8$ resolution. Rigorous calculation results reveal the near-field circular diattenuation of 35 dB from the geometrically achiral nanoellipse ensemble emerging from the interference of the propagating plasmon modes launched from individual nanoholes. The given data demonstrate that the polarization-sensitive metamaterials are capable of versatile polarization control independently of polarization basis both at macro- and nanoscales.

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