Plasmonic rack-and-pinion gear with chiral metasurface

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ABSTRACT

The effect of circularly polarized beaming excited by traveling surface plasmons, via chiral metasurface is experimentally studied. Here we show that the propagation direction of the plasmonic wave, evanescently excited on the thin gold film affects the handedness of the scattered beam polarization. Nanostructured metasurface leads to excitation of localized plasmonic modes whose relative spatial orientation induces overall spin-orbit interaction. This effect is analogical to the rack-and-pinion gear: the rotational motion into the linear motion converter. From the practical point of view, the observed effect can be utilized in integrated optical circuits for communication systems, cyber security and sensing.

Keywords: plasmonics, metasurface, chirality, nanostructure

1. INTRODUCTION

Metasurface can be regarded as a two-dimensional 2D realization of metamaterial, i.e. a periodic or quasi-periodic structure made out of especially arranged and accurately designed unit cells in a thin film [1, 2]. This quazi-periodic structure exhibits a collective behavior, fundamentally different, from the bulk material of the thin film [2, 3]. Such a structure can be realized on an optical device such as photonic waveguide [4], nurturing the waveguide with a novel functionality [5–7]. Specifically, while the guided mode is propagating within the bandgap of a given medium, one can design a special metasurface which locally perturbs the bandgap, providing a specific momentum matching with a certain mode. Therefore, an optical mode can be extracted from the waveguide or injected into the waveguide under certain conditions via the metasurface. Generally, the waveguide is a multiple bounce planar element in which discrete guided mode i propagates with the propagation constant β_i [5]. The light can be launched into the waveguide in different configurations such as: but-coupling with fiber [4], waveguide end-firing, prism coupling, grating coupling, tapering and more [8]. These techniques are suffering from the modal mismatch resulting in a low coupling efficiency. In addition, the listed above approaches lack versatility and dynamical switching. Here we utilize spatially varying, chiral, plasmonic metasurface in order to obtain a specific momentum matching between a waveguide mode, propagating in a given direction with a free space light with given handedness. In particular, right (left) circularly polarized scattered light corresponds to right wise (left wise) guided mode. The structure produces plasmonic spin-orbit interaction [9, 10] (SOI) that results in a transfer of a linear light momentum to a spin, analogically to the mechanical action of a rack and pinion gear (see Fig. 1).

Spin-orbit interaction is manifested by light propagation trajectory dependence on its polarization handedness [11]. Various optical phenomena based on the surface plasmon spin-orbit interaction were recently presented and several optical devices were proposed [12–14]. In general the concept of spin-orbit interaction stems from the generalized optical angular momentum conservation where its intrinsic part, an optical spin, is coupled to the extrinsic part which is an orbital angular momentum. In analogy with a spinning top, that exhibits a precession when tilted, a light beam that fails to conserve its intrinsic spin (polarization helicity) get tilted or twisted. Mathematically, this problem can be treated as a private case of an holonomy arising as a result of a local

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polarization state manipulation [15]. Recently, this effect was presented in order to directionally launch surface plasmons on a plasmonic surface [16]. Here, we propose the plasmonic metasurface, which couples a waveguide mode propagating inside a glass slab with a far-field radiation by using spin-orbit interaction. Accordingly, the light extracted by the metasurface carries a specific circular polarization that corresponds to the mode propagation direction. Although according to the classical definition of chirality by Lord Kelvin [17] our structure is not chiral neither in $3D$ nor in $2D$ sense, here we refer to the new definition of chirality given by Barron that accounts for the dynamics of the involved electromagnetic fields. *True chirality is exhibited by systems that exist in two distinct enantiomeric states that are interconverted by space inversion, but not by time reversal combined with any proper spatial rotation* [18]. Hereafter we discuss in detail the basic physical model as well as the experimental realization of the system.

2. PHYSICAL MODEL

Our proposed metasurface is a two-dimensional array of elongated rectangular subwavelength holes whose orientation angle varies along the x-axis as shown in the inset of Fig. 1. Let us define the local period of the metasurface as Λ_x and Λ_y and a total number of periods for obtaining one π rotation as N. Now, let us assume that an surface plasmon (SP) plane wave propagates through the metasurface with a wave-vector $\mathbf{k}_{SP} = (2\pi\lambda_{SP})\hat{\mathbf{x}}$. As long as each rectangular aperture is subwavelength, it behaves as a localized scattering defect and can be regarded as a short dipole antenna. For a dipole aligned in $\hat{\mathbf{y}}$ direction the radiation pattern of the electrical component is given by a well-known expression in spherical coordinates, $\mathbf{E}(\rho, \theta, \phi) \propto (ikd/4\pi\rho) \exp{(ik\rho)} \sin\theta\hat{\theta}$, where $k = 2\pi/\lambda_0$ is the radiation wavenumber. Close to the optical axis, i.e. at $(\theta \longrightarrow \pi, \phi \longrightarrow 0)$ the field is clearly linearly polarized at the direction of the dipole. When an array of identical rectangular apertures is considered to be excited by a plasmoic wave propagating in x direction the far-field radiation pattern can be evaluated by Huygens construction of the retarded dipolar sources, $E_m = E(\rho, \theta, \phi) \exp(ik_{SP} m \Lambda_x)$, where m is an integer index, $k_{SP} = k\sqrt{(\epsilon_r/(\epsilon_r + 1))}$ is the plasmonic wavenumber with ϵ_r as the real part of the dielectric index of bulk material of a thin film (here gold). When $k_{SP} = 2\pi\Lambda_x$, the retardation phase between the apertures is $2m\pi$ and the scattered field is a normally propagating linearly polarized plane wave.

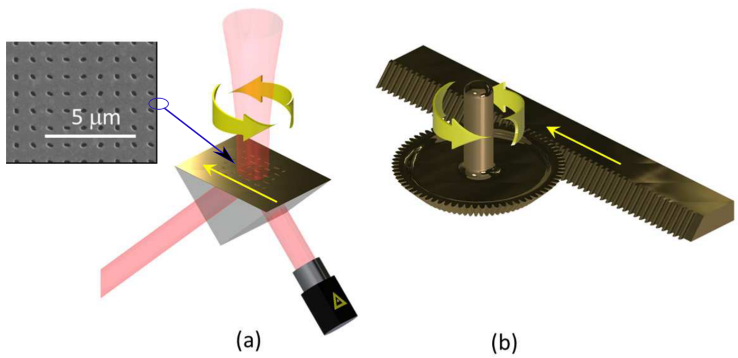

Figure 1. Conceptual scheme of the experiment and its mechanical analogy. (a) - Incident light is evanescently coupled to surface plasmonss via Kretschmann configuration while a metasurface is used to scatter light to the far-field with a desired circular polarization.Inset shows scanning electron microscope image of the metasurface.(b) - Mechanical Rack and Pinion gear.

When the rectangles are being constantly rotated along the x axis, the polarization in the vicinity of the metasurface is made to vary following their local orientation angles given by $\vartheta(x) = \pi x/(N\Lambda_x)$. In this situation it worth analyzing the system in a circular polarization basis, where right-handed and left-handed circular polarizations are given by $E_\pm = ((E_x \pm iE_y))/\sqrt{2}$, where (E_x, E_y) are the rectangular components of the scattered electric field, $E(\rho, \theta, \phi)$. In the paraxial regime, this local polarization rotation leads to a spin-dependent geometric phase of $\Phi_g = (\pm 2\pi x)/(\Lambda_x N)$ acquired by the respective polarizations [9, 13]. Using $k_x = (-\partial\Phi)/\partial x$ one can write the resultant momentum equation for surface plasmon wave propagating in x direction as:

$$k_{SP} - \frac{2\pi}{\Lambda_x} \pm \frac{2\pi}{\Lambda_x N} = k_0 \quad (1)$$

By demanding normal propagation of the scattered field we obtain the corrected condition for the rotated aperture array period as,

$$\Lambda_x^{\pm} = \frac{2\pi}{k_{SP}}(1 \mp \frac{1}{N}) \quad (2)$$

Again, the $\pm$ index corresponds to the desired circular polarization handedness of the scattered light. In particular, when a plasmonic wave is propagating in a positive x direction a metasurface with Λ_x^+ will excite the right-handed circular polarization (E_+) while back propagating surface plasmon wave will excite the left-handed circular polarization (E_-). When a metasurface with Λ_x^- is chosen the situation is reversed and rightwise propagating surface plasmon will excite left-handed circular polarization and vice-versa. Note, that for all the experiments the priodicity of the structure in y direction is kept constant, $\Lambda_y = 2\pi/k_{SP}$.

3. FABRICATION

To demonstrate the concept, discussed above, we designed and fabricated a chiral metasurface in a thin gold film. Cover slip borosilicate glass was solvent cleaned in the ultrasonic bath and blow dried. A 80 nm thick gold layer was thermally evaporated on 0.16 mm thick glass cover slip. Nanopattern was fabricated by focused ion beam milling using Strata 400 STEM DualBeam system . The resulting structure comprised of 18 by 18 periods of rectangular apertures 200 nm by 100 nm in size. The apertures orientation was varied along x direction so that the inclination of its long axis was changed in 6 steps ($N = 6$) between 0 to π. In total each aperture was rotated by 3π along x axis, while in the y direction the orientation of all the apertures was identical (see Fig.1).

4. EXPERIMENTS AND DISCUSSION

The fabricated sample was placed on the basis of the bk7 prism using index-matching oil. The prism was illuminated by pre-collimated horizontally polarized laser beam at $\lambda = 785$ nm , with a waist of 2 mm. The incident light was total internally reflected from the prism, where the sample with metasurface was mounted and evanescently exited surface plasmons propagating through the structure. Propagating plasmons were then scattered by the metasurface to the far-field and were collected by means of a 10X microscope objective towards an imaging system comprising of a tube lens ($f_1 = 100mm$) Fourier lens ($f_2 = 100mm$) and an imaging lens ($f_3 = 150mm$) and finally imaged by an industrial camera (Pixelink PL-B771U). We filtered out the circular polarization by introducing a quarter wave plate (QWP) followed by a linear polarizer (LP) in the image plane as shown in Fig. 2a.

Fig. 2 b,c illustrate the measurement results for two metasurfaces having periods of 760 nm and 890 nm. While referring to Eq. 2 the latter period perfectly balances the momentum equation ,(1). On the other hand, the former period should provide the momentum matching when the geometric phase is disregarded, for instance when the structure is non-rotating. We compare the scattered light intensity, captured by the camera, at right hand (R) and left hand (L) circular polarizations. Note that in both cases the prism is illuminated with a linear polarization, required to efficiently excite TM polarized plasmonic wave. It is easy to notice from the cross section in Fig. 2c that in the case of the shorter period high intensity is obtained at both circular polarizations while with the longer period right hand polarization clearly dominates. We make a cross section through the captured intensity distributions and find out that the longer period leads to a 7.5 fold polarization discrimination compared to 1.5 fold discrimination with the shorter period. This shows, that with properly designed period of our metasurface one can produce almost pure circular polarization. Additional point that worth discussing is the fringe pattern that is visible in the intensity distribution produced by the shorter period but disappears when the longer period is used. The periodicity of the pattern corresponds to the rotation period of the nanoaperture. The fringes arise due to the spatially varying elliptical polarization emitted from the element. Each nanoaperture emits nearly linear polarization and in the first case those dipolar sources are uncoupled because of the phase

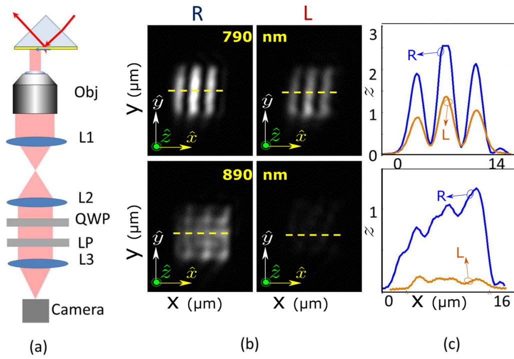

Figure 2. (a) - A detailed scheme of the imaging setup. Details of the objective (Obj) and the lens system (L1, L2, L3) are given in the text. (b) Intensity distribution measured by the system for two metasurfaces with different periods. (c) Cross sections of the intensities measured across the dashed lines in (b).

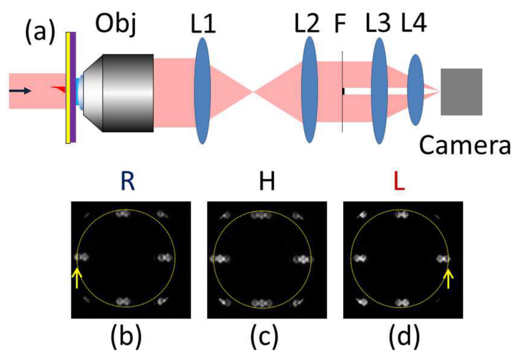

Figure 3. Momentum space imaging. (a) Leakage microscopy setup. (b)–(d) Fourier plane images received in the camera for right (R), horizontal (H) and left (L) polarizations.

mismatch. In the second case, the absence of the fringes is a witness of a collective behavior of the scattering apertures leading to an effective plane wavefront emitted from the structure.

The physical mechanism, responsible for the spin-orbit interaction in our system can better investigated when the structure is excited at normal incidence using laser. In this case, the element is coherently illuminated at $\lambda = 785nm$ with given polarization state. Our metasurface supplies the momentum matching condtion for surface plasmon excitation on the thin gold film. In this configuration, a structure with a properly chosen period should excite an surface plasmon wave propagating in either positive or negative x direction depending on the handedness of the polarization used to excite it. We use a leakage radiation microscopy system [19] with 100x oil immersion objective ($NA = 1.25$) to explore the propagating surface plasmons (see Fig. 3a). The light propagating directly through the thin gold film is filtered in the Fourier plane, behind the L2 lens. An additional Fourier lens ($f_4 = 50mm$) is used in order to visualize a momentum space of the excited plasmonic beams. Figure 3b depicts the resulting distributions captured by the camera. We illuminate the structure with right hand (R), left hand (L) circular polarizations and with a horizontal linear polarization (H). The momentum space, shown in the Figure represents a peculiar diffraction pattern arising from our periodic structure. A dashed circle corresponds to a momentum of the surface plasmons, i.e. $k_x^2 + k_y^2 = k_{SP}^2$. The first diffraction order with $k_i = \pm 2\pi/\Lambda$ where $i = x, y$ is visible close to the field of view limit of our microscope. Besides the first order one can clearly distinguish additional, spots that appear on both sides of it (see Fig. 3b-d). These spots correspond to the polarization orders that acquire a spin-dependent geometric phase. When the structure is illuminated by circularly polarized light (Fig. 3 b and d) only one polarization order appears and the other is totally extincted. The design of the structure period as proposed in Eq. 2 demands an overlap between these polarization orders and the plasmonic circle. One can see, how this requirement is fulfilled in Fig. 3, whith different polarzation states of the illumination. Now it is easy to see that when a right-hand circular polarization is used the plasmonic beam propagates to the left and for the left-hand circular polarization - to the right. When a linear polarization is used, an surface plasmon wave will be launched to both sides equally. Hence, our metasurface behaves as a spin-dependent router of the surface plasmon waves. Note, that when period $\Lambda_x = 760nm$ is used, the matching is obtained between the central (non polarization dependent) order of diffraction and the plasmon momentum. Thus, in this case the coupling is not spin-dependent and both, right-wise and left-wise propagating plasmons are excited. Their interference results in the fringes, which appear in the Fig. 2c.

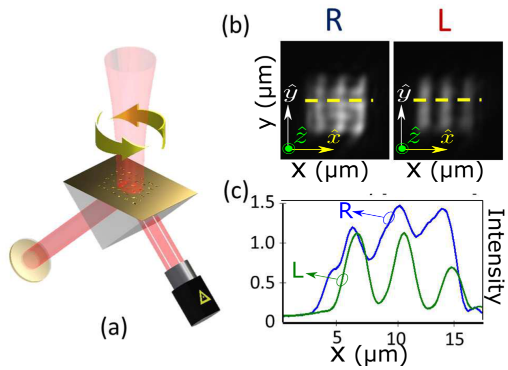

Figure 4. Interaction of counter propagating SPs with metasurface. (a) - Scematic representation of the setup using a mirror to redirect the light back to the metasurface. (b) - The intensity distributions captured for different polarizations. (c) - Cross section of the distributions in (b).

The momentum space representation demonstrated how the propagation direction of the surface plasmons is linked to the circular polarization handedness in our device. Bearing in mind the above examples, it would be interesting to investigate the behavior of our metasurface when plasmons are simultaneously propagating in both, positive and negative directions. In order to test this we return to the prism setup, but this time we use a mirror, placed normally to the excitation beam at the exit from the prism side (see Fig.4). The light in this scheme is reflected back to the prism after first surface plasmon excitation and excites additional surface plasmon wave propagating in the opposite direction. The two counter propagating surface plasmons are scattered by the metasurface and the intensity is measured via circular polarizer. In Fig. 4 one can clearly appreciate that for both circular polarizations the light intensity is almost equal. This occurs due to the fact that plasmon waves are travelling in both positive and negative x direction. We beleive that a small degradation in the intensity of the left-hand polarized distribution is attributed to the spatial deviation of the beam propagating from the mirror back into the prism.

5. CONCLUSION

To conclude, the effect of circularly polarized beaming excited by the traveling surface plasmons, via chiral metasurface is experimentally studied. The metasurface was designed to attain a momentum matching between the plasmons and the far-field raduiation. We experimentally demonstrated how the propagation direction of a plasmonic wave, affected the handedness of the scattered beam polarization and theoretically explained the phenomenon. Our results show, that with properly designed metasurface one can efficiently couple light directionally propagating in a dielectric slab to an almost pure circular polarization analogically to rack and pinion gear in mechanics. The observed effect can be utilized in integrated optical circuits for optics communication systems, cyber security and sensing.

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