Spinoptics: Spin symmetry breaking in plasmonic nanostructures

Erez Hasman, Yuri Gorodetski, Nir Shitrit, Itay Bretner, Avi Niv, and Vladimir Kleiner
Micro and Nanooptics Laboratory, Faculty of Mechanical Engineering, and Russell Berrie Nanotechnology Institute, Technion – Israel Institute of Technology, Haifa 32000, Israel
mehasman@tx.technion.ac.il

ABSTRACT

The spin-Hall effect – the influence of the intrinsic spin on the electron trajectory, which produces transverse deflection of the electrons, is a central tenet in the field of spintronics. Apparently, the handedness of the light's polarization (optical spin up/down) may provide an additional degree of freedom in nanoscale photonics. The direct observation of optical spin-Hall effect that appears when a wave carrying spin angular momentum interacts with plasmonic nanostructures is presented. The measurements verify the unified geometric phase, demonstrated by the observed spin-dependent deflection of the surface waves as well as spin-dependent enhanced transmission through coaxial nanoapertures even in rotationally symmetric structures. Moreover, spin-orbit interaction is demonstrated by use of inhomogeneous and anisotropic subwavelength dielectric structures. The observed effects inspire one to investigate other spin-based plasmonic effects and to propose a new generation of optical elements for nano-photonic applications.

Keywords: nanoaperture, plasmon-polariton, spin-orbit interaction, geometric phase

1. INTRODUCTION

The interaction of light with metallic subwavelength structures exhibits various anomalous effects such as extraordinary optical transmission and beaming. These effects have been elegantly explained by a mechanism involving the coupling of light to collective surface-confined electronic oscillations known as surface plasmon-polaritons (SPPs). Extensive research has been carried out in the field of electromagnetic surface waves due to its technological potential and fundamental implications. Apparently, the handedness of the light's polarization (optical spin up/down) may provide an additional degree of freedom in nanoscale photonics. The dynamics of spinning light was investigated, and the effect of spin on the trajectories of polarized light beams (spin-orbit coupling) was experimentally observed, with results that agree with the predictions of Berry's phase theory [1]. We examine the spin-orbit coupling effects that appear when a wave carrying intrinsic angular momentum (spin) interacts with a nanoscale structures. The Berry's phase is shown to be a manifestation of the Coriolis effect in noninertial reference frame attached to the wave. The theory is supported by experiment demonstrating the spin-orbit coupling of electromagnetic waves via a surface plasmon anisotropic inhomogeneous nanostructure. The measurements verify the unified geometric phase, demonstrated by the observed polarization-dependent deflection (spin-Hall effect) of the waves [2,3].

2. TOPOLOGICAL SPIN-ORBIT INTERACTION OF LIGHT IN ANISOTROPIC INHOMOGENEOUS SUBWAVELENGTH STRUCTURES

Spin-orbit interaction resulting from spatial polarization state manipulation is demonstrated. Polarization state manipulation is achieved by utilizing the effective birefringent nature of subwavelength structures acting as an anisotropic inhomogeneous medium. Experimental verification is obtained by measuring the effect of the unavoidable spin-dependent Pancharatnam-Berry phase modulation on the far-field diffraction pattern of the beam. Unlike the usual dynamic spin-orbit interaction that splits spin-states in the temporal frequency (energy) domain, this topological spin-orbit interaction results in the splitting of spin-states degenerated by their spatial frequencies (momentum) [4].

Plasmonics: Metallic Nanostructures and Their Optical Properties VII, edited by Mark I. Stockman,
Proc. of SPIE Vol. 7394, 73941W · · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.828941

Propagation of light in linear anisotropic media brings about an interaction between the polarization (spin up/down for right- and left-handed circularly polarized light) and the material. If, in addition inhomogeneity is introduced, spin-orbit interaction may occur. In our case, non-absorbing media were used; therefore, inhomogeneity was manifested only by the orientation of the anisotropy axis. Let us consider a π-retardation waveplate. As this device elastically scatters light, the spin of the emerging beam has a sign opposite to that of the incident beam. If, in addition, the π-retardation waveplate is rotating, spin-orbit interaction results in a rotational Doppler effect,

$$\Delta\omega = 2\sigma\Omega \tag{1}$$

Here, $\sigma = \pm 1$ is the spin value of the incident wave (corresponding to $\boldsymbol{R}$, and $\boldsymbol{L}$ polarizations, respectively), Ω is the rotation rate of the waveplate and $\Delta\omega$ is the frequency shift. In Eq. (1) temporal rotation is usually assumed (i.e., Ω is measured in *radians per unit of time*). However, for spatial rotation in a plane transverse to the propagation direction of the beam (i.e., Ω is measured in *radians per unit of length*), Eq. (1) is valid albeit with a spatial frequency shift $\Delta\mathbf{k}_{\perp}$ replacing the temporal frequency shift $\Delta\omega$. The geometric Pancharatnam-Berry phase (ϕ_{PB}) results from this spatial version of the rotational Doppler effect according to

$$\phi_{PB} = 2\sigma\int \Omega d\xi \tag{2}$$

where ξ is a spatial coordinate. As the geometric phase can be viewed as having arisen from a topological monopole charge at the center of a suitable parameter space, we consider this spin-orbit interaction to be a topological effect (rather than a dynamic one).

Experimental verification was obtained by exploiting the effective birefringence of quasiperiodic subwavelength structures; when the periodicity of a grating is sufficiently smaller than the illumination beam's wavelength, it

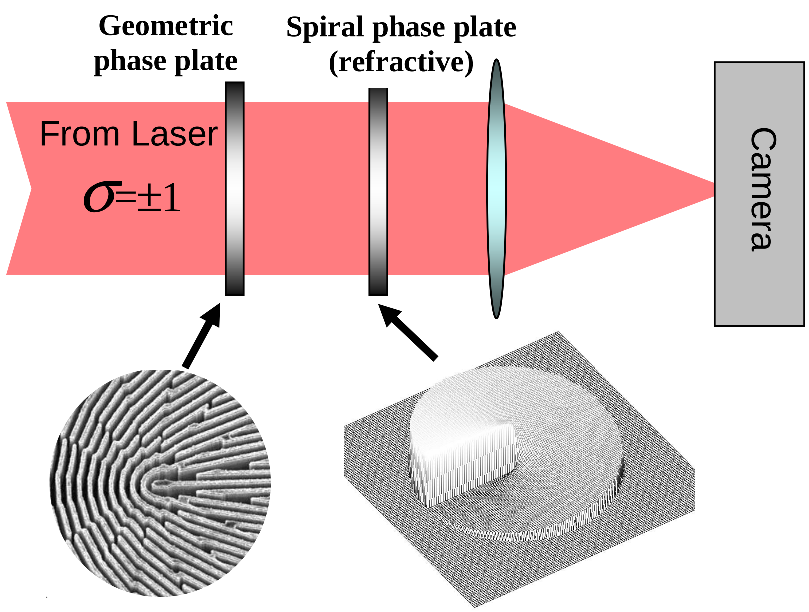

Fig. 1. Schematic illustration of the experiment.

effectively behaves as a uniaxial crystal with optical axes that are parallel and perpendicular to the grating strips[5,6]. By correctly controlling the etched depth of the grating, an effective π-retardation waveplate can be achieved. In addition, unlike natural crystals, subwavelength gratings allow for variations in the grating orientation, thereby introducing inhomogeneity to the already existing anisotropy of the device. Let us consider an effective π-retardation subwavelength grating with a local groove orientation θ (effective fast axis orientation) given by

$$\theta = m\vartheta/2 \tag{3}$$

where (r,ϑ) are polar coordinates and m is an integer number. In this case, the spatial rotation rate is $\Omega = m/2$, and according to Eq. (2), the Pancharatnam-Berry phase has a spiral structure given by

$$\phi_{PB} = \sigma m \vartheta \tag{4}$$

Thus, spin-orbit interaction results in the appearance of vortex with topological charge σm at the phase of the beam.

Figure 1 shows a schematic illustration of the experiment. A collimated beam of 10.6 μm wavelength light from CO_2 laser, with a spin set to either $\sigma = \pm 1$, traversed a space-variant □-retardation subwavelength grating with a clear aperture of 10*mm*. The grating consisted of a 2 μm subwavelength period that was etched 5 μm deep into a

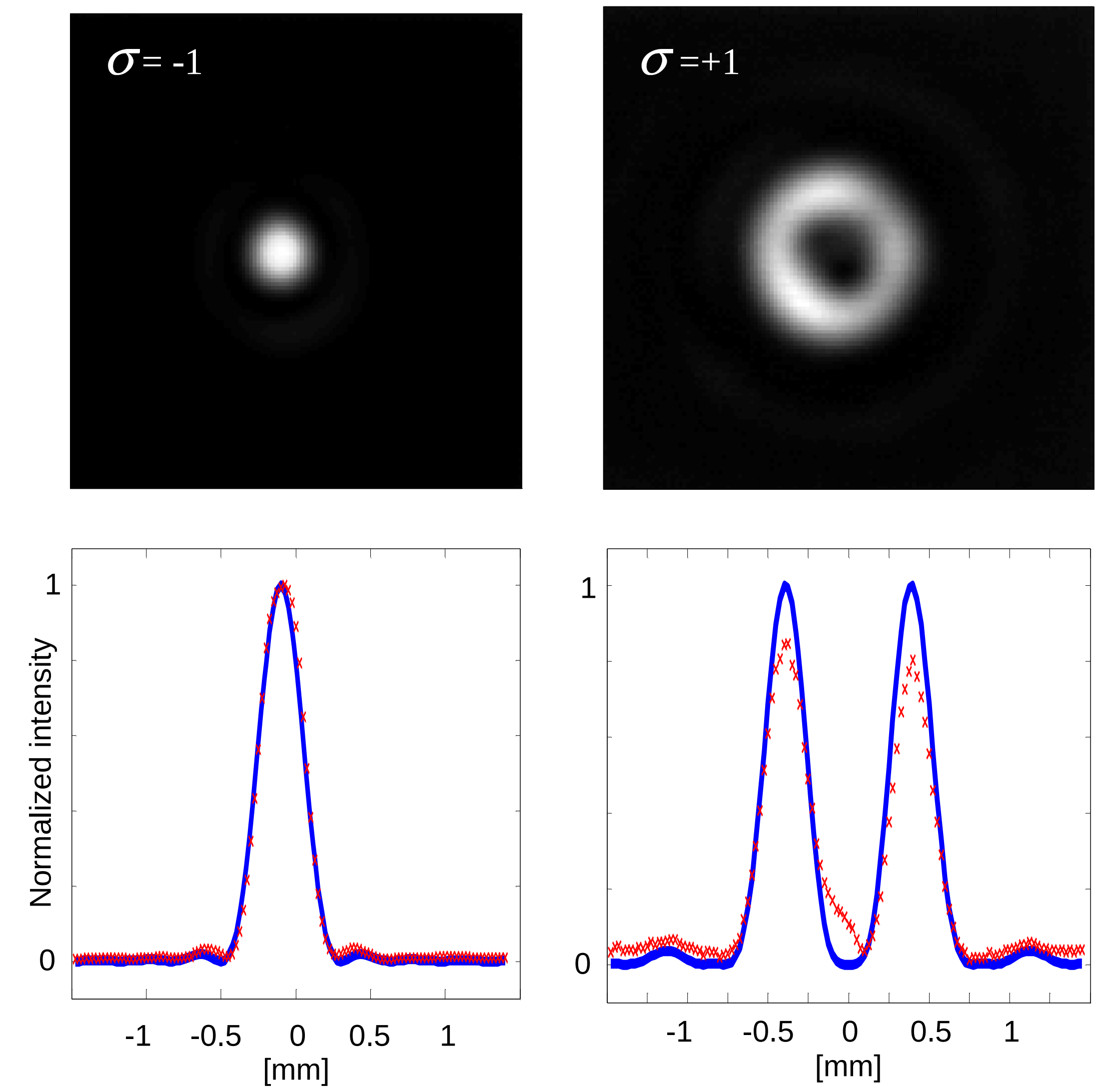

Fig. 2. Upper row shows the captured intensity distributions for different illumination helicities, (circular polarized light: left-handed $\sigma = -1$, and right-handed $\sigma = +1$). The lower row shows experimental (red 'x's) and predicted (solid blue line) typical cross-sections.

GaAs wafer. The inset shows a scanning electron microscope image of the grating. Note the local grating orientation according to Eq. (3) with *m*=1. According to Eq. (4), this device is expected to induce a helical phase of unit charge whose sign depends on the spin of the incident wave. However, the measured quantity is the intensity of the wave, which is identical with respect to the sign of the helical phase. The beam that emerged from the space-variant subwavelength structure impinged on a *refractive* helical phase plate (ZnSe), depicted as a spiral in Fig. 1. This device adds a unit charged helical phase regardless of the spin of the incident wave. Therefore, the cumulative phase will have a zero charge for $\sigma = -1$ and a charge of two for $\sigma = +1$. Consequently, we expected the far-field diffraction pattern to consist of a confined intensity lobe for $\sigma = -1$, and a charge two doughnut-shaped distribution for $\sigma = +1$. Far-field intensity distributions were captured at the focus of a 1*m* focal length lens using a pyroelectric camera (Spiricon, Pyrocam III). Figure 2 shows the measured spin-dependent diffraction patterns. For a left-hand circularly polarized beam ($\sigma = -1$), a confined intensity lobe appeared, while for a right-hand circularly polarized beam ($\sigma = +1$), a doughnut-shaped intensity lobe was seen. Typical cross-sections of the diffraction patterns are also shown in Fig. 2; a good agreement between calculated and measured values confirms the zero and double charge of the intensity distributions, respectively. In addition, the spins of the emerging beams were verified to be of opposite signs with respect to the incident beam, as expected. Our experiment demonstrates the spin-dependent phase modulation of a transmitted wave, confirming the topological spin-orbit interaction for light impinging upon an anisotropic inhomogeneous structure.

In conclusion, we have verified that the origin of the Pancharatnam-Berry phase results from a topological spin-orbit interaction within anisotropic inhomogeneous media. This connection is important both for an understanding of the fundamental principle involved, as well as its role in the future development of spin-based optical applications such as mode switching.

3. OBSERVATION OF THE SPIN-BASED PLASMONIC EFFECT IN NANOSCALE STRUCTURES

The proposed anisotropic inhomogeneous plasmonic structure was produced on top of a thin metal film evaporated onto a glass plate. The element consisted of a cavity (a spiral Bragg grating with a central defect), surrounded by a coupling grating [Fig. 3(a)]. The structure was illuminated by circularly polarized light (**R** – right-handed, **L** – left handed). The intensity in the plasmonic cavity was measured by a Near-field Scanning Optical Microscope (NSOM). The measured intensity distribution exhibits a strong dependence on the incident spin [see Fig. 3(a)]. An annular ring structure with a dark spot in the center for **R** illumination and with a bright spot for **L** illumination indicates coupling to different spiral plasmonic modes. The origin of the spin-dependent change in the near-field intensity distributions lies in the geometric phase of the excited plasmonic mode. In the most general case, when a wave carrying an arbitrary spin angular momentum changes its direction of propagation and polarization state, the geometric phase is given by a simple expression stemming from the Coriolis effect [2]. The Coriolis effect is a result of the rotation of the reference frame, represented by the local direction of the grating grooves. Accordingly a spiral geometric phase with spin-dependent helicity arises in a circular grating [3]. In the spiral structure, [see Fig. 3(a)] an additional dynamic phase arises as a result of a space-variant path difference. The overall phase in the spiral cavity is the sum of the geometric and dynamic phases, which is manifested by different spiral modes that are obtained in the cavity for different polarizations.

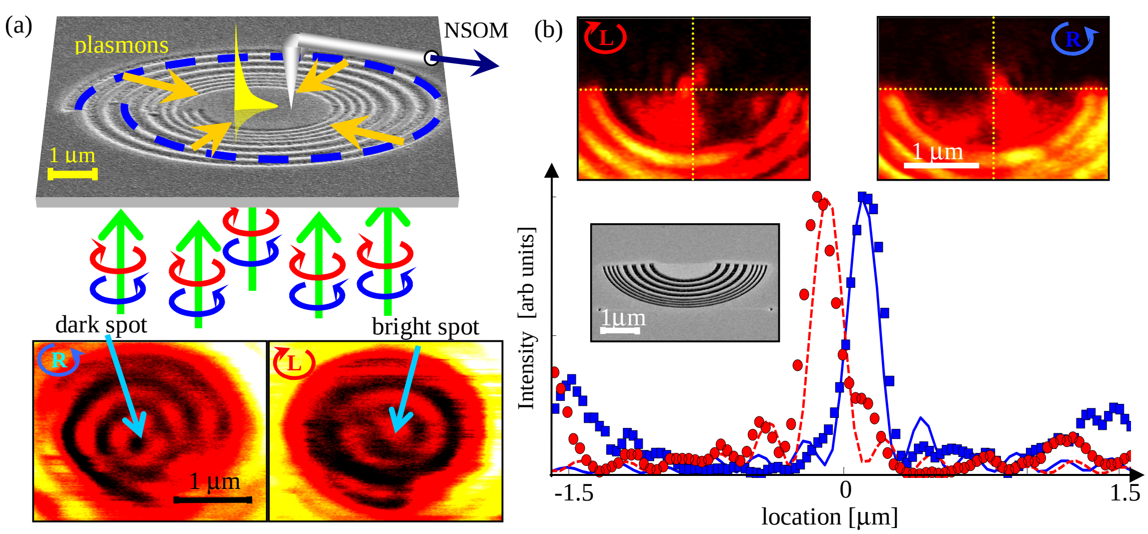

Fig. 3. (a) The scanning electron microscope image of the spiral nanostructure and the scheme of the optical setup. Intensity distribution in the cavity measured by a NSOM for **R** and **L** illumination. (b) Spin-dependent plasmonic lens based on a plasmonic spin-Hall effect. The intensity distributions measured by a NSOM for **R** and **L** illumination and the corresponding transverse cross-sections of the measured intensity distributions in the focal plane of the lens (**R** - blue

squares, **L** - red circles) Calculated cross-sections are plotted for each polarization (solid blue line -**R**; dashed red line - **L**). The SEM picture of the element is depicted in the inset.

One of the possible technological implementations of the plasmonic geometric phase could be a spin-dependent plasmonic focusing lens. The proposed structure is presented in Figure 3(b). This structure was illuminated from the bottom with **R** and **L**-polarized plane waves and the near-field intensity distribution was collected by the NSOM. A spin-dependent transverse shift of the focus is observed by comparing the spots [Fig. 3(b)]. This shift can be regarded as a manifestation of the optical Magnus effect (optical spin-Hall effect) which arises in our system due to a spiral geometric phase. The observed effects inspire one to investigate other spin-based plasmonic effects and to propose a new generation of optical elements for nano-photonic applications.

4. OBSERVATION OF OPTICAL SPIN SYMMETRY BREAKING IN NANOAPERTURES

Observation of a spin symmetry breaking effect in plasmonic nanoscale-structures due to spin-orbit interaction is presented. We demonstrate a nanoplasmonic structure which exhibits a crucial role of an angular momentum (AM) selection rule in a light-surface plasmon scattering process. In our experiment, the intrinsic AM (spin) of the incident radiation is coupled to the extrinsic momentum (orbital AM) of the surface plasmons via spin-orbit interaction. Due to this effect, we achieved a spin-controlled enhanced transmission through a coaxial nanoaperture[7]. In our experiment the spin-orbit interaction mechanism and the AM selection rules were experimentally verified by investigating the effect in a circularly symmetric – *achiral* – nanostructure. For this purpose we induced an external OAM carried by the incident beam. We fabricated the element, which consisted of an individual coaxial aperture, surrounded by an annular coupling grating (see Fig. 4a). This aperture was illuminated by a green laser light (Verdi of Coherent; $\lambda = 532nm$) whose phase was modulated by a spatial light modulator (SLM Hamamatsu – PPM X8267) to achieve a spiral phase with topological charges $l_{ext} = 0, \pm 2$. We obtained a spin-dependent enhanced transmission by controlling the behavior of the device with external orbital AM, (see Fig. 4(b)).

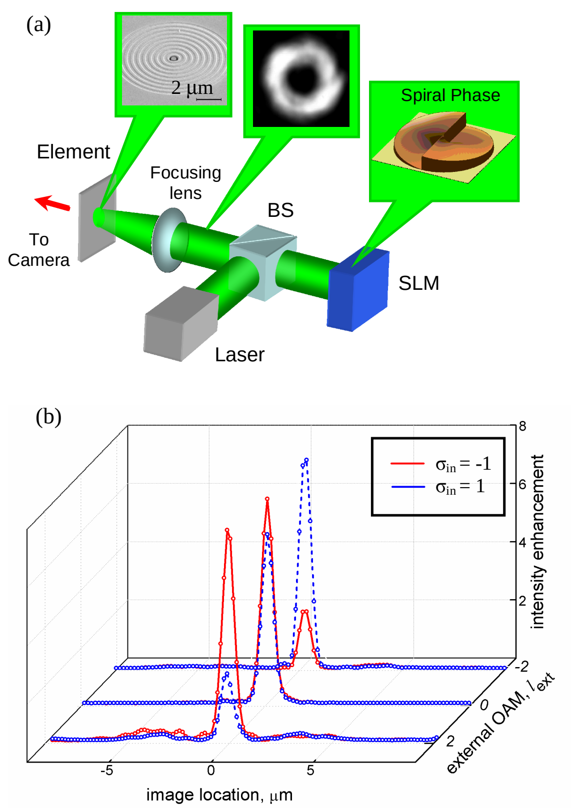

Fig. 4. Removal of the spin-degeneracy in circular corrugation by use of externally induced OAM. (a) experimental setup. A laser beam is modulated by a Spatial Light Modulator (SLM) to obtain a spiral phase and then incident through a Beam Splitter (BS) onto a coaxial aperture with circular corrugation. The transmitted light is captured in the image plane by the camera.

The spiral phase with $l_{ext} = 2$, the measured intensity distribution across the incident beam, and the SEM picture of the element are presented in the figure. (b) intensity distribution cross-sections captured by the camera for different l_{ext}. The blue dashed lines correspond to $|\sigma_+\rangle$ illumination and red solid lines correspond to $|\sigma_-\rangle$ illumination. The intensity was normalized by the transmission measured via a coaxial aperture without the surrounding corrugation (the horizontal dimension was scaled according to the optical magnification).

5. SUMMARY

In summary, the spin Hall effect, an interaction between particles because of their spin, is a central tenet in the field of spintronics. The direct observation of an optical equivalent of the spin Hall effect is reported in this work. The development of a new branch of physics – *spinoptics* – has taken a step forwards thanks to a direct observation of the influence of the spin Hall effect of light on photon trajectories. We believe that modern nanooptics and photonics operating with light at a subwavelength scales [4], provide a promising new avenue for exploiting these fundemental effects.

REFERENCES

[1] Bliokh, K. Y., Niv, A., Kleiner, V. and Hasman, E., "Geometrodynamics of spinning light", Nature Photonics 2, 748-753 (2008).

[2] Bliokh, K. Y., Gorodetski, Y., Kleiner, V. and Hasman, E., "Coriolis effect in optics: unified geometric phase and spin-Hall effect", Phys. Rev. Lett. 101(3), 030404-1 – 030404-4 (2008).

[3] Gorodetski, Y., Niv, A., Kleiner, V. and Hasman, E., "Observation of the spin-based plasmonic effect in nanoscale structures", Phys. Rev. Lett. 101(4), 043903-1 – 043903-4 (2008).

[4] Niv, A., Gorodetski, Y., Kleiner, V. and Hasman, E., "Topological spin-orbit interaction of light in anisotropic inhomogeneous subwavelength structures", Opt. Lett. 33(24), 2910-2912 (2008).

[5] Niv, A., Biener, G., Kleiner, V. and Hasman, E., "Polychromatic vectorial vortex formed by geometric phase elements", Opt. Lett. 32(7), 847-849 (2007).

[6] Hasman, E., Biener, G., Niv, A. and Kleiner, V., "Space-variant polarization manipulation", Progress in Optics, 47, 215, E. Wolf, ed., Elsevier (2005).

[7] Gorodetski, Y., Shitrit, N., Bretner, I., Kleiner, V. and Hasman, E., "Observation of optical spin symmetry breaking in nanoapertures", in press, Nano Lett. (2009).