Plasmon vortex-modes generation in the near-field region: Role of the rotational symmetry breaking of the nanostructures.

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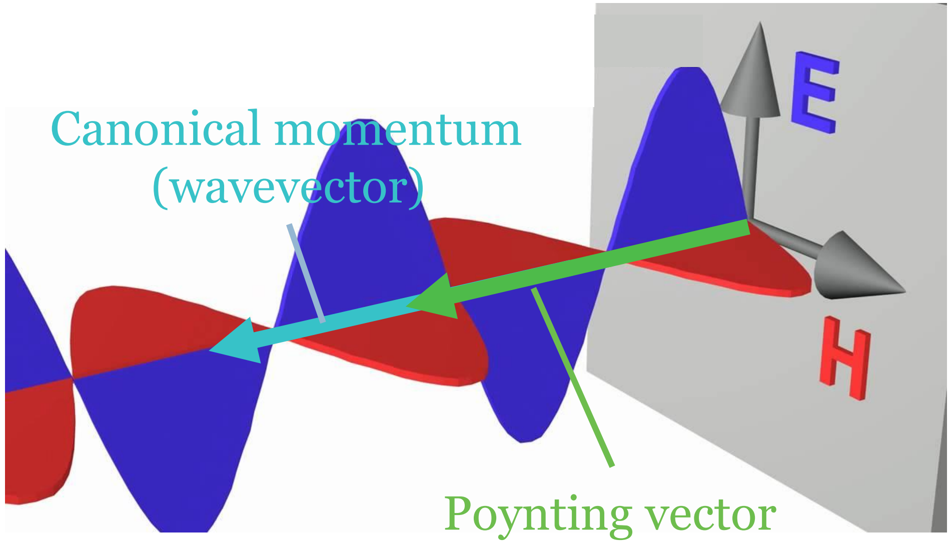
Spin & Orbital angular momentum of light.

Light possesses the angular momentum (AM) that can be distinguish in **spin** AM and **orbit** AM.

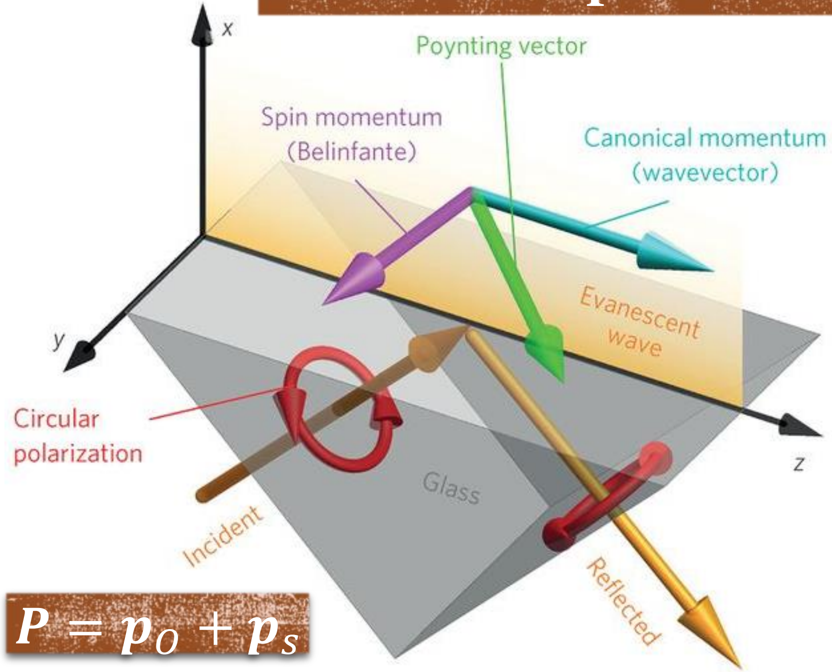
For a paraxial beam:

- ✓ Spin AM is associated with the polarization of light ($\sigma = \pm 1$) and it is aligned with the direction of propagation light.
- ✓ Orbital AM (or canonical momentum) is indipendent of the polarization and it is produced by the phase and momentum circulation (i.e. optical vortex).

Plane wave



Structured optical fields



$P = p_O + p_s$

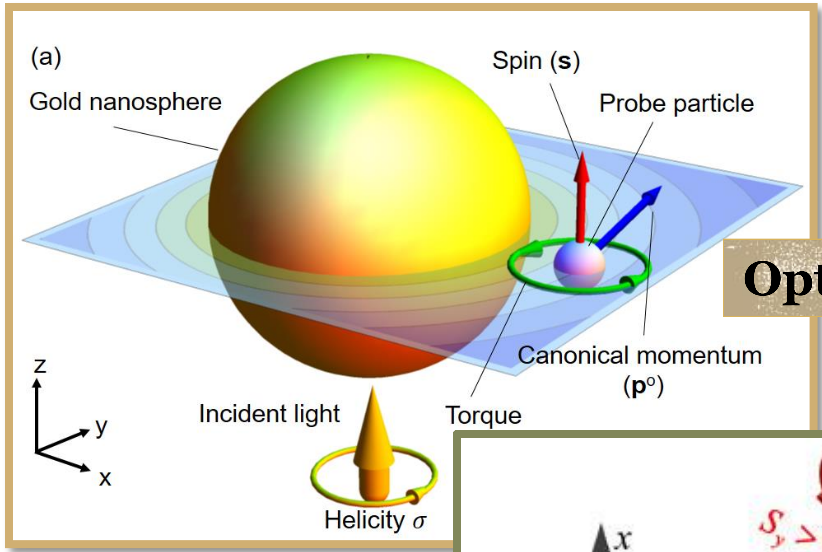
Spin & Orbital angular momentum of light.

In presence of the structured optical field, spin and orbital properties become strongly coupled to each other **(spin-orbit interactions of light (SOI))**.

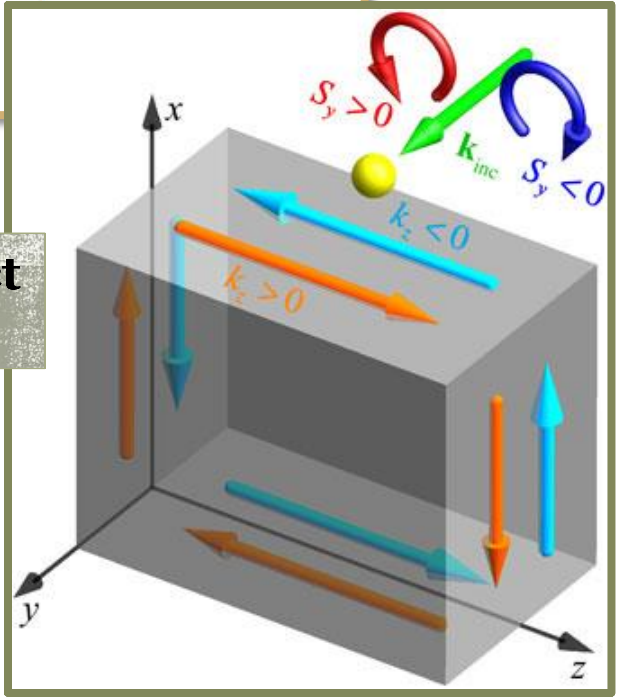
SOI phenomena allow to **control** the spatial degree of freedom of light (**intensity distribution of electromagnetic field**) **selecting the spin state of the incident photons** (right- and left-hand circular polarization of light).

In order to enhance the experimental observation of the SOI effect, plasmonic metamaterials are largely used. Exploiting the **rotational symmetry breaking** of a single elongated nanohole, we generate a **plasmonic vortex** by illuminating the hole with an incident **light beam without a spin state** (σ = 0 corresponds to the linearly polarized light).

[Bliokh & Nori, Physics Reports 592 (2015) 1-38.]



Optical forces

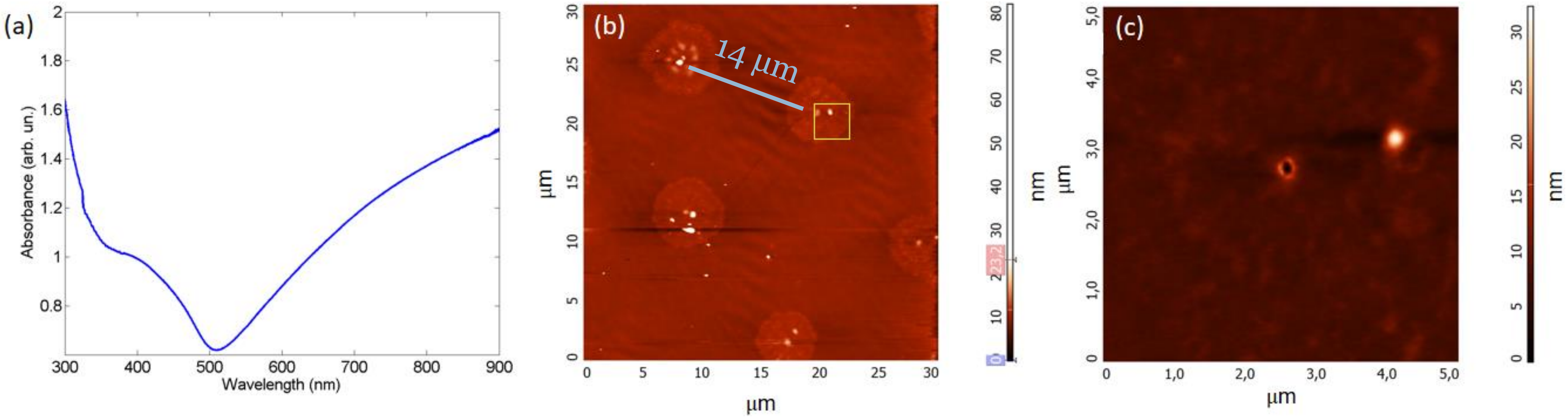


Spin Hall effect of light

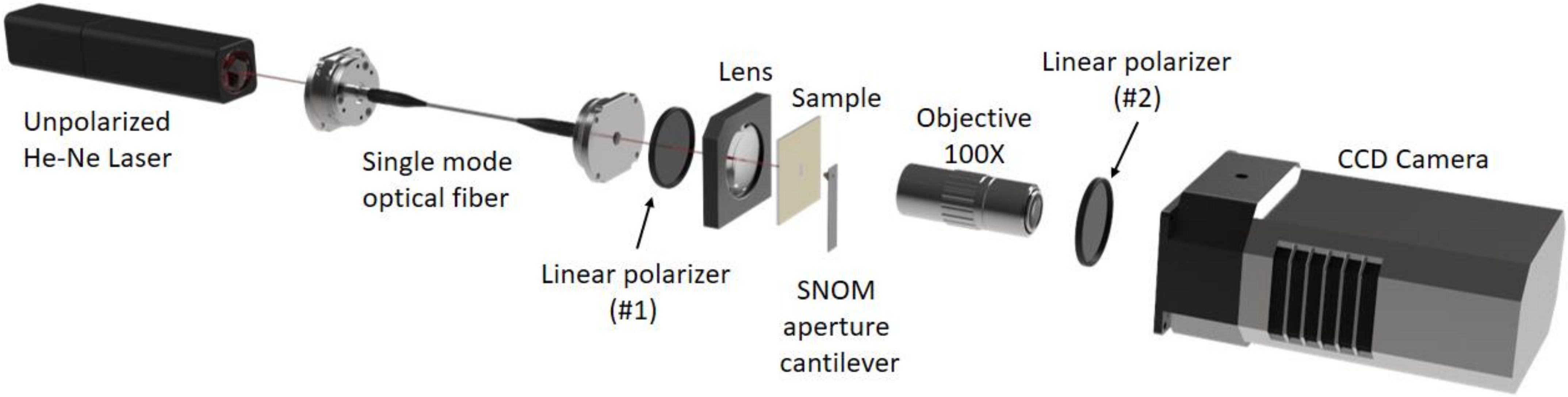
Sample preparation & morphological characterization.

Sample consists of a multilayers with titanium 1 nm/gold 88 nm evaporated sequentially onto the cover slip using an Electron Beam Evaporator.
A Focused Ion Beam (FIB, FEI NanoLab 600 dual beam system) milling at 80 pA current and 30 kV voltage was used to drill **elliptical holes with sizes of 130 nm and 80 nm**.

AFM (Atomic Force Microscopy) images of the sample surface were acquired with a NT-MDT NTEGRA Spectra microscope working in semi-contact mode.



Scanning Near-field Optical Microscopy (SNOM) setup.

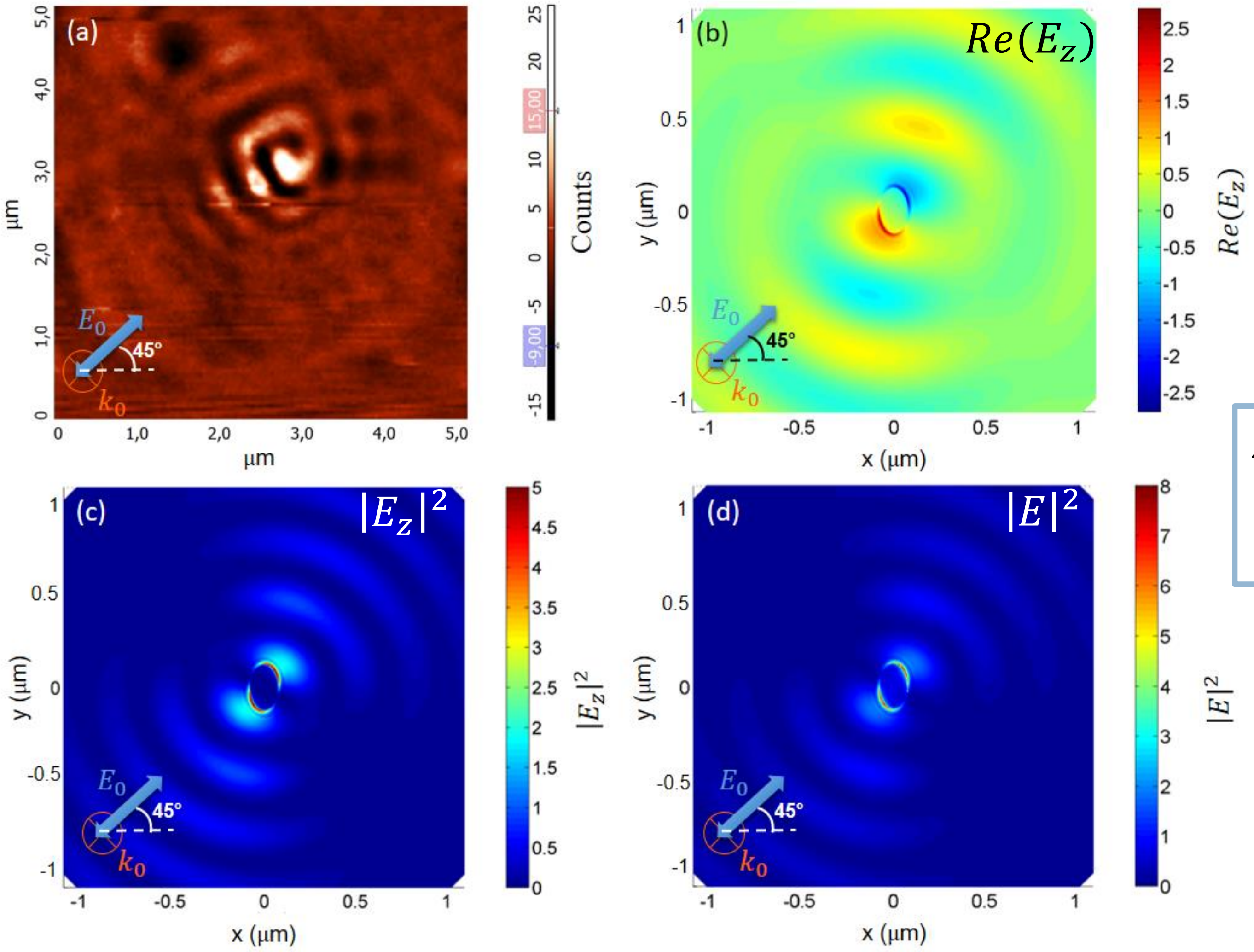


SNOM measurements were performed in **transmission mode with hollow-pyramid cantilever** working **in contact mode**.

Using two linear polarizers (#1 and #2), it is possible to decide **whether or not to exclude the incident electromagnetic field contribution** and to observe the de-polarization process of light that goes through the elongated nanohole.

Results & Discussion.

Normal incidence and linear polarization at 45° respect to the symmetry axes of the nanohole. (#1 ⊥ #2)



The peculiarity of the SNOM technique is that the **image gives information about the magnitude and the phase** of the detected optical signal, which can be written as:

$$I(\mathbf{r}) = \left|E_{bg} + \alpha E_z(\mathbf{r})\right|^2 \cong \left|E_{bg}\right|^2 + 2Re\left(\alpha E_{bg}^* \cdot E_z(\mathbf{r})\right)$$

z-component of the electric field in the near-field region.

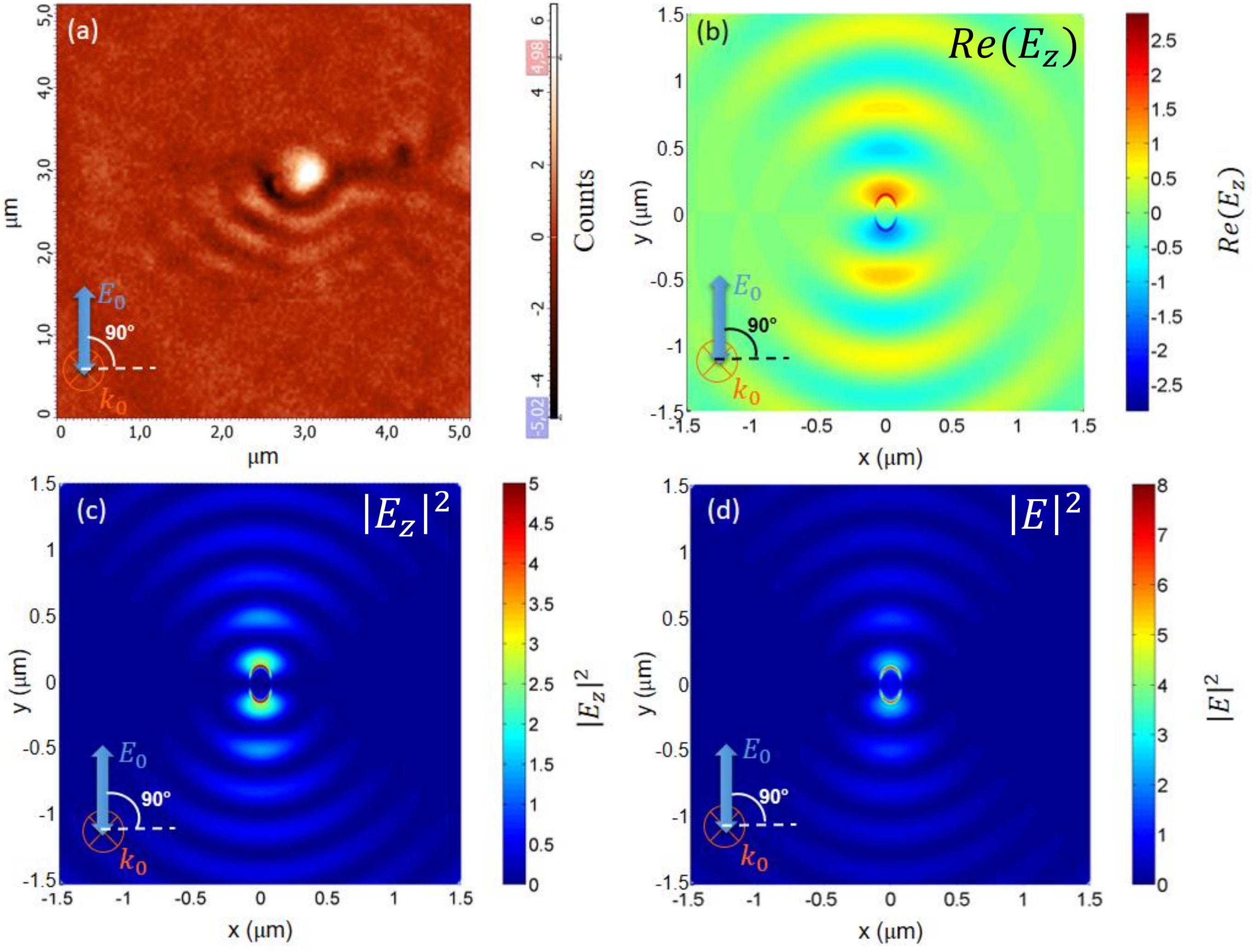
Position-indipendent background intensity

Interference term that depends on the probe-sample position.

The optical vortex is reproduced by FEM simulation considering **ONLY** the real part of the *z*-component of the total electric field $Re(E_z)$.

Results & Discussion.

Normal incidence and linear polarization at 90° respect to the symmetry axes of the nanohole. (#1 ⊥ #2)

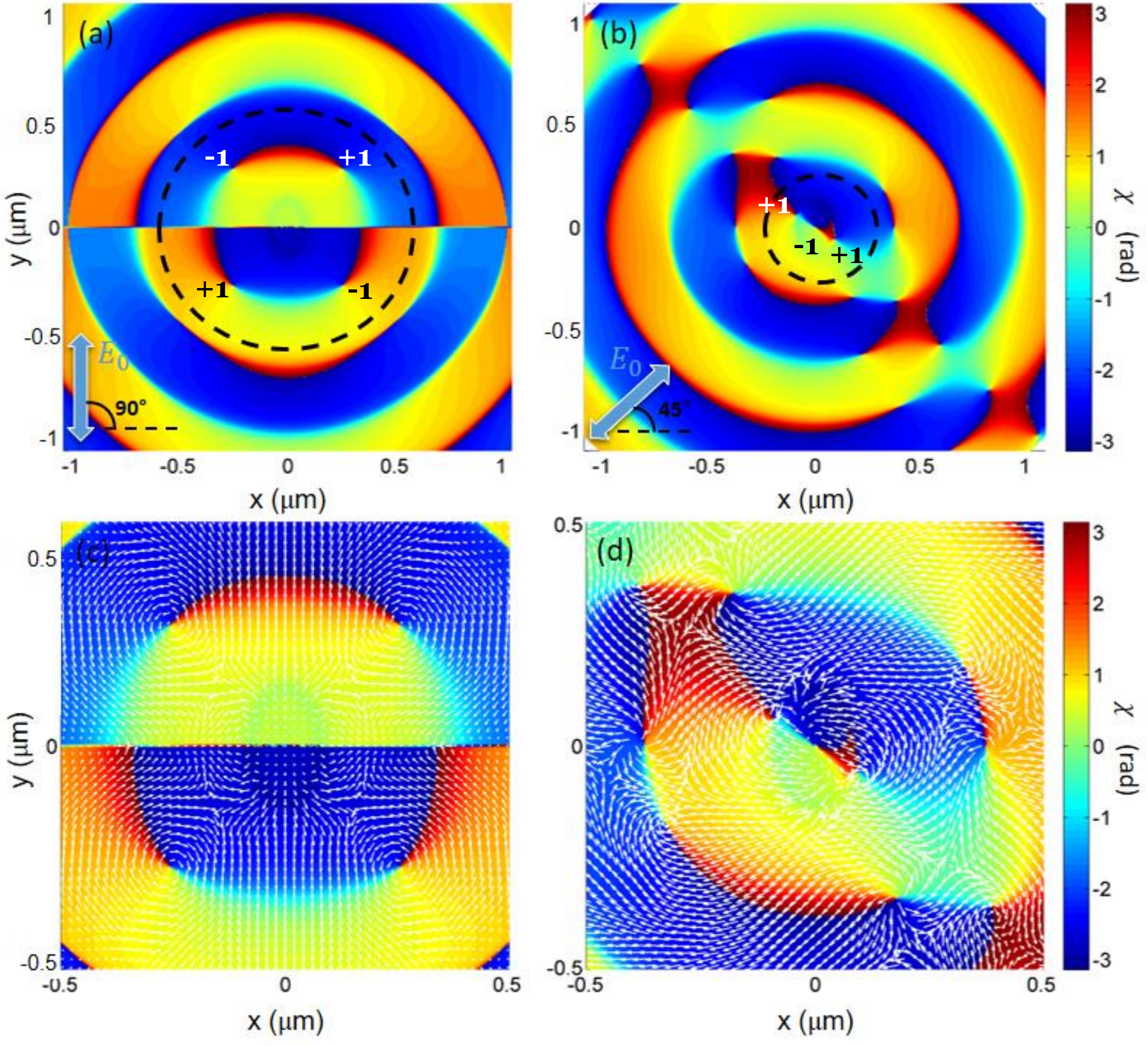


Surface plasmon vortex modes, carrying orbital angular momentum, **can be induced under linearly polarized illumination** of individual anisotropic nanostructures **when the polarization direction differs from the symmetry axes of the nanostructure.**

This effect is a manifestation of SOI of light.

Results & Discussion.

Phase distribution of E_z



The elliptical hole can be viewed as the combination of two dipole-like oscillators of different lengths, and the phase pattern is the result of the **interference between** these **two dipoles and the SPPs propagating on the gold surface**, which generates **phase singularities** that determine the **total topological charge** (ℓ_{tot}) of the system.

In figure (a), ℓ_{tot} is balanced:

$$\ell_{tot} = \sum_{i=1}^{4} \ell_i = 0$$

For each nodal point, the can be defined as:

$$\ell = \frac{1}{2\pi}\oint$$

In figure (b), ℓ_{tot} is unbalanced:

$$\ell_{tot} = \sum_{i=0}^{2} \ell_i = +1$$

The energy flow can be define as:

$$\boldsymbol{j} = E_z^* \cdot \nabla E_z = \rho(\boldsymbol{r}) \cdot \nabla \chi$$

Conclusions.

Some References

Bliokh & Nori, Physics Reports 592 (2015) 1-38.
C. Triolo et al., Scientific Reports 9 (2019) 5320.
C. Triolo et al., ACS Photonics 4 (2017) 2242-2249.
Greffet & Carminati, Progress in Surface Science 56 (1997) 133-237.

- SPR with orbital angular momentum can be induced under linearly polarized illumination and vortex modes arise ONLY when the incident polarization direction differs from one of the ellipse axes.
- A direct observation of the vortex mode was possible thanks to the ability of the SNOM technique to provide information on both the amplitude and the phase of the evanescent field.
- A vorticity originates from the presence of nodal points with an overall charge different from zero, leading to an overall circulation of the energy flow.
- $\boldsymbol{p}_O$ and $\boldsymbol{s}$ are orthogonal to each other in correspondence of the phase singularities. This is a clear manifestation of the "**spin-momentum locking**" effect, due to the evanescent behavior of the light.