Universal Near-Field Spin Properties of Polarized and Chiral Dipoles

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***Abstract*—Universal spin-momentum locking of light dictates the direction of transverse spin in the evanescent waves. The coupling between the guided modes of a waveguide and radiating dipoles is also governed by universal spin-momentum locking phenomenon. The spin of the dipole determines the direction of propagation of the coupled wave in the waveguide. We experimentally investigate the radiation behavior of circular and chiral dipoles near a tapered optical fiber. We show that the intrinsic chirality of a chiral dipole plays the role of the spin of a circular dipole in coupling to the modes of an optical fiber.**

I. Introduction

The evanescent electromagnetic waves possess intrinsic spin [1]–[3]. The direction of this spin is governed by universal spin-momentum locking of light (USML) and is locked to the direction of propagation of electromagnetic energy. This intrinsic spin can induce a circular dipole in a polarizable particle interacting with it. The direction in which the dipole is rotating would be determined by the direction of spin of the field. Therefore, the direction of rotation of the dipole will be locked to the momentum of the field as well.

USML can be used for routing the electromagnetic waves and controlling the interaction between a waveguide and a particle. If an atom is placed close to a waveguide, the interaction of the atom and the waveguide would depend on the spin-state of the atom [4]. USLM phenomenon can control the spin transition of the atom in an absorption scenario or the spin transition of the atom can determine the direction of propagation of the coupled wave to the waveguide in a photoemission scenario.

Metasurfaces have been heavily investigated for controlling the polarization of light in the far field [5]. Chiral metasurfaces have been shown to be able to distinguish between the left- and right-handed incident waves by changing the direction of propagation of the transmitted wave. However, the nearfield polarization properties of metamaterials have not been rigorously studied so far.

In this work, we investigate the near field spin properties of metasurfaces both theoretically and experimentally. We show that the use of polarizable particles in a periodic structure can determine the spin properties of the surface in the near field. Moreover, we show the difference in the spin properties of the metasurfaces for a metasurface composed of circularly polarized and chiral dipoles.

II. Spin-Momentum Locking of Light

The spin of evanescent waves has an intrinsic transverse component which is controlled by the direction of propagation. The spin is defined by,

$$\vec{s} = \frac{1}{2i\omega}\left(\epsilon_0 \vec{E}^* \times \vec{E} + \mu_0 \vec{H}^* \times \vec{H}\right). \tag{1}$$

The spin is directly related to the polarization of the light and can be expressed in terms of the third Stokes parameter. This equation shows that the spin is composed of electric and magnetic part. The electric spin interacts with the electric dipoles while magnetic spin interacts with magnetic dipoles.

Fig. 1 shows USML for HE_{11} mode of an optical fiber. This figure shows the relation of the spin to the polarization of the field at each point and how the direction of the spin is locked to the direction of propagation and direction of decay. At each location around optical fiber, the only way to change the direction of the spin to the opposite direction is to excite the optical fiber in the opposite direction.

III. Near Field Spin Measurements

To investigate the near field spin properties of metasurfaces, we use a tapered optical fiber to probe the local spin near the surfaces. The evanescent fields of a tapered optical fiber can extend around the fiber and interact with the surrounding medium. Fig. 2 shows an example of this interaction. When an object is brought close to the fiber, light can be coupled in or out of the fiber through this interaction.

If a metasurface is excited by an incident beam, the scattered field by the surface will have spin properties in the near field. The spin properties of the surface would depend on the properties of the meta-atoms. By taking the tapered fiber close to the surface the scattered field of the surface couples to the fiber in the near field regime. The direction of this coupling depends on the relative direction of the near filed spin and the optical fiber. By measuring the amplitude and direction of this coupling, we determine the direction of the near field spin of the metasurface.

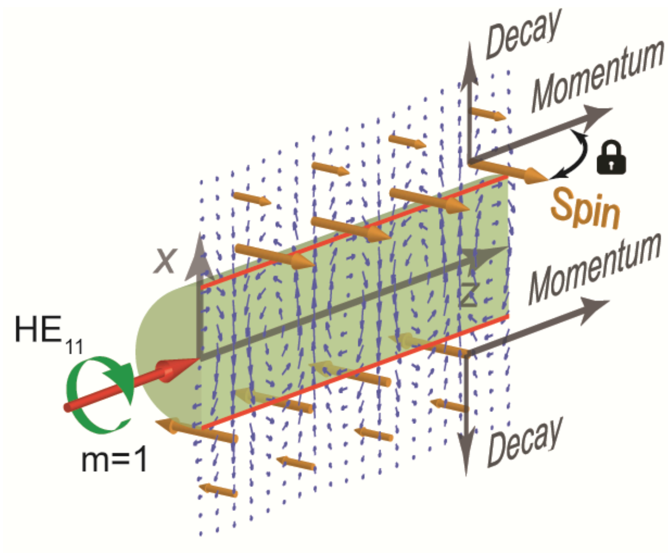

Fig. 1. USML for HE_{11} mode of an optical fiber. This figure shows that for a certain direction of propagation of the HE_{11} mode, the direction of the spin is locked. Moreover, the direction of propagation, direction of decay, and direction of spin form a right-handed triplet.

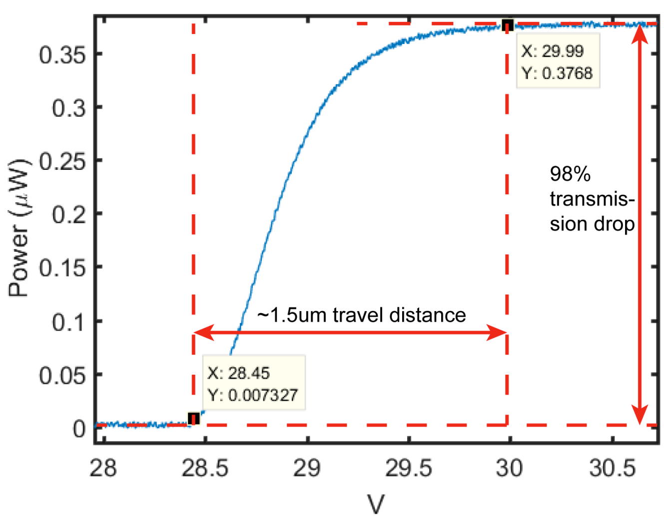

Fig. 2. Evanescent interaction of a tapered optical fiber with a spherical object. The diameter of the sphere is D=250 μm. The horizontal axis shows the voltage applied to the piezoelectric stage controlling the distance between the fiber and the sphere. Lower voltages correspond to closer distances. The vertical axis shows the power transmitting through the fiber. As the fiber comes closer to the sphere, the transmission drops which shows the evanescent interaction between the fiber and the sphere.

Changing the polarization of the incident light to the metasurface can change the near filed spin properties of the surface. For example, using circularly polarized light could create circular polarized dipoles if the metasurface is made of simple gold nanoparticles. Therefore, we can study the spin properties of the circular or linear dipoles by changing the polarization of light. Moreover, by using dielectric resonators in the metasurface, where both magnetic and electric dipole resonances are present [5], we can study chiral dipoles. Chiral dipoles are dipoles with both magnetic and electric components.

This study shows the different behavior of polarized and chiral dipoles. The direction of spin of the polarized dipoles only depends on the polarization of the incident light. But, the direction of spin of the chiral dipoles is intrinsic to the dipole and comes from the relative direction of the magnetic and electric dipole components.

This study opens up a new way of using metasurfaces by understanding their near field properties. The near field spin plays an important role in light matter interaction. Therefore, we can engineer the interaction between metasurfaces and quantum emitters on the surface.

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