Magnetic spin-locking of light

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***Abstract* – We show the directional excitation of Bloch surface waves controlled by the optical magnetic field, thus demonstrating the first magnetic spin-orbit interaction of light. Because it solely relies on the helicity of the optical magnetic field, this magnetic effect appears to be non-negligible even with a non-resonant dielectric scatterer (electric dipole) used as a Bloch surface wave coupler. Magnetic spin-locking opens new degrees of freedom in the manipulation and detection of light.**

I. INTRODUCTION

The magnetic field of light is often considered to be a negligible contributor to light-matter interaction. However, with the advent of the left-handed metamaterials [1], nanophotonics has recently investigated magnetic response in nanostructures to reveal the hidden magnetic part of the light-matter interaction to achieve new scientific prospects [1], [2]. In this paper, we show that the magnetic field of light has also the appealing ability to control the light coupling into optical surface waves.

Optical angular momenta are manifestations of polarization and spatial degrees of freedom of light. Remarkably, spin and orbital momenta are not independent quantities, the spin angular momentum (SAM) can be converted into orbital angular momentum (OAM), and vice versa [3]. Such a spin-orbit interaction (SOI) has recently drawn much interest in applications involving light manipulation. For example, SOI has demonstrated the remarkable property of controlling the propagation direction of guided modes, such as surface plasmons, fiber and waveguide modes, leading to the concept of a spin-controlled unidirectional waveguiding [4]-[7]. With the help of a subwavelength (dipolar) coupler, the longitudinal SAM of an impinging wave can be transferred into the transverse SAM of the evanescent tail of a guided mode, leading to a spin-directional coupling of the guided mode [4]-[6]. So far, such investigations mainly focused on the rotating electric component of light as the source of SAM originating the transverse spin-direction coupling.

II. RESULTS AND DISCUSSION

BSWs are surface modes on top of a 1D photonic crystal [8]. Importantly, when the BSW is TE-polarized, its evanescent tail in the surrounding medium is described by a rotating magnetic field (Fig. 1(a)), instead of a rotating electric field as for the (TM-polarized) surface plasmons or the guided mode of a nanofiber [4], [5]. The SAM of the surface wave is thus carried solely by its rotating magnetic field, the electric field shows no helicity.

We numerically studied (by a 2D-FDTD method) the coupling of a single magnetic dipole (MD) to such TE-polarized BSW [7], [9]. To this end, the dipole is positioned 10 nm above the top surface of the 1D photonic crystal described above, which radiates continuous light at λ = 1.55 µm. The MD rotates in the (yz) plane perpendicular to the surface, i.e., in the helicity plane of the rotating magnetic field of the TE-polarized BSW.

Figures. 1(b, c) show the snapshots of the resulting electric field amplitude along the (yz) plane. The MD, whose dipole moment is $\vec{m} = \vec{e}_y \pm j \cdot 0.53\,\vec{e}_z$ $(j = \sqrt{-1})$, rotates either anti-clockwise (Fig. 1(b)) or clockwise (Fig. 1(c)). The portion of the incoupled power that propagates in one of the two possible directions becomes larger than 99,9% of the total incoupled power. These results reveal a tunable unidirectional optical coupling controlled by the magnetic field of light.

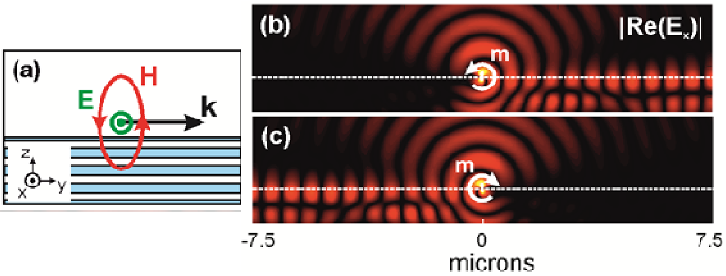

Fig. 1. (a) Schematic diagram of the electromagnetic field distribution of a TE-polarized BSW. (b) and (c): results by FDTD simulating the coupling of a spinning MD source, to a TE-polarized BSW. Above two simulation results represent, in false colors, the absolute value of the real part of the electric field ($|Re(E_x)|$). The MD rotates either (b) anti-clockwise or (c) clockwise.

The BSWs are produced on a 1D photonic crystal made of thin layers of silicon oxide and silicon nitride deposited alternately onto a glass wafer. A 600-nm wide and deep groove, used as a light-to-BSW coupler, is milled by FIB over a length of 20 µm. The structure is characterized in the far-field by projecting a slightly focused beam of controlled polarization onto the subwavelength groove, at an incidence angle of about 80° (λ=1.55 µm). The structure is imaged with an objective coupled to an infrared camera. Owing to the light scattering at the free surface of the 1D photonic crystal, a direct measurement of the relative intensities of the surface waves excited on both sides of the groove is possible.

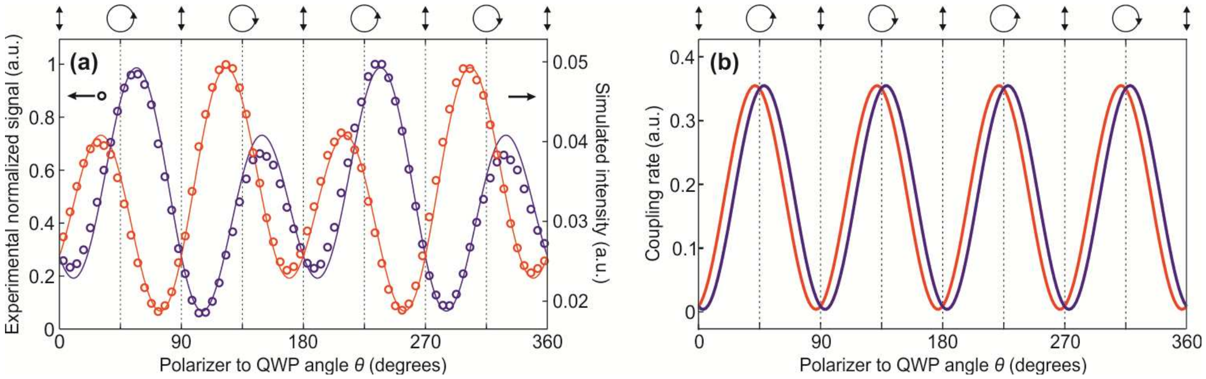

Fig. 2. (a) Detected signals (circles) and simulated intensities (FDTD method, dashed lines) on the right (blue) and left (red) BSWs, as a function of the angle. (b) Plots of the coupling rates R_r (blue) and R_l (red) (electric coupling) as a function of the angle θ.

We studied the distribution of incoupled power between the two surface waves, as a function of the incident polarization. The polarization is defined by the angle θ between the fast axis of a quarter-wave plate and the transmission axis of a polarizer. When $\theta = k90^\circ$ the polarization is linear whereas a circular polarization is achieved for $\theta = 45^\circ + k90^\circ$, $k = 0,1,2,3$. For intermediate angles, the polarization is elliptical. We plotted the intensities on both the right and left BSWs (noted S_r and S_l, respectively) as a function of the angle θ (Fig. 2(a)). The experimental plots are represented with circles together with the simulation results obtained with the 3D FDTD method (solid curves).

Because subwavelength scatterers are optically governed by an electric dipole moment, one may consider that a subwavelength groove on top a 1D photonic crystal interacts with the electric field of an incoming wave to transfer energy to the BSWs. Following this pure electric model, and assuming an incident plane wave, coefficients S_r and S_l defined previously become proportional to the coupling rates:

$$\alpha\left|\vec{e}_i \cdot \vec{E}_{inc}(\vec{r}_0)\right|^2, \tag{1}$$

where $i = r, l$ denotes the right and left sides of the groove and α is a constant. $\vec{E}_{inc}$ is the incident electric field at a single point of coordinate $\vec{r}_0$ along the subwavelength groove. $\vec{e}_i$ is the unit vector along the directions of the electric field of the emerging right and left BSWs.

R_r and R_l are described by two 4θ-dependent sinusoids with a relative shift of 8°. The experimental results show two sinusoids, shifted by 30°, whose amplitudes are modulated. We have shown that this helicity-dependent modulation (not predicted with our model of a pure electric coupling) is due to a magnetic spin-orbit interaction of light.

III. CONCLUSION

We described a new magnetic effect in light-matter interaction, called magnetic spin-locking. Based on this magnetic SOI, individual elliptically polarized MDs are shown to develop a tunable unidirectional coupling of light into TE-polarized BSWs. This phenomenon was demonstrated using a simple subwavelength groove as a light-to-BSW converter. Despite the ED nature of this coupler, the magnetic effect is of the same order of magnitude as the electric effects in play in the coupling process. In this case, the optical magnetic field does not influence the total energy transferred to the BSWs, but instead, it controls the directionality of the incoupled energy. Beside the fundamental questions raised regarding magnetic optical control of light-matter interaction, our results open new possibilities for controlling optical flows in ultra-compact architectures. Reciprocally, BSWs can be used as integrated probes to locally investigate the magnetic spin density of light.

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