Photonic Spin-Orbit Interaction in Few-Mode Optical Fiber

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Abstract: We demonstrate interaction between spin and orbital angular momentum of light in a straight few-mode fiber, evidenced by rotation of output intensity patterns controlled by input spin handedness.

OCIS codes: (060.2310) Fiber Optics, (350.5500) Propagation

1. Introduction

Interaction between spin angular momentum (SAM) and orbital angular momentum (OAM) degrees of freedom, which gives rise to diverse electronic phenomena such as atomic energy level splitting and spin-Hall effects, can also appear in optical systems, even though photons have no magnetic moment or mass [1]. Surprisingly, in the case of propagation in cylindrical waveguides, the same formalism for spin-orbit interaction (SOI) describes both photons and electrons, and can be interpreted as a splitting of the modal dispersion curves [2]. The effect may allow for precise control over modal dispersion in waveguides [3], and has potential applications in quantum information science.

Previous theoretical investigation [2, 4-6] and experimental studies of SOI in optical fibers have provided some evidence for the effect, but the experimental demonstrations have involved speckle patterns in highly multimode fibers [6] or the special case of unit-value OAM where mode degeneracy complicates the dynamics [7]. We report observation of a particularly clean and elegant manifestation of the SOI as the rotation of a spatial mode pattern at a constant rate in degrees/cm as the light travels in the fiber. The mode rotation occurs inside the fiber, and not in free space, as the SOI occurs only in inhomogeneous media.

The observations are qualitatively consistent with the predictions for spin-orbit interaction as described in [2]. The effect leads to macroscopic mode rotation rates (~few degrees per cm), in contrast to the exceptionally small effects observed in the context of the optical spin-Hall effect [8], where transverse beam shifts of tens of nm were observed [9]. In the case of propagation in a fiber, the continual interaction of the light with the index gradient leads to such large rotation rates.

2. Theory [2]

Consider a fiber with permittivity profile $\epsilon(\rho) \equiv \epsilon_0 n^2(0)\left(1 - \Delta\chi(\rho)\right)$ where, ϵ_0 is the permittivity of free space, n is the refractive index, and $\Delta \equiv \frac{\epsilon(0) - \epsilon(a)}{\epsilon(0)} = \frac{n^2(0) - n^2(a)}{n^2(0)}$ is the index change between the core and the cladding (which extends from $\rho = a$ to $\rho = \infty$). A circularly polarized (CP) mode basis can be created by adding together the well-known linearly polarized (LP) modes, ($LP_{m,q}\hat{x} + i\,\sigma\, LP_{m,q}\hat{y} = CP_{m,q}\hat{e}_\sigma$) where $\sigma = \pm 1$ is the helicity of the light, and m and q are the OAM and radial quantum numbers, respectively. For a CP mode, the first-order polarization correction to the propagation constant, β, for $|m| \neq 1$ is

$$\delta\beta = -\sigma\mu \frac{\pi |m| \Delta}{2\beta_0} N^2 \int \frac{\partial \chi}{\partial \rho} |\psi_{m,q}(\rho)|^2 \, d\rho, \tag{2}$$

where $\mu = \frac{m}{|m|} = \pm 1$, N is a normalization constant, and $\psi_{m,q}$ is the radial mode function. Combining two modes with the same circular polarization but equal and opposite m

$$\frac{1}{\sqrt{2}}\left(CP_{m,q}\, e^{-i\,\sigma\mu\,|\delta\beta| z} + CP_{-m,q}\, e^{+i\,\sigma\mu\,|\delta\beta| z}\right)\hat{e}_\sigma \propto CP_{|m|,q} \cos(|m|\,\phi - \sigma|\delta\beta|z)\hat{e}_\sigma, \tag{3}$$

produces an intensity pattern with a simple rotation versus propagation distance, with σ controlling the direction and $|\delta\beta|$ controlling the rotation rate. The effect is simple only when $|m| = 2$ or greater, because in the m = 0 case there is no SOI, and in the $|m| = 1$ case the modes mix and alter shape and polarization rather than simply rotating [7].

3. Experiment

Thin crossed wires and an adjustable iris in an external-cavity HeNe laser are set to excite a HG_{11} mode and a zoom lens is adjusted to select a beam waist that maximizes the overlap between the input mode and the CP_{22} fiber modes.

The fiber used has multiple index steps and is designed to separate the LP_{02} modes from the LP_{21} modes in β value [3]. It is not yet clear what role this has in isolating the LP_{22} modes, although clean and repeatable coupling into the LP_{22} modes is observed. A polarizing beam splitter passes the horizontally polarized input beam, which is transformed to circular polarization by the quarter-wave plate immediately prior to the input microscope objective. Light reflected off of the fiber input face is transformed to vertical polarization and reflected onto a viewing screen and allows for imaging of the fiber input face to aid in precision input coupling.

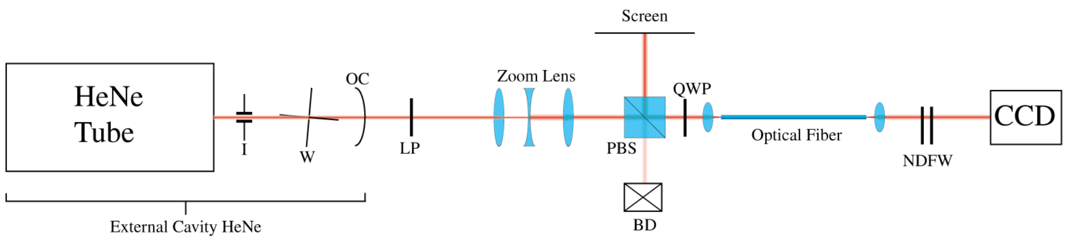

Fig. 1 Experimental setup. OC = output coupler. W = crossed wires. LP = linear polarizer. PBS = polarizing beam splitter. QWP = quarter-wave plate. NDFW = neutral density filter wheel. BD = beam dump. CCD = charge-coupled device camera. The linear polarizer is set to horizontal polarization. The QWP is set to create left- or right-circularly polarized light.

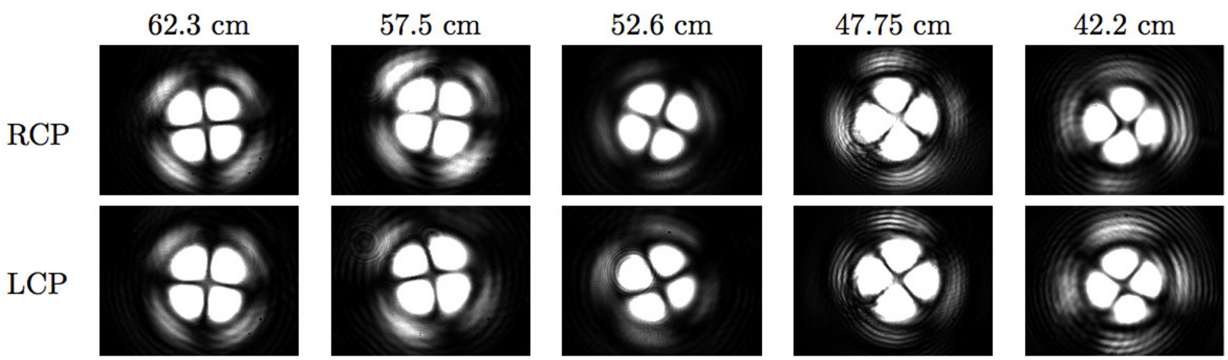

Fig. 2 Images of a subset of the recorded output modes illustrating the rotation. The fiber length traversed is indicated across the top and the input circular polarization is denoted on the left.

The entire length of fiber is stripped of its jacket and the input end of the fiber is epoxied into a v-groove and positioned on a 5-stage fiber mount. Once the input mode is coupled so as to create a clean output mode, none of the input optics, except for the quarter-wave plate, are adjusted for the remainder of the data run. Iteratively, beam images are recorded for both right and left circularly polarized input, and then about 1.2 cm is removed from the output end of the fiber with a cleaving tool. A subset of the pictures recorded is shown in Fig. 2. The rotation rate is found to be constant but of opposite sign for right- and left-circularly polarized light, as predicted, with a rate of about 3 degrees/cm.

4. References

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