Photonic spin Hall effect for precision metrology

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Spin-dependent spatial beam splitting in the photonic spin Hall effect is sensitive to variations in the thickness of metal and graphene nanofilms.

The photonic spin Hall effect (SHE) manifests itself as spin-dependent spatial splitting of left- and right-handed circularly polarized components when a spatially confined light beam is reflected or transmitted at an interface.\(^1\)\(^-\)\(^3\) This interesting phenomenon is generally believed to result from an effective spin-orbit coupling that describes the mutual influence of the spin (polarization) and the trajectory of the light beam.\(^4\)\(^-\)\(^6\)

Remarkably, the spin-dependent splitting in photonic SHE is sensitive to the physical parameter variations of different systems and holds great potential for applications in precision metrology. However, the splitting leads to displacement too small to be detected directly.

We have used a precise signal enhancement technique called quantum weak measurement, which has attracted much research attention.\(^7\)\(^-\)\(^13\) Using quantum weak measurement, the photonic SHE can be detected with the desired accuracy to determine the corresponding physical parameters. In our recent work, we found that the photonic SHE can be an effective way of measuring the thickness of a metal nanofilm\(^14\) and identifying the number of layers of graphene.\(^15\)

A schematic diagram of the weak measurement experimental process is shown in Figure 1. Our sample is a BK7 (specialist glass) prism covered with a metal or graphene nanofilm. A Gaussian beam generated by a helium-neon laser is first focused by the lens (L1) and selected as horizontally or vertically polarized by the polarizer (P1). When the light beam reflects from the sample interface, the photonic SHE splits the left- and right-handed circularly polarized components in the y-direction, corresponding to transverse displacement. In quantum mechanical terms, this process is a weak interaction coupling the observable and the measurement equipment. The beam then passes through the second polarizer (P2), where it is once again selected approximately as vertically or horizontally polarized. At the surface of the second polarizer, the two spin components experience destructive interference, making the enhanced shift in the meter much larger than the initial one. Calculating the reflected field distribution yields the amplified shifts of the photonic SHE. After passing through the second lens (L2), a CCD is used to capture the optical signal and measure the amplified shifts.

We first used the photonic SHE to measure the thickness of a metal nanofilm.\(^14\) We found that the spin-orbit coupling in the photonic SHE can be effectively modulated by adjusting the film thickness. In addition, the transverse displacement is sensitive to the thickness (in a given range) of the metal film for a horizontally polarized light beam, and a large negative transverse shift can be observed. We measured the amplified displacements of light beam deflection on a BK7 glass substrate coated in three different thicknesses (10, 30, and 60nm) of silver film.
Our experimental results are shown in Figure 2. Note that these results are in good agreement with the theoretical ones when the film thicknesses are 30 and 60nm. However, the SHE is very sensitive to error when the film is as thin as 10nm, and we observe a small deviation between experiment and theory when the film is actually about 12nm.

We also propose using the photonic SHE to identify the number of layers of graphene in a sample. A quick and convenient technique for counting the layers of graphene film is important for accelerating the material's study and exploration. Many methods exist, but they all have limitations. We have found that the photonic SHE is sufficiently sensitive for this purpose.

First we need to calibrate the system by establishing the relationship between the spin-dependent displacement and the number of graphene layers. To do this, we need to know the refractive index of graphene, which is complex, nonlinear, and dependent on wavelength and the graphene thickness. We calculated its value as $3.0 + 1.14i$ for light of wavelength $633\text{nm}$, and showed experimentally with one- and two-layer graphene films that this value is appropriate for films with few layers. It should be noted that experimental conditions prevent us from precise fabrication of graphene with more than two layers. In this example, we know just the approximate number of layers (three to five). To determine this more precisely, we measure the photonic SHE transverse displacements with the incident angle changing from $56$ to $62^\circ$ (see Figure 3). To avoid the influence of impurities and other surface quality factors of graphene film, we carried out the experiment for three different areas of the graphene sample and concluded that there are actually three layers in the film.

In summary, we have investigated the photonic SHE of a light beam reflected from the surfaces of metal and graphene nanofilms. After establishing the quantitative relationship between the spin-dependent shifts in photonic SHE and the physical parameters in these systems, we used the quantum weak measurement technique to characterize the thickness of metal nanofilm and identify the number of graphene layers. Continued on next page
These findings provide a practical application for the photonic SHE and the possibility of developing a spin-based nanophotonic device. We are also working to use the photonic SHE to determine the magneto-optical constant of magnetic film. In addition, we plan to use the photonic SHE to determine the photon momentum in a transparent dielectric.

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