Observing the spin Hall effect of pseudothermal light through weak measurement

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The spin Hall effect of light (SHEL) can be observed by the dark strip resulting from weak measurement. We find that the SHEL of a partially coherent beam (PCB) has a similar phenomenon as well. However, the dark strip in the SHEL of a PCB cannot be explained by considering the beam as an assemblance of coherent speckles. Also, the dark strip in a PCB is not purely dark. By analyzing the autocorrelation, we show that the SHEL of a PCB is the result of overlapping coherent speckles' SHEL. We further prove our conclusion by adjusting convergence and incident angles. Finally, we develop a qualitative theory to clarify the SHEL of a PCB.

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The spin Hall effect of light (SHEL)[1] has attracted growing attention as a result of the rapid development of optics at nano- and subwavelength scales[2,3]. The SHEL and the Goos–Hänchen (GH) shift[4], which are both caused by the conservation of a photon's momentum, have been explored in different areas[5–11]. The research of the SHEL of complex incident beams and the SHEL at special incident angles bring about brand-new analysis of reflection/refraction[12,13] and the new experimental technique: weak measurement[14,15]. The applications of the SHEL also produce new methods for examining the optical properties of complex media[16–19].

Pseudothermal light is created to simulate the fluctuation of thermal light by manipulating coherent light[20–22]. It can be generated by focusing a laser on a ground glass disk. The rough surface of the ground glass disk causes diffraction and scattering, which give a speckle pattern fluctuating like thermal light. When the disk is rotating, the pattern fluctuates with a higher rate. By changing the rotation speed, one can change the coherence time of the pseudothermal light. In real applications (like the examination of complex media's optical properties using the SHEL), temporal and spatial coherence of the signal light cannot be as good as a laser beam[23]. How to extract useful information (like the SHEL) from the signal, which is only partially coherent, remains a problem to be solved. Therefore, it is important to study the SHEL with different degrees of temporal and spatial coherence.

The spin Hall effect of pseudothermal light has been predicted theoretically[24] and confirmed experimentally[25,26]. It is shown that partially coherent light exhibits the same property with coherent beams in spatial shifts, but behaves differently in angular shifts. Different from Refs. [25,26], in this Letter we use weak measurement to observe the SHEL of pseudothermal light. Weak measurement[14,15] is useful in the amplification and detection of weak effects. It amplifies the SHEL of each individual speckle of the pseudothermal light, making detection and processing easier.

In our measurement, the SHEL measurement is equivalent to measuring the spin projection along the central propagation direction. The spin of single photons $\hat{\sigma}_3$ have an eigenstate $|+\rangle$ and $|-\rangle$ (right and left circular polarization). In our case, we preselect and postselect the polarization of the light as $|\psi_1\rangle$ and $|\psi_2\rangle$. $|\psi_1\rangle$ is horizontal polarization, given as $|H\rangle = (|+\rangle + |-\rangle)/\sqrt{2}$. The postselected polarization is detuned from vertical polarization $|V\rangle$ by a small angle Δ in order to get the enhancement effect of weak measurement: $|\psi_2\rangle = |V \pm \Delta\rangle = -i\ \exp(\mp i\Delta)|+\rangle + i\ \exp(\pm i\Delta)|-\rangle$. Then the amplified measurement of the observable $\hat{\sigma}_3$ is given by

$$(\hat{\sigma}_3)_W = \frac{\langle\psi_2|\hat{\sigma}_3|\psi_1\rangle}{\langle\psi_2|\psi_1\rangle}. \tag{1}$$

By using the theory introduced in Ref. [14], we can first predict the SHEL of pseudothermal light. Coherent beams are transferred to pseudothermal light with a rotating frosted glass. The roughness decides the spatial coherence of the output beam and the rate of rotation affects the temporal coherence. For a highly coherent beam, the visual appearance of the SHEL via weak measurement is the dark strip on the observation plane resulting from the splitting of right and left circular polarization light[27]. Therefore, the experimental appearance of the SHEL of pseudothermal light should merely be a homogeneous darkening of the intensity distribution if we regard a pseudothermal light beam as an assemble of small coherent Gaussian speckles. In contrast, our results are not as simple as our expectation. In our experiment, the SHEL of a partially coherent beam (PCB) shows a dark strip in the center of the beam, which is similar to the SHEL of a coherent beam.

We use the setup shown as Fig. 1(a) for the observation of the SHEL of pseudothermal light via weak measurement. The 632.8 nm laser beam is first filtered by a polarized beam splitter (PBS) in order to purify the incident beam as linear polarized. By adding a half-wave plate, we get the ability to change the direction of polarization. After a set of lens-diffuser-lens, the beam is transferred to pseudothermal light and focused onto the surface of the glass prism. Our diffuser is made of ground glass mounted on a motor. It rotates slowly with an angular velocity of about 0.027 rad/s, giving an average speckle size of 120 μm. The speckle correlation time is about 500 ms[28]. The fluctuation frequency of the speckles is much lower than the camera capturing rate of 100 captures/second (10 ms exposure time). Thus, the ground glass can be approximated as at rest. Due to the conservation of the photon's momentum in reflection, the SHEL of the PCB happens on the prism's surface. The beam is then collimated and passes through a second PBS, which accomplishes the weak measurement process. Afterward, we acquire the result by a charge-coupled-device (CCD) camera. The intensity distribution captured

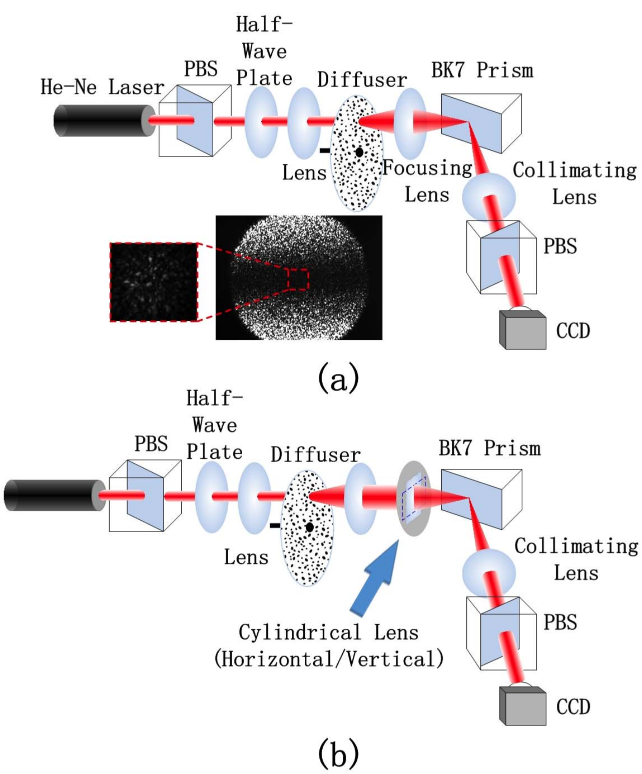

Fig. 1. (a) Setup used to observe the SHEL of pseudothermal light via weak measurement. The diffuser is kept still when taking the inset picture. The incident angle is set to be 48.3°. (b) The setup to test the effect of overlapping density. A cylindrical lens is added to vary the overlapping density of the speckles. When the cylindrical lens is set horizontal (vertical), the overlapping density is relatively large (small), thus the dark strip of pseudothermal light is expected to be narrow (broad). The results captured by CCD are given in Fig. 2. The polarizer is deviated by 0.3° from being crossed with the incident beam's polarization, which decides the amplification factor of the weak measurement.

appears as a dark strip, as shown in the inset of Fig. 1(a). However, the dark strip is not purely dark. Even though the average intensity in the strip is lower than the adjacent parts, there are speckles spreading in this area. As mentioned above, this result cannot be fully explained if regarding the pseudothermal light as a simple assemblance of coherent speckles.

To explain this result, we undertake several experiments. Autocorrelation is commonly used to reveal the information about individual speckles when dealing with pseudothermal light. Same as the method used in Ref. [25], the autocorrelation is obtained and shown in Fig. 2, especially for the central part of the dark strip. The autocorrelation exhibits that, aside from the general shape of the Gaussian distribution, there are pairs of peaks spreading symmetrically about the center. One reasonable interpretation is that the peaks are the SHEL of coherent units that form statistically the SHEL of the pseudothermal beam. We may regard this as our preliminary guess.

To verify our preliminary guess of the formation of the pseudothermal SHEL, we add a cylindrical lens in the setup, as shown in Fig. 1(b). Here, we take two steps to explain the function of the cylindrical lens. In the first step, we need to notice if the cylindrical lens can change the overlapping density of the speckles in one direction. Given that the degree of spatial coherence is fixed, the total number of speckles is a constant. So, by limiting the dimension of the beam along one specific dimension using the cylindrical lens, the overlay density of the speckles along that direction will increase. The second step is to clarify the effect of the overlay density on the width of the dark strip. If the SHEL of pseudothermal light is built by the SHEL of coherent speckles, the residue speckles in the dark strip should be due to the incoherence between single speckles. Now, it is natural to think that if the overlay density is increased more residues will be generated in the dark strip, i.e., the width of the dark strip will decrease.

Let us summarize the effect of the cylindrical lens supposing our guess is right. We use the setup as shown in Fig. 1(b) to adjust the overlay density of the speckles. If the speckles are converged tightly in the vertical direction onto the prism, then the strip, which is horizontal for the SHEL, should be relatively narrow. On the other hand, if converged loosely, the strip should be relatively broad since the speckles are spread in a larger area. By switching the cylindrical lens to a horizontal/vertical position, the overlay density of the speckles along the vertical/horizontal direction can be changed. We can anticipate that, if our preliminary conclusion is correct, the strip would be relatively narrow if the lens is horizontal, while the strip would be broad if the lens is vertical.

The results captured by the CCD match our predictions, as shown in Fig. 2. This demonstrates that the whole picture of the SHEL of pseudothermal light is composed of a large amount of the SHEL of the speckles. The red lines in Fig. 2 illustrate the positions where the average light intensities are equal. When the cylindrical lens is set horizontally, the strip in the center of the intensity

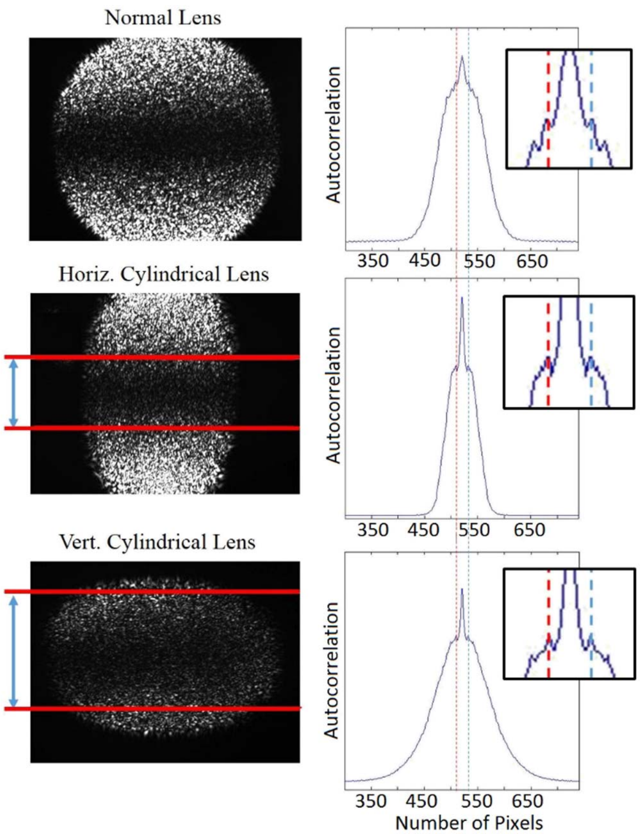

Fig. 2. SHEL of pseudothermal light in different cases. The first row shows the SHEL observed using a normal lens to focus the pseudothermal light, the second is using a vertical cylindrical lens, while the third is using a horizontal cylindrical lens. The autocorrelations are listed in the second column. It can be seen that pairs of peaks emerge in each picture, but the positions are the same. This can be interpreted as the SHEL of the PCB being a superposition of the coherent speckles' SHELs. Autocorrelation reveals the SHEL of unit speckles. The outermost pair of peaks can be seen as higher-order autocorrelation peaks. (The frosted glass is rotating with an angular velocity of 0.027 rad/s in this experiment. Autocorrelations are obtained by averaging 20,000 results. Each picture's exposure time is 10 ms. The gain is set to be 500. The size of the CCD pixel used is 6.45 μm by 6.45 μm.)

intersection is narrower than the scenario when set vertically. However, the positions of the peaks (see insets) in the autocorrelation remain the same. The reason for this result is that at the same incident angle, every individual speckle acts on its own. For speckles that are incident at the same angle and are of similar sizes, the spatial shifts for different polarization components in the SHEL of each speckle are more or less the same. Thus the linear polarized portion in the central part of every speckle has the same width. Then, filtered by the polarizer (key step of weak measurement), in every speckle there appears a dark strip of the same width and this width is invariant with overlay density. By overlapping a large amount of these speckles, we get the SHEL of pseudothermal light.

To further prove our interpretation, we test it at different incident angles. Some researchers have revealed that the SHEL of coherent beams decreases as the incident angle approaches to the Brewster angle (56.55° here)[29]. Assuming our interpretation is right for pseudothermal light, the SHEL of the PCB should also decease when the incident angle is set close to the Brewster angle. By setting the pseudothermal light incident at different angles, we obtain a general trend of how the width of the dark strip in the pseudothermal beam varies. We track the strip width of the whole beam rather than the autocorrelation results since we are limited by the CCD resolution. In our experiment, one speckle occupies an area of about 20 pixels by 20 pixels on the CCD camera and it is separated into two parts by the dark strip. It is almost impossible to resolve each part's center (maximum intensity point), since each part is only around 6 pixels in length. In Fig. 3, two typical pictures captured at different incident angles (53.6° and 56°) are given. As before, the red lines in the pictures represent the same average light intensity. We can see that, by altering the incident angle approaching to the Brewster angle, the width of the strip decreases. This matches the previous work done for coherent light[29]. Therefore, our interpretation is legitimate to explain the SHEL of pseudothermal light.

It also worth noting that, not limited in the SHEL scenario, our interpretation can also be applied to the GH shift. By using incident beams with different polarizations, the case when the SHEL and GH shifts both happen can be settled, as given in Fig. 4. The first row illustrates the cases for highly coherent beams with different polarizations and the second is for pseudothermal beams. The

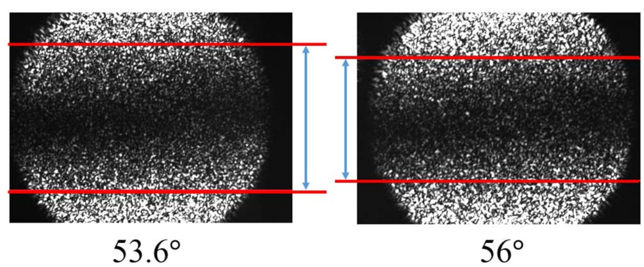

Fig. 3. SHEL of PCBs at different incident angles. It is confirmed that the SHEL of coherent light decreases if the incident angle is approaching the Brewster angle (56.55° for a BK7 prism)[29]. This experiment proves that PCBs follow the same trend.

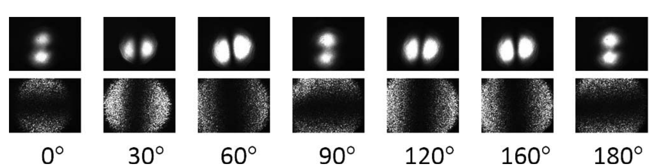

Fig. 4. Rotation of the strip of PCBs at different polarizations agrees with the rotation of coherent beams. We can determine that our theory applies to both the Imbert–Fedorov (IF) shift and the GH shift.

angles listed are the polarizer's angles relative to the initial position. It is shown that the directions of the strip for both the coherent and pseudothermal beams are synchronous. This synchronization means that regardless of what type of shifts (GH/Imbert–Fedorov) that happens, the explanation of the speckle's shifts forming the whole beam's shift is feasible.

Until now, our experiment's results indicate that the formation of the SHEL of pseudothermal light is due to the large collection of the SHEL of small individual speckles, but we still lack a proper explanation about the cause of the dark strip. As a matter of fact, the origin of the dark strip of the pseudothermal profile is the coherence remaining in the pseudothermal light. A sketch is given in Fig. 5. The average intensity profile of the speckles has a Gaussian distribution, and the polarization properties are shown with the black arrows. On the other hand, the pseudothermal light as a whole abides by the super-Poisson distribution. Considering the super-Poisson distribution is also Poisson-like (high in the center) and the pseudothermal beam is at least partial coherent, therefore the general intensity and polarization profile of pseudothermal light can also be roughly described by Fig. 5. Furthermore, both the individual speckles and PCB have a dark strip appearing after weak measurement. Thus, the strip of the pseudothermal light is not purely dark due to the incoherence of the pseudothermal light. If the beam is totally coherent, the strip will be purely dark just like coherent light.

In conclusion, we propose an unsolved phenomenon observed when weak measurement and pseudothermal light are utilized in the experiment of the SHEL. Similar to coherent light, the SHEL of pseudothermal light also shows a dark strip. But the strip of pseudothermal light scatteres speckles in it. To figure out the reason, we perform several experiments. The autocorrelation of the central part of the strip is first retrieved and pairs of peaks emerge on top of the general Gaussian intensity distribution. We make the preliminary guess that the SHEL of pseudothermal light is composed of the SHEL of the coherent speckles statistically. Then two more tests are conducted, including changing the overlay density of the speckles, and changing the incident angles of the beam. All the results can be properly anticipated and explained by our interpretation. Finally, the appearance of the strip is also explainable when the intensity distribution is taken into account. Hence, we make the conclusion that because of the coherence of the speckles and the Gaussian-like intensity distributions, individual coherent speckles and the PCB both have dark strips when weak measurement is applied. However, there exists a difference that, thanks to the incoherence of the pseudothermal light, there are speckles remaining in the dark strip, which makes the retrieval of the SHEL of individual speckles through autocorrelation possible.

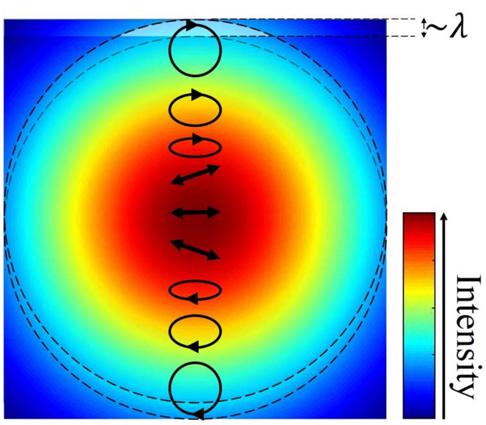

Fig. 5. Sketch of the intensity and polarization distribution of coherent individual speckles with an SHEL. The right/left circular polarization part of the incident beam is shifted due to the IF effect. The separation of two polarization components is on the order of a wavelength. Because the intensity follows a Gaussian-like distribution, the overall polarization is illustrated with the black arrows. The pseudothermal beam, as a whole, also follows this distribution.

Nevertheless, we admit that there is still a lot of work not done yet. Our interpretation only gives a qualitative explanation, short of quantitative analysis. Due to the limit of the CCD resolution, we are unable to reveal the variance of the SHEL of single speckles. With a CCD with a higher resolution, measurement of pseudothermal light combining weak measurement and autocorrelation could be developed into a new method of measurement that may give a better accuracy.

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