Polarization beam splitting in a Glan-Taylor prism based on dual effects of both birefringence and Goos-Hanchen shift

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ABSTRACT

With the structure of biprism, polarization beam splitting in a Glan-Taylor polarizer was explored based on the birefringence and Goos-Hanchen shift. Due to the birefringence of the light in calcite crystal, the extraordinary light worked as the position calibration. As for the ordinary light, the propagated direction tilted noticeably due to the refraction as well as Goos-Hanchen effect at the prism-air interface of in the air gap. The Snell's law and stationary-phase approach were utilized for the calculation of the beam splitting between the two orthogonal polarization elements. By choosing appropriate incident angle and initial polarization, remarkable beam splitting was realized. With this configuration, the resolution with a magnitude of $10^{-5}$ and $10^{-3}$ was achieved for the response of the incident angle and polarization detection respectively.

1. Introduction

Polarization beam splitting (PBS), which means the space separation along different directions of the light with orthogonal polarizations via specific technical method, plays a great role in the design of optical devices and integrated optics. Conventional technology, such as Wollaston prism, Rochon prism, Glan-Thomson prism, etc. are based on birefringence effect [1]. In addition, the different energy band structures of orthogonal polarizations of specific materials could be utilized for PBS [2, 3]. Besides, Spin-orbit interaction based Spin Hall Effect of Light (SHEL) [4, 5, 6] and the polarization-dependent Goos-Hanchen (GH) effect [7, 8] also exhibits a great potential in PBS.

GH effect was predicted by Newton in 1672 about the phenomenon that a shift of the reflection light would occur at the interface of two medium in the condition of total internal reflection (TIR) [9]. Since F. Goos and H. Hanchen experimentally demonstrated GH shift through multiply-reflection [10], more and more researches have been carried out for the detection of sub-wavelength GH shift, numerous approaches based on multilayered and periodic structures [11], a single thin dielectric layer [12], surface plasmon resonance [13], Brewster angle [14] and graphene-coated surface [15, 16] and Fano resonance [17], were proposed to enhance the displacement between reflecting point and incident point. In addition, the quantum weak measurement, which has unique advantage in the detection of tiny physical parameter through the weak value amplification, was introduced into the exploring of GH about the direct observation as well as indirect application study [18, 19, 20, 21]. However, most of these investigations were conducted based on TIR.

As reported, for the reflected light, the GH shift could be positive or negative. But as for the transmitted beam, it should always be positive [22, 23], which is of great significance for the application of GH shift in various fields. Actually, frustrated total internal reflection (FTIR), in which the light could propagated through an air gap in a biprism configuration with an incident angle larger than the critical angle, has been a hotspot in the research of GH shift about transmitted light [24, 25, 26, 27, 28, 29]. In most scenarios, the reflection and transmission of the light in FTIR was explored with a large incident angle that satisfying the criteria of TIR. However, in 2002, with an incident angle less than critical angle, Jacob Broe and Ole Keller realized the Quantum-well enhancement of the GH shift by coating a metal film in the internal surface of two-prism [30]. Two years later, Chunfang Li et al. investigated the GH shifts for TE and TM light beams in an asymmetric double-prism configuration with a small incident angle, and reported that even no evanescent wave in the configuration, the GH shift of reflected light still exists with a high value [31]. Hence, a new approach about the research...
on GH shift was provided with configuration of biprism and the condition of less incident angle.

As a common polarization splitting prism, Glan-Taylor prism is primarily investigated about the configuration design [32], intensity transmittance [33] and extinction ratio [34], for a better application. In this work, a Glan-Taylor prism was utilized for the exploration of PBS with a biprism configuration, which contributed to the GH shift except birefringence. Due to the birefringence effect in the crystal, two orthogonal polarization lights were produced. For the ordinary light (o-light), the incident angle on the first prism-air surface was slightly less than the critical angle, a remarkable GH shift occurred. Combined with extraordinary light (e-light), which was taken as a position calibration, a conspicuous PBS was observed. Hence, in this work, the dual effects (i.e. Birefringence and Goos-Hanchen shift) were considered and investigated for the PBS of Glan-Taylor prism. By analysing the position of the outgoing beam, the incident angle and the polarization of the incident light could be detected with a high sensitivity.

2. PBS in Glan-Taylor prism

The experimental system was mainly constituted with a Glan-Taylor prism (Thorlabs Inc., GT15-B) and a half-wave plate, which was exploited for a polarization adjustment of the incident light. The angle between the fast axis of the half-wave plate and the horizontal direction is $\alpha$. The Glan-Taylor prism consisted of two identical right-angle trapezoidal calcite crystals with a wedge angle of 52°. The distance between the two crystals was 0.25 mm, and the optical axis direction was on $y$-axis. The incident angle of the light at the first interface of the prism was $\theta$, as shown in Figure 1. The light with a center wavelength of 795nm was prepared to be vertical polarization by a polarization splitting prism (PBS) and a half-wave plate, i.e. $\alpha = 90^\circ$. Due to the birefringence effect in the calcite crystal, two beams of refracted light with mutually perpendicular vibrational directions, i.e., o-light and e-light, were produced. The outgoing light was received by the Laser Beam Profiler for a spot analysis.

In the circumstance of a normal incidence, i.e. $\theta = 0$, the incident angle of o-light at the first prism-air interface in the prism met the condition of TIR, and could not transmit to Laser Beam Profiler. However, with a tilted angle $\theta$, the incident angle could be less than the critical angle, and GH shift of the transmitted beam occurred in the air gap. As reported, in the barrier with the width $a >> 1/k$, where $k$ represented by $2\pi/\lambda$ is the wave vector of the laser with the wavelength of $\lambda$. The tunneling time of particles saturated, and the GH shift would not increasing with the width of air gap of biprism [35]. In this work, the air gap of the Glan-Taylor Polarizer utilized in this work was 0.25 mm, which was far outweigh the wavelength of light. Therefore, when the incident angle at the first prism-air interface was near the critical angle, the resulting GH shift will be a constant value independent of $a$, and expressed with $S$, as shown in Figure 1. The dashed line that exists in the air gap shown is the gap length in the saturated state of the GH shift.

Then, due to the long air gap, when the o-light passing through the longitudinal displacement reached the second air interface, the corresponding angle and displacement could be calculated by Snell’s law. Finally, the o-light continued to propagate through the second crystal to reach the exit surface. Through Snell’s law, the exit angle and exit position at this interface could be calculated. For the e-light, the propagation path of the beam was calculated according to the refractive index ellipsoid. Then, the exit position and displacement of the e-light at each dividing surface of the Glan-Taylor prism were obtained.

As shown in Figure 1, the light incident into the Glan-Taylor prism at the point of A. Through the polarization beam splitting, the o-light and e-light exited from point B and C respectively. The splitting distance between B and C was represented with $S_a$. For e-light, the displacement $S_b$ from point A to C on the $y$-axis was calculated with the principle of refractive index ellipsoid and combining the geometric relationship. Hence, with this method of geometrical optics, the difference between the displacement of o-light and e-light could be theoretically expressed with spot separation distance, as the following equation presents.

$$S = abs(S_a - S_b) \quad (1)$$

Taking the left bottom of Glan-Taylor prism as the origin, an x-y coordinates was built as shown in Figure 1. The light beam is incident at the center of the incident surface of the Glan-Taylor prism that is 15 mm wide. The short side length of the bottom edge is 3 mm, while the long side is 12 mm and the air gap is 0.25 mm. The angle of o-light and e-light at each interface of Glan-Taylor prism was calculated and displayed in Table 1, corresponding positions were exhibited in Table 2 and Table 3.

Thereby, the theoretical beam splitting of the outgoing o-light and e-light, i.e., the theoretical distance of the centers of the two light beams at different incident angles, were calculated as shown in the red spots in Figure 2(a).

Obviously, with the increasing incident angle, the separation amount of o-light and e-light decreases. For a further confirmation, this model was simulated by Zemax software with the same parameters, and the result was greatly consistent with theoretical calculation, as shown in Figure 2(a). In addition, the incident angle tilting about A-centered and that around the center of Glan-Taylor were simulated. The results displayed in the inset of Figure 2(a) showed that the polarization beam splitting in both conditions was the same at a certain incident angle. According to the theoretical calculation with current parameters of Glan-Taylor prism, the incident angle less than 1.1°, which was the critical angle of o-light with total internal reflection (TIR), leads a single emitting light beam (e-light). Experimentally, with the width of air-gap, the o-light with an incident angle less than 1.18° could not be detected by the Laser Beam Profiler. And in the experiment results shown in Figure 3, the data collection begins from the incident angle of 1.18°. With different incident angle, the PBS versus the width of the air-gap was calculated theoretically, as shown in Figure 2(b). It illustrated that the width of air-gap in the prism positively contributed to the PBS, especially in the case of small incident angle, corresponding to an incident angle near critical point at the interface of prism-air for o-light.

3. The detection of incident angle and polarization

In the experiment, the Glan-Taylor prism was fixed on a rotating table with a control accuracy of 0.04°. The incident light was adjusted to be

![Figure 1. The propagation of o-light and e-light in Glan-Taylor prism.](image)

| Table 1. The refraction angle calculation of o-light and e-light. |
|-----------------|--------|--------|--------|
| Angle (°)       | 1.2    | 1.4    | 1.6    |
| Angle of the first prism-air interface (°) | 0.65   | 0.76   | 0.97   |
| Angle of the second prism-air interface (°) | 1.11   | 63.27  | 62.92  |
| Angle of the first prism-air interface (o-light) (°) | 0.73   | 0.85   | 0.97   |
| Angle of the second prism-air interface (o-light) (°) | 86.92  | 84.73  | 83.21  |
vertical polarization that coincided with the z-axis. The optical-axis direction of the Glan-Taylor prism was aligned with the y-axis. With the tilt of the prism, the output spots of ordinary and extraordinary light were obtained by the Laser Beam Profiler as shown in Figure 3. By detecting the distance from peak to peak, the beam splitting was obtained as the blue squares presented in Figure 3. Actually, the center position of e-light moved barely, and that of o-light had a significant shift with a varied incident angle. Because of the hardware limitation, rotational axis was not coincided with the center of the prism. Hence, the Zemax simulation results displayed in the inset of Figure 2 should be revised with actual parameters of the experiment, as shown in Figure 3 with the black triangles. Obviously, they could not agree with the experimental data. That was because the simulation of Zemax contained the polarization beam splitting caused by birefringence effect, but ignored the contribution of GH effect.

| Angle (°) | 1.2 | 1.4 | 1.6 |
|-----------|-----|-----|-----|
| x-axis coordinates of the first prism-air interface (mm) | 8.78 | 8.77 | 8.76 |
| y-axis coordinates of the first prism-air interface (mm) | 7.40 | 7.38 | 7.37 |
| x-axis coordinates of the second prism-air interface (mm) | 8.94 | 9.16 | 9.15 |
| y-axis coordinates of the second prism-air interface (mm) | 7.28 | 7.57 | 7.55 |
| x-axis coordinates of the exit point (mm) | 15.25 | 15.25 | 15.25 |
| y-axis coordinates of the exit point (mm) | 7.21 | 7.49 | 7.46 |

Table 2. The coordinates of each interface incident point of e-light.

| Angle (°) | 1.2 | 1.4 | 1.6 |
|-----------|-----|-----|-----|
| x-axis coordinates of the first prism-air interface (mm) | 8.77 | 8.76 | 8.74 |
| y-axis coordinates of the first prism-air interface (mm) | 7.39 | 7.37 | 7.35 |
| x-axis coordinates of the second prism-air interface (mm) | 11.18 | 10.23 | 9.91 |
| y-axis coordinates of the second prism-air interface (mm) | 10.15 | 8.93 | 8.54 |
| x-axis coordinates of the exit point (mm) | 15.25 | 15.25 | 15.25 |
| y-axis coordinates of the exit point (mm) | 10.10 | 8.86 | 8.45 |

Table 3. The coordinates of each interface incident point of o-light.

Figure 2. (a) The polarization beam splitting in the Gelan-Taylor prism through birefringence due to theoretical calculation and Zemax simulation. The inset shows the Zemax simulation result by tilting light beam as well as the Glan-Taylor prism. (b) The polarization beam splitting with respect to the width of air gap in different incident angle.

Figure 3. The comparison between the experimental result and Zemax simulation including GH shift. The error bars for the experimental data were obtained with 3 repeating detections in the same condition. The spots represented the exited spot signal of o-light and e-light with different incident angle.
As reported, in this biprism configuration, with a small incident angle, the GH shift could have a significant impact on the PBS. Based on stationary-phase approach [36], the shift of the light on the output plane of the prism caused by the GH effect could be expressed as $S$:

$$S = a \tan \theta \cdot \frac{2xk_0}{k_a} \cdot \left( \frac{k_0^2(x^2k_0^2 + k_1^2) - \left(k_1^2 + x^2k_0^4 - k_2^2k_0^2(x^2 + 1) \right) \sin 2\theta_0}{k_0^2 + \sin^2 \theta_0} \right)$$

(2)

Here, $a$ is the saturated width of air gap, which could be calculated with $\pi(1 - n^2 \sin^2 \theta_0)^{1/2}/\omega_0 n^2 \sin \theta_0$ [36]. $\theta_0$ is the incident angle of o-light on the first prism-air interface, and $\theta$ is the refraction angle. Depend on Eq. (2), the shift of o-light on the Laser Beam Profiler was calculated and displayed with purple spots in Figure 3. As shown in Figure 1, The role of GH promoted the distance between o-light and e-light. As shown in Figure 3 with the red stars, coupled with the contribution of GH shift, the GH promoted the distance between o-light and e-light. As shown in Figure 3, the experimental data largely agreed with the simulation results. In the situation of small incident angle, which could lead an incident angle near the critical point at the prism-air interface in the prism, corresponding to a large refraction angle in the air-gap. Thus the width of $a$ in the calculation with geometrical optics could not be ignored. Additionally, due to the large refraction angle in the air-gap, the spot of o-light would be reshaped to be an oval and the intensity would be greatly lost. Hence the measurement of the distance may vary from the simulation result.

As for the incident angle detection shown in Figure 3, the sensitivity, which could be represented by the slope of the curve, was up to 21.63 mm/r. The resolution of the Laser Beam Profiler was 1.2 μm. Consequently, the resolution of the incident angle could be $5.55 \times 10^{-3}$ that was calculated by formula $R' = R/S$, where $R'$ and $R$ were the resolution of the measuring angle and the Laser Beam Profiler respectively, and $S$ is the slope of the measuring curve. It could be furtherly improved by optimizing the resolution of the detector. Moreover, according to the simulation curve displayed with the red stars in Figure 3, it may be more sensitive to the angle detection in the range with small incident angle. Hence, by detecting the splitting distance of the two orthogonal polarized beams, the incident angle could be determined with a high sensitivity. Additionally, with an appropriate incident angle, the intensity of the two polarization corresponding to the appearance of output spot was determined by the incident polarization. Actually, at the first interface between the crystal and the air gap, the o-light has an extremely low transmission due to its near total internal reflection angle. The incident polarization should be selected appropriately. In the experiment, in order to match the intensity of two spots of outgoing light, the initial polarization was almost perpendicular to the polarization of e-light selected by Glan-Taylor polarizer. On the other hand, a suitable angle of incidence was selected, and the two outgoing polarized spots are completely and uniformly separated. At this point, the angle of incident polarization is fine-tuned and the outgoing light spots were observed. By rotating the polarization of incident light, the proportion of o-light and e-light varied with the fixed optical axis of the prism. Thus, the intensity of o-light and e-light of the outgoing light was changed accordingly, resulting in a barycenter shift of the two spots.

With the own analytical software of Laser Beam Profiler, the centroid position, could be collected with a frequency of 10 Hz, as shown in Figure 4(a), which was achieved by rotating the half-wave plate a certain distance before the prism. The step in Figure 4(a) resulted from a polarization rotation of 0.08°. The inset of Figure 4(a) displayed the detail in this period, which implied a stability with a standard deviation of 0.61 μm. By averaging the data in this period, and comparing with the initial centroid position, the response curve of the polarization angle was obtained, as shown in Figure 4(b).

![Figure 4](image-url)

Figure 4. (a) The centroid position detection with a frequency of 10 Hz. (b) The center shift of output spot versus polarization angle. The error bars are obtained with six repeating measurements. (c) Exit light spots recorded by the Laser Beam Profiler with different rotating angles of half-wave plate for the polarization adjustment.
As revealed in Figure 4(c), with different rotating angles of half-wave plate, the two spots that represented o-light and e-light respectively, presented the reverse change tendency about the light intensity. Consequently, the barycenter of the two spots shift with a monotone increasing curve. The ordinate values of Figure 4(b) are the absolute values of the center shifts, and they exhibited a distinct linear relationship with the rotation angle of the incident polarization. Similar with the analysis of incident angle detection, the sensitivity could be calculated to be 150.83 μm/°, corresponding to the resolution of 7.9 × 10⁻³ for polarization detection, by fitting the data of Figure 4(b) with a line.

4. Conclusion

Thus, in this investigation, with appropriate incident polarization and the direction of Glan-Taylor prism, polarization beam splitting could be realized based on dual mechanism of birefringence and GH effect. With theoretical simulation and experimental measurement, it was demonstrated that the PBS in the biprism configuration of Glan-Taylor presents a sensitive approach for the simultaneously detection about incident direction and polarization angle. Such a proposed merit with the merit of simple structure and easier integration may play an essential role in engineering optics and optical design for the investigation of high precision detections.

Declarations

Author contribution statement

Dongmei Li: Conceived and designed the experiments; Wrote the paper. Guoan Cai; Chenyao Song: Performed the experiments; Analyzed and interpreted the data.

Chaofan Weng; Chaoyi Chen: Analyzed and interpreted the data. Weniqiang Zheng; Yilong Zhang; Kan Li: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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