Measurement of Surface Plasmon Polariton Enhanced Goos–Hanchen Shift Based on Grating and Liquid Crystal Technologies

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***Abstract*—We measured the surface plasmon polariton (SPP) enhanced Goos–Hanchen (GH) shift based on liquid crystal (LC) and grating technologies. An optical setup is used to convert the spatial displacement to incidence angle variation to a Littrow mounted diffraction grating. As a consequence, the GH shift information could be obtained from the back-reflected center wavelength that fulfills the Littrow condition. An LC cell is used to adjust the polarization state of the incident light without mechanical movement. About 10-μm GH shift difference between transverse-electric (TE) and transverse-magnetic (TM) mode lights were measured associated with the SPP excitation. The corresponding center wavelength shift of the returned beam is 404 pm. The relationship between energy conversion and GH shift is also investigated.**

***Index Terms*—Goos–Hanchen (GH) shift, liquid crystal (LC), surface plasmon polariton (SPP).**

I. Introduction

THE Goos–Hanchen (GH) shift is a special optical phenomenon with respect to geometric reflection [1], [2]. When TE or TM polarized incidence beam is reflected by dielectric-air interface, the reflection beam has a displacement in spatial. This is due to the evanescent waves that penetrate into the low index medium near the interface. Previous research work has revealed that both TE and TM polarized beam have shifts when beam are reflected by the medium interface [3]. However, the displacement of TM polarized beam is larger. The Goos–Hanchen shift also has incidence angular dependence [4]. GH shift is observed when the incidence angle is above the critical angle. However, the closer the incidence angle to the critical angle is, the larger the GH shift is observed. Moreover, research on GH shift becomes more and more attractive along with the growing interests on Surface Plasmon Polariton (SPP). Yin *et al.*'s research work [5] reveals that the GH shift is greatly enhanced when SPP is excited, which is quite larger than those of the traditional cases. As Plasmonics has become a very hot topic in nanophotonics, the excitation and extraction processes of SPP thus are critical because they may dominate the input and output of a future "plasmonic circuit". It is very important to investigate the SPP related phenomena and processes, such as GH shift. In addition, some refractive index (RI) sensor [6], [7] and displacement sensor [8] based on SPP enhanced GH shift are also expected.

However, the GH shift is in the order of light wavelength that it much smaller than the beam size. It is difficult to measure it directly in the experiment. Normally some special instruments are required. For example, a prism coupling system along with high resolution motor-driving rotation stage, a high-voltage electrooptical polarization modulator, a position sensitive detector (PSD), high sensitive charge coupled device (CCD) and a monitor system are required [9]–[11].

In this letter, we propose a method to characterize the GH shift, especially the SPP induced GH shift in a prism coupling system. A simple optical setup is utilized in our design. A 90° twisted nematic (TN) liquid crystal (LC) cell is used to adjust the incidence beam's polarization state with a low voltage. A biconvex lens is employed to convert the displacement of GH shift to angular change of the beam. A Littrow mounted reflective grating is employed to diffract the light back to its original route. For a given incidence angle to the grating, only a specific wavelength could satisfy the diffraction condition at this Littrow mounting, the incidence angle is just the diffraction angle. In another word, as long as the incidence angle makes any tiny change, the corresponding center wavelength of the returned diffracted light changes accordingly. In this case, the GH shift thus could be characterized by the wavelength shift of the Littrow peak displayed in an optical spectrum analyzer (OSA). Furthermore, the polarization state of the incident light could be reconfigured by resetting the driving voltage on the LC cell. As we know, only the TM mode light could excite SPP, the different GH shifts of TM and TE modes thus reflects SPP's effects. In comparison with previous methods, our setup only contains some passive optical components with low driving voltage and no moving parts.

II. Optical Setup

The schematic diagram of our optical setup is depicted in Fig. 1. A wideband light source (ASE) performs as the light source. Then it is connected to the input port of an optical circulator. A collimator is utilized to collimate the light that comes out from the circulator. A polarization beam splitter (PBS) is placed behind the collimator. A 90° TN LC cell is employed to tune the incidence light's polarization state. A high-index glass

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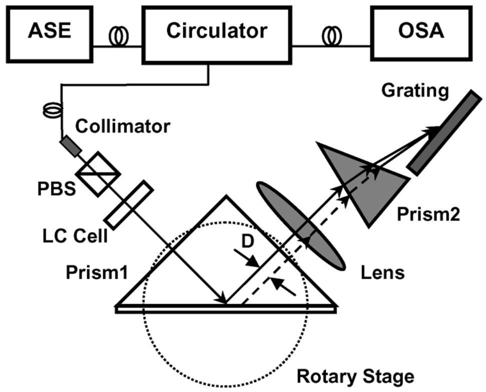

Fig. 1. Schematic diagram of the setup for GH shift measurement.

prism with 50 nm gold coated at the bottom is mounted on a rotary stage to excite the SPP. After that, a biconvex lens with 40 mm focal length and a BK7 prism are used to convert the light's displacement to the change of the incidence angle in spatial. Finally, light that satisfies the Littrow condition is diffracted back by a 1200 lines/mm grating then pass through the former optical components. An optical spectrum analyzer (OSA) (Ando AQ 6317B) monitors the spectrum of the reflected light that routed by the circulator.

In our setup, the TN LC cell is 11.5 μm-thick with AR coating and filled with Merck 6647 LC. When there is no field applied, it rotates the passed TM-polarized light from PBS by 90° so the incident light to Prism 1 is TE-polarized. However, after a 3.6 $V_{\rm rms}$ AC voltage is applied on the cell. The polarization rotation effect of the TN LC is destroyed. The light remains at the TM-mode. Therefore, by applying different driving voltages, we can control the polarization state of the incident beam easily. In addition, the high index glass prism is made with H-ZF52A glass $(n\_1550 = 1.8)$ prism from Chengdu Glass Corp., which is mounted on a rotary stage. The incidence angle to the Au-film and glass interface thus could be tuned by the rotary stage. For TE polarized beam, it could not excite the SPP. Hence, the TE polarized beam could act as the reference. Only TM polarized beam could excite the SPP, leading to the enhancement of the displacement. In this situation, the propagating directions of TE and TM lights after passing through the lens have a tiny difference $\delta\theta = D/f$, where D showing in Fig. 1 is the lateral offset and f is the focal length. Prism 2 and the grating form a diffraction unit with enhanced and linearized dispersion in telecommunication band [12]. Because this is a Littrow mounting grating, the back-diffracted beam should satisfy with the Littrow condition, that is $2d\sin\alpha = \lambda$, where d is the grating pitch, α is the incidence angle to the grating, λ is the wavelength. The relationship between the change of wavelength and the incidence angle could be deduced from the Littrow condition equation, which is

$$\delta\lambda = 2d\cos\alpha \cdot \delta\alpha = 2d\cos\alpha \cdot D/f$$

From the equation, we can see that the lateral displacement is converted to the wavelength shift of the diffracted light that satisfies the Littrow condition. This provides the possibility to demonstrate the displacement by the spectra showing in the OSA.

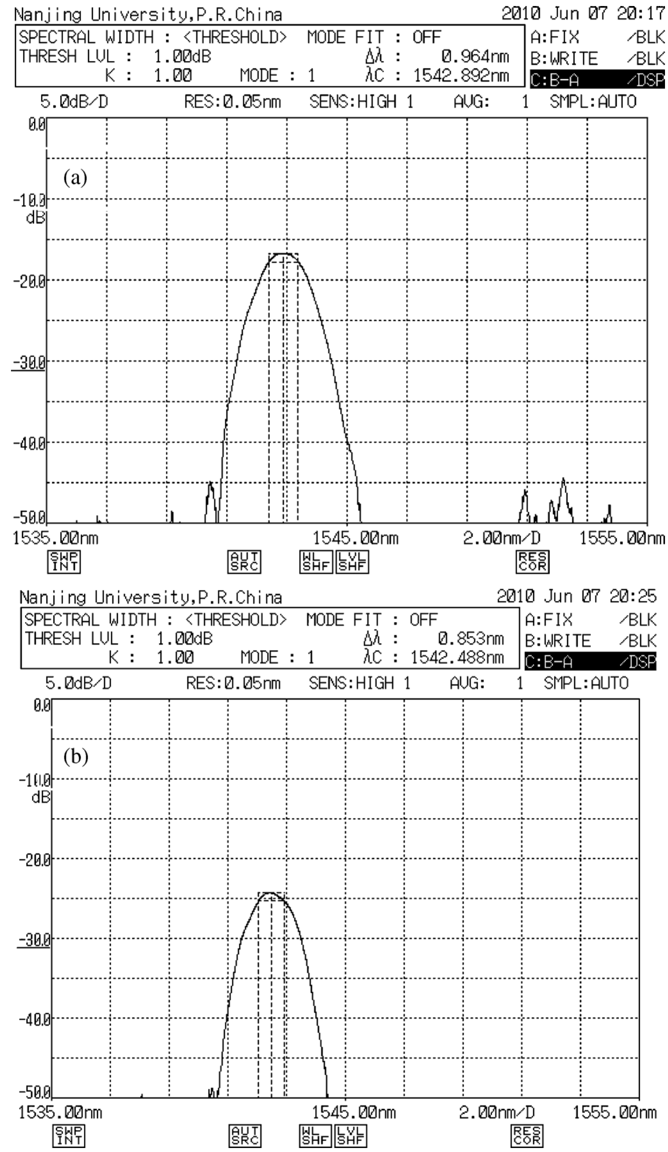

Fig. 2. Spectra of the back-diffracted (a) TE and (b) TM lights.

III. Experimental Results and Discussion

Fig. 2 shows the original OSA screen snapshots that display the spectra of back-diffracted lights around Littrow condition. The spectral resolution of the OSA is set at 0.05 nm. For TE and TM modes, the center wavelengths of the reflected lights are 1542.892 nm and 1542.488 nm, which can be read in Fig. 2(a) and Fig. 2(b), respectively. The center wavelength shift is 404 pm that is the largest one we have measured. Then we may further rotate the stage to record more back-diffracted spectra. Center wavelength shift and GH shift thus could be obtained at different incidence angles.

Fig. 3 shows the measurement results of GH shift as we discussed above. The positions represent the change of micrometer in rotary stage and they actually mean the change of the incidence angle to Prism 1's bottom surface. Since our rotary stage does not have a motor-driving micrometer, we cannot read the

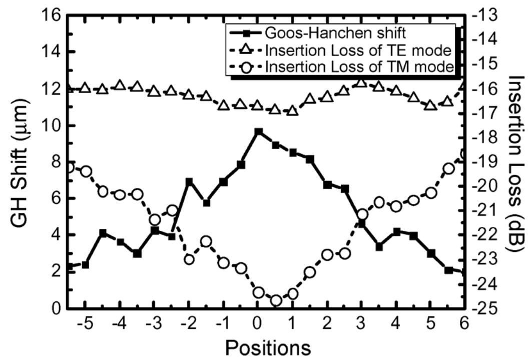

Fig. 3. Goos–Hanchen shift and change of insertion loss (IL) for TE and TM modes, respectively.

incidence angle directly. Each unit in position change means about 28″ angle change. Besides, all the position changes of incidence angle are around the SPP excitation angle, which is about 43°. The total angle change range is about $5'18''$, which means the SPP excitation is very angular sensitive.

The lateral shift between the TE and TM polarized beams is shown in Fig. 3 (represented by the solid line with squares). Remarkable difference between different modes is clearly observed ranging from 2–10 μm. This result agrees well with previous reports [3], [4]. As we know, the GH shift difference at a totally internally reflected dielectric surface could be qualitative explained by the different effective penetration depth of TE and TM polarized evanescent waves. The TM mode has a deeper penetration that results in a larger phase shift associating with a lateral shift. In our case, the TM mode is more likely to excite the SPP at outside metal-air boundary meaning it still have more penetration than the TE mode. This picture could give a rough but straightforward picture on the GH-shift difference, although it is actually a wave phenomenon and hence outside the scope of ray physics.

To further reveal the role of SPP excitation in the GH shift, the insertion loss (IL) of TM polarized light is measured by the OSA (represented by the dash line with circles in Fig. 3). It is clear that the TM light has a high loss right at the displacement peak. The highest IL is -24.63 dB. From the figure, the trend of lateral shift and IL are just opposite. More lateral shift is obtained while the insertion loss is higher. It means the light power is really exhausted though SPP excitation. As a consequence, more TM mode penetrates to the metal-air boundary then travels laterally as a SPP wave, which results in a great GH shift enhancement right at the SPP resonance angle.

In comparison, the IL of TE mode is also measured. It shows only slight fluctuation (Fig. 3), meaning there is no SPP excitation, which makes the GH shift difference for TE and TM modes.

IV. Conclusion

In conclusion, the difference of the GH shift between TE and TM lights are experimental studied. A well-designed optical setup is utilized to convert the spatial displacement of GH shift to the angular change. Then the GH shift could finally be characterized by the center wavelength shift of a diffracted spectrum. We found that there is large beam position shift when the SPP is excited. The largest corresponding center wavelength difference between TM and TE modes reaches 404 pm, corresponding to a 10 μm GH shift variation. The IL measurement further reveals the close relation between SPP excitation and large GH shift. The inherent mechanism still needs further investigation.

References

[1] F. Goos and H. Hanchen, "Ein neuer und fundamental Versuch zur Totalreflexion," *Ann. Phys.*, vol. 1, pp. 333–346, 1947.
[2] F. Goos and H. Hanchen, "Neumessung des Strahlversetzungseffektes bei Totalreflexion," *Ann. Phys.*, vol. 5, pp. 251–252, 1949.
[3] H. K. V. Lotsch, "Beam displacement at total reflection: The Goos-Hanchen effect, I*," *Optik*, vol. 32, pp. 116–137, 1970.
[4] H. K. V. Lotsch, "Beam displacement at total reflection: The Goos-Hanchen effect,II*," *Optik*, vol. 32, pp. 189–204, 1970.
[5] X. B. Yin, L. Hesselink, Z. W. Liu, N. Fang, and X. Zhang, "Large positive and negative lateral optical beam displacements due to surface plasmon resonance," *Appl. Phys. Lett.*, vol. 85, no. 3, pp. 372–374, Jul. 2004.
[6] X. B. Yin and L. Hesselink, "Goos-Hanchen shift surface plasmon resonance sensor," *Appl. Phys. Lett.*, vol. 89, p. 261108, 2006.
[7] Y. Wang, H. G. Li, Z. Q. Cao, T. Y. Yu, Q. S. Shen, and Y. He, "Oscillating wave sensor based on the Goos-Hanchen effect," *Appl. Phys. Lett.*, vol. 92, p. 061117, 2008.
[8] T. Y. Yu, H. G. Li, Z. Q. Cao, Y. Wang, Q. S. Shen, and Y. He, "Oscillating wave displacement sensor using the enhanced Goos-Hanchen effect in a symmetrical metal-cladding optical waveguide," *Opt. Lett.*, vol. 33, no. 9, pp. 1001–1003, May 2008.
[9] H. G. L. Schwefel, W. Kohler, Z. H. Lu, J. Fan, and L. J. Wang, "Direct experimental observation of the single reflection optical Goos–Hanchen shift," *Opt. Lett.*, vol. 33, no. 8, pp. 794–796, Apr. 2008.
[10] M. Merano, A. Aiello, G. W. Hooft, M. P. van Exter, E. R. Eliel, and J. P. Woerdman, "Observation of Goos–Hanchen shifts in metallic reflection," *Opt. Express*, vol. 15, no. 24, pp. 15928–15934, Nov. 2007.
[11] H. Gilles, S. Girard, and J. Hamel, "Simple technique for measuring the Goos–Hanchen effect with polarization modulation and a position-sensitive detector," *Opt. Lett.*, vol. 27, no. 16, pp. 1421–1423, Aug. 2002.
[12] Z. D. Huang, S. S. Li, F. Xu, X. Liang, X. J. Wang, and Y. Q. Lu, "Dispersion enhancement and linearization in a dynamic DWDM channel blocker," *J. Lightw. Technol.*, vol. 28, no. 5, pp. 822–827, Mar. 1, 2010.