Giant non-specular effects at the interface of Bloch surface wave structures

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Abstract

The interference of reflections and refractions in a periodical dielectric structure generates a surface electromagnetic wave named Bloch surface wave. The absence of ohmic losses renders the Bloch surface wave strongly enhance the non-specular effect, like the Goos-Hanchen shift, with low optical loss. In that case, giant non-specular effect induced by the Bloch-surface-wave is easy to observe. Here the spatial phase distribution is experimentally measured as well as the intensity distribution. Experiments reveal that the non-specular reflection could lead to strong spatial phase variation across the beam profile besides the intensity distortion. This discovery helps better understanding of the physical process of the non-specular reflection, and the observed giant non-specular effect provides potential applications involving high performance optical sensors.

1. Introduction

Non-specular effects refer to the unconventional phenomena of a reflected bound light beam where the reflected beam derivate from the predicted pathway, including lateral and longitudinal displacements, focal and angular deviations [1-2]. Non-specular effects raise wide interest of research for the profound connotation, among which the lateral displacement of the reflected beam from the geometrical prediction, known as Goos-Hanchen (GH) shift, has been most widely studied. Normally, the non-specular effects are too minute to be observed. So in the first experimental demonstration of the GH shift, the non-specular reflection was repeated a hundred times in order to accumulate the minute beam shift which is only at the order of the incident wavelength [1]. This feeble phenomenon has no practical usage till it is found that the Goos-Hanchen shift can be significantly enhanced by the surface wave. The surface plasmon wave along the interface between the metal and dielectric has been demonstrated to enhance the GH shift to ~50 folds of wavelength [3]. This great enhancement makes it possible for sensing applications, albeit it is limited by the critical problem that the maximum GH shift always corresponds to the minimum reflectance, which often reaches near 0 at surface plasmon resonance. The huge optical loss of the reflected beam makes it difficult to measure its accurate position of the poor SNR. The Bloch surface wave (BSW) is another type of surface electromagnetic waves, which propagates along the interface between two dielectrics. The excitation of the Bloch surface wave is attributed to the interference of reflections and refractions in a periodical structure. Recently, the BSW is widely considered as alternative to the surface plasmon wave, because it shows similar characteristics except that the polarization and wavelength of the incident is more flexible for the designability of BSW structures. Due to the absence of the ohmic loss, the optical loss is tremendously reduced, which not only makes it easy to measure the position of the beam, but also boosts the GH shift by orders of magnitude [4]. The significantly enhanced, sub-millimeter GH shift, as well as the greatly improved SNR makes it possible for practical application, such as sensing [5] and switching [6].

As early as the GH shift first experimentally observed, the stationary phase method is raised by Artmann, where this effect is attributed to the different phases experienced by different spatial frequency components of the beam, and the GH shift is assumed to be proportional to the phase variation of the angular dependent reflectivity. Further research shows that the GH shift, as well as the intensity distribution of the reflected beam, depends on both the angular phase distribution and the incident beam size, i.e., the divergence of the incident beam [7-8]. The conventional GH shift, defined as the shift of the whole beam which only happens when the beam is relatively well collimated, is proportional to the first order derivative of the phase. However, if the beam is poorly collimated and the phase change cannot be assumed linear within the divergence angle of the incident beam, the reflected beam is split into two parts instead of shifting as a whole. In that case, the so called "GH shift" is more general, and is calculated through the change of the intensity distribution of the reflected beam, where a centroid is often used to mark the position of the reflected beam. Furthermore, studies on propagation behavior of the non-specular reflected beam show that the intensity distribution of the reflected beam varies during propagation [7], which indicates that different components of the reflected beam is experiencing different phase change when propagating. As the intensity/phase distribution in the angular frequency domain can be considered as Fourier counterparts in the spatial domain, there should be the spatial phase distribution as well as the spatial intensity distribution of the reflected beam. However, until now, most research on non-specular effects is focused on the intensity distribution and variation. In this paper, we study the spatial phase distribution of the

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Bloch surface wave enhanced nonspecularly reflected beam, where the spatial phase distribution is experimentally measured, showing that the spatial phase distribution varies with the spatial intensity distribution.

2. Experiments and results

The Bloch surface wave structure consists of 10-period of alternating TiO_2 (n=2.30) and SiO_2 (n=1.434) layers evaporated on a ZF10 glass slide (n=1.668), terminated with a TiO_2 buffer layer. The thickness of the TiO_2 layer and SiO_2 layer in one unit cell, and the buffer layer are 163nm, 391nm, and 23nm, respectively. The structure is designed to be able to excite the BSW for P-polarized incident beam, with the surface of the structure covering water. The light source is a fiber-pigtailed Fabry–Perot 980nm laser, which illuminates the Bloch surface wave structure through a high refractive index ZF3 glass prism (n=1.695) under the Kretschmann configuration. The spatially filtered Gaussian beam has a waist of ~750 μm, whose state of polarization is controlled by a Glan-Taylor prism and a following$\lambda/2$ wave plate. The incident angle is controlled by a motorized rotation stage. A CCD camera (Toshiba, IK-SX1) captures the intensity distribution of the reflected beam, based on which the GH shifts are calculated. In order to compare the BSW enhanced non-specular reflection with the specular reflection, a flowcell made of Polydimethylsiloxane (PDMS) is attached to the buffer-layer-side of the structure to facilitate the injection of different aqueous solution or air to the surface of the device, where the surface of the structure covering water for BSW excitation and covering air for nothing.

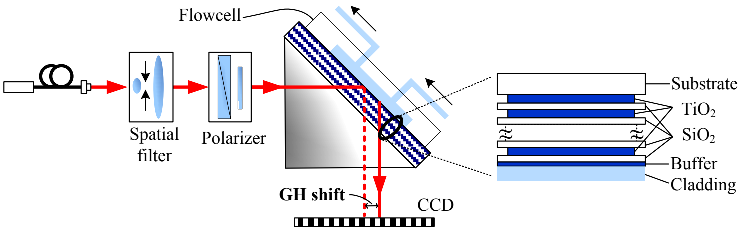

Fig. 1schematic diagram of the experimental setup for measurement of the Bloch surface wave enhanced GH shift

As shown in the inset of Fig. 2, the intensity distribution of both the specularly reflected beam and the BSW enhanced non-specularly reflected beam are captured by the CCD and plotted together. The reflected beam with non-specular effect, i.e. the GH shift in this case, is split into two parts, and the majority of the beam is shifted away. By calculating the centroid of the intensity distribution of the reflected beam, the angular-dependent GH shift curve is obtained in Fig. 2, where the maximum GH shift is boosted to ~ 740 μm (i.e. ~750 times of the wavelength)in presence of the BSW.

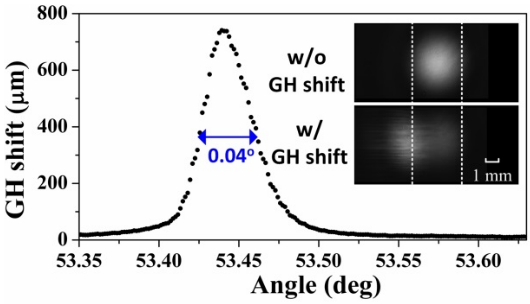

Fig. 2Angular dependent Goos-Hanchen shift (inset: CCD captured reflected beam)

The schematic diagram of the proposed spatial phase measurement scheme is shown in Fig. 3, where the non-specular reflection occurs upon a Bloch surface wave structure and the configuration of the experimental setup is similar to that in Fig. 1. The BSW structure can be expressed as substrate/$(HL)^9$/H/L', where the materials for the high and low refractive index layers are TIO_2 (n=2.30) and SIO_2 (n=1.434) respectively, the thicknesses for the layers are d_H=163nm, d_L=391nm, $d_{L'}$=500nm respectively. The stack of multilayer are evaporated on a ZF10 (n=1.668) glass substrate. Also, this BSW structure is designed to be able to excite BSW with water covering the surface of the buffer layer for the P polarization. A polarization beam splitter and a following$\lambda/2$ wave plate are placed after the source to set the intensity of the S polarized and P polarized components equal. A quarter wave plate and an analyzer are placed after the BSW structure, and the reflected beam is measured by a CCD camera (Toshiba, SK1). The quarter wave plate and the analyzer are rotated to several different angles to measure the Stokes parameters of the reflected beam [9]. During the measurement, a Glan-Taylor prism is used as the analyzer and fixed to let P-polarization pass only, and the quarter wave plate is rotated. The rotation angle α changes from 0^o, 15^o, 30^o to 105^o. Then Stokes parameters $S=(S_0, S_1, S_2, S_3)'$ can be calculated through the measured intensity $I^{(\alpha1)}$, $I^{(\alpha2)}$, $I^{(\alpha3)}$ and $I^{(\alpha4)}$,

$$\begin{bmatrix} I^{(\alpha_1)} \\ I^{(\alpha_2)} \\ I^{(\alpha_3)} \\ I^{(\alpha_4)} \end{bmatrix} = \begin{bmatrix} 1 & \cos^2(2\alpha_1) & \sin(2\,\alpha_1)\cos(2\,\alpha_1) & -\sin(2\alpha_1) \\ 1 & \cos^2(2\alpha_2) & \sin(2\,\alpha_2)\cos(2\,\alpha_2) & -\sin(2\alpha_2) \\ 1 & \cos^2(2\alpha_3) & \sin(2\,\alpha_3)\cos(2\,\alpha_3) & -\sin(2\alpha_3) \\ 1 & \cos^2(2\alpha_4) & \sin(2\,\alpha_4)\cos(2\,\alpha_4) & -\sin(2\alpha_4) \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{1}$$

where $S_0=E_P+E_S$, $S_1=E_P-E_S$, $S_2=2E_PE_S\cos\theta$, $S_3=2E_PE_S\sin\theta$, E_P and E_S are the electric field components, and θ is the phase difference between the reflected P- and S-polarizations.

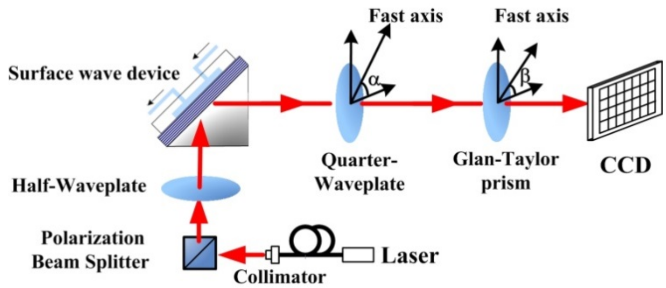

Fig. 3 Schematic diagram of the experimental setup for spatial phase measurement of the Bloch surface wave enhanced non-specular effect

Fig. 4(a) shows the measured spatial intensity distribution of the non-specularly reflected beam retrieved from the CCD capture and (b) shows the correspondingly retrieved spatial phase difference between P- and S-polarizations, with the variation of the incident angle. As the reflected beam moves in the CCD camera with the incident angle during the experiment, the coordinate of the spatial distribution is normalized to the specularly reflected beam. From Fig. 4(a), it is found that the excitation of the Bloch surface wave significantly distorts the spatial intensity distribution of the reflected beam, where the reflected beam is split into two parts, and the GH shift can be clearly observed. Fig. 5 shows the angular dependent GH shift that calculated through the measured spatial intensity distribution. As the excitation of the BSW is very sensitive to the incident angle, the spatial phase change of the reflected beam, as well as the spatial intensity distribution, distorts with the incident angle change. And the spatial phase change moves with the spatial intensity change correspondingly with the variation of the incident angle, where the GH shift of each incident angle shown in Fig. 4 is marked in Fig. 5 with the same color for comparison.

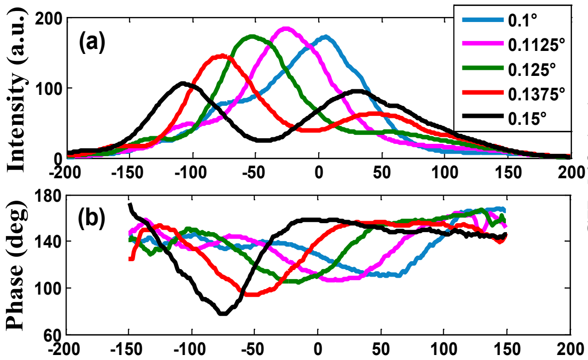

Fig. 4 (a) Spatialintensity and (b) spatial phase distribution for different incident angles

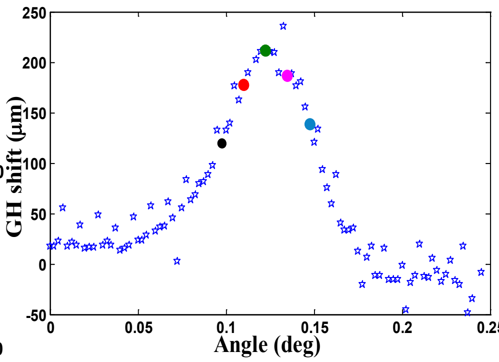

Fig. 5 Measured angular-dependent GH shift

3. Conclusion

Bloch surface wave, as well as the surface plasmon resonance, is able to significantly enhance several non-specular effects, like the GH shift. The longer propagation distance of the low-loss Bloch surface wave results in much more pronounced non-specular effects. A few orders of magnitude of enhancements in the far-field GH shift is observed for the first time in our experimental demonstrations. Our results reveal that the Bloch surface wave enhanced GH shift can reach sub-millimeter order, which makes it feasible for high performance sensing applications. Also, the spatial phase distortion of the surface-wave-enhanced non-specularly reflected beam is experimentally measured together with the known spatial intensity distortion. It is also observed that the phase changes abruptly in the region of intensity profile with distortion of the non-specular reflected beam, and both the phase jump and intensity profile distortion are very sensitive to the excitation of the BSW. This discovery helps the understanding of the phase property of the non-specular reflection, and could have profound implication for phase-based sensing schemes.

4. Acknowledgments

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5. References

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