Angular Goos-Hanchen shift in subwavelength gratings enhanced by surface plasmon resonance

N I Petrov¹, V A Danilov¹ and B A Usievich²

¹ Scientific and Technological Centre of Unique Instrumentation of the Russian Academy of Sciences, 15 Butlerova str., Moscow 117342, Russia
² Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

Corresponding author: petrovni@mail.ru

Abstract. The angular Goos-Hanchen shift dependence on the subwavelength grating parameters and the incident Gaussian beam width is investigated theoretically. High sensitivity of the angular Goos-Hanchen shift to the incident angle of a light beam near the surface plasmon resonance is demonstrated. Splitting of the reflected beam into two angularly separated beams is shown for strongly focused beam incident at the surface plasmon resonance angle.

1. Introduction

Plane waves of infinite width are widely used to describe the optical properties of diffraction gratings (see, for example, [1-3]). However, the fields associated with laser optical systems and other sources are spatially limited. Moreover, the fields of reflected and transmitted beams demonstrate diffraction phenomena that are not found in a plane wave. A variety of interesting phenomena emerges from the consideration of a bounded incident beam. If we consider the finite beam, it becomes obvious the excitation of surface plasmons, Goos-Hanchen (GH), focal and angular shifts [1, 4, 5]. In [6], the shift of the trajectory of sagittal rays propagating in a graded-index fiber was studied. In [7, 8] positive and negative GH shifts are demonstrated for the reflected beams from subwavelength gratings near the surface plasmon resonance. In [9] the theory of Goos-Hanchen shift and reshaping shift are developed and the GH shift for surface plasmons experimentally examined. In [10] the angular shift of a Gaussian beam reflected by a dielectric interface near the Brewster angle is analyzed. Angular shift and significant oscillations in the intensity distribution of the beam reflected by a dielectric interface was demonstrated for strongly focused incident beam in [11]. In [12] experimental demonstration of this angular deviation at reflection of an optical beam from an air-glass interface has been reported. A description of the spatial and angular Goos-Hänchen and Imbert-Fedorov shifts occurring at reflection of a light beam from plane interface is presented in [13]. GH shift has been observed experimentally in reflection from an air-gold plane interface [13]. In [14] an angular GH shift near the surface plasmon resonance (SPR) excitation is demonstrated.

In this paper, we investigate the angular GH shift when the surface plasmon resonance is excited in a subwavelength silver grating with a period \( \Lambda = 400 \) nm. The angular splitting of the reflected beam into two separated beams is shown for specific values of the width of the incident Gaussian beam and the depth of the grating.
2. Angular GH shift

A rigorous electromagnetic theory based on the C-method is used for calculations [2, 3, 7, 8, 15]. Note that an s-wave does not excite surface plasmon waves, so we consider the GH shift for the p-polarized incident wave only.

In Fig. 1 the intensity profiles as function of reflection angle are presented for different incident beam waists $w_0$. The wavelength of the incident beam is $\lambda = 632.8$ nm, the incident angle corresponding to SPR is $\theta_i = 33.25^\circ$, the silver grating depth $h = 30$ nm and the sinusoidal grating period $\Lambda = 400$ nm.

![Intensity profiles](image)

**Figure 1.** Intensity profiles as function of the reflection angle for different incident beam waists $w_0$: (a) $w_0 = 40 \mu$m; (b) $w_0 = 25 \mu$m; (c) $w_0 = 12 \mu$m; (d) $w_0 = 6 \mu$m.

It follows that negative angular GH shift of the order of the angular beam width occurs near the resonance angle of incidence. The reflected beam is divided into two beams when the incident beam is tightly focused. The spatial shift in this case becomes negligible and the angular shift becomes dominated.

In Fig. 2 the intensity distributions as function of the reflection angle are presented for the grating depth $h = 20$ nm. Note that this value of the depth corresponds to the minimum reflection of the plane wave at the resonance incidence angle [8]. Other parameters are the same as in Fig. 1.

We found that the angular shift of the reflected beam is sensitive to the angle of incidence and the depth of the grating. For tightly focused incident beams, there is a significant change in the shape of the reflected beam. In this case, two reflected beams appear, separated by an angular distance. At a certain value of the beam width, the amplitudes of these reflected beams become the same. This indicates that the subwavelength grating can work as a beam splitter.
Figure 2. Intensity profiles as function of the reflection angle for different incident beam waists \( w_0 \): (a) \( w_0 = 60 \) \( \mu \)m; (b) \( w_0 = 40 \) \( \mu \)m; (c) \( w_0 = 12 \) \( \mu \)m; (d) \( w_0 = 6 \) \( \mu \)m.

It follows from the simulation that there is an effect of splitting the reflected beam into two parts with positive and negative angular shifts, respectively, when the width of the incident beam decreases. Such angular shifts are caused by energy flows propagating forward and backward along the grating–air interface at resonance. Indeed, in this case, a sharp change in the value of the phase and its sign of the reflected beam takes place. Noticeable distortions of the reflected beam appear near the critical grating depth \( h_{cr} \approx 20 \) nm even for incident beams with large waists (Fig. 2 (a, b)). However, at depths other than the critical depth of the grating, the distortions also disappear for highly focused beams. Note that positive and negative lateral beam shifts were observed on the flat surface silver–air interface near the surface plasmon resonance in [16]. The existence of forward and backward surface plasmon waves propagating along the metal–air interface at resonance is responsible for such positive and negative spatial shifts.

3. Conclusions

Thus, the angular GH shift near the SPR is investigated for different grating depths and the incident beam widths by using rigorous electromagnetic calculation. For the reflected beam, an angular shift is demonstrated, enhanced by a surface plasmon resonance of the order of the angular width of the beam. It is shown that the reflected beam splits into two angularly separated beams with large negative and positive angular shifts. The angular distance between the intensity peaks increases with the decrease of the incident beam waist.
The results can be useful in the development of different sensors, as well as in angular metrology and cantilever-based surface microscopies. They can be also used in the angular alignment of LIGO or LISA gravitational wave detectors [17].

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