Available online at www.sciencedirect.com

ScienceDirect

Optics Communications 276 (2007) 206–208

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Large negative Goos–Hanchen shift at metal surfaces

P.T. Leung [a,*], C.W. Chen [b,c], H.-P. Chiang [b,c,*]

[a] *Department of Physics, Portland State University, P.O. Box 751, Portland, OR 97207-0751, USA*
[b] *Institute of Optoelectronic Sciences, National Taiwan Ocean University, Keelung, Taiwan, ROC*
[c] *Institute of Physics, Academia Sinica, Taipei, Taiwan, ROC*

Received 28 November 2006; received in revised form 9 April 2007; accepted 12 April 2007

Abstract

It has been previously established that for p-polarized light incident onto a semi-infinite absorbing medium, large negative Goos–Hanchen (GH) shifts can be expected in the case of weak absorption at incidence close to the Brewster angle. The effect has been demonstrated for certain semiconducting media at optical frequencies. Here we point out that similar phenomenon can take place for strongly reflecting and attenuating medium such as metal at IR frequencies, with large incident angles close to grazing incidence. Moreover, unlike the previously-studied case with semiconductors, the Brewster angle in the present case with metals plays an insignificant role in the possible hindrance of the observation of such large negative shifts.

Keywords: Goos–Hanchen shifts; Attenuating materials; Metal optics

The Goos–Hanchen (GH) effect refers to the lateral shift of a well-collimated incident beam upon reflection from an interface [1,2]. Traditionally, this most often refers to the situation of total reflection, with the incident beam in a transparent medium (e.g. glass) reflected back at the interface of this medium and another one of lower reflective index (e.g. air). The GH shift in this situation is most of the time positive and in the forward direction, i.e., in the same direction of the component of the incident wave vector along the interface. Recently, however, there has been much excitement in the discovery of negative GH shifts in various systems which include non-absorbing [3] and weakly-absorbing interfaces [4–6] and slabs [7]; metallic gratings [8]; transparent dielectric slabs [9]; dielectric slabs backed by a metal [10]; photonic crystals [11] and left-handed materials [12].

In this communication, we would like to point out the possibility of observing a *large* negative GH shift from a much simpler system – a metallic surface at almost grazing incidence with p-polarized light. The phenomenon of a "backward surface wave" incident on a plasma (including the free electron plasma of a metal) was studied long ago [13], and the electromagnetic energy flow at the interface was also studied recently [3]. However, to our knowledge, the possibility of a large negative GH shift at a bare metal surface has not been reported in the literature. Compared to the previously investigated systems which are mostly weakly-absorbing [4–7,9,11,12], a highly conducting metal is strongly reflecting and attenuating at optical/IR frequencies of light. We will see that this large negative shift will take place close to grazing incidence and unlike the previous case [6], the presence of the Brewster angle will *not* interfere significantly the possibility of observing these shifts in an experiment. To begin, we would also like to stress that the effect discussed below is quite different from the recently observed negative GH shift from a metal-backed dielectric film, where the shift arises from interference effects [10]. The one reported below has little to do with interference of light reflected from different interfaces, as it takes place at a bare metal surface. On the other hand, the condition being close to grazing incidence will have led

---

[*] Corresponding authors. Tel.: +1 503 725 3818; fax: +1 503 725 9525 (P.T. Leung).
E-mail addresses: hopl@pdx.edu (P.T. Leung), hpchiang@mail.ntou.edu.tw (H.-P. Chiang).

0030-4018/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2007.04.019

to a large incident wave vector component along the surface, and hence a large backward energy flux for frequency far below that of the metal plasma [3].

To illustrate the present GH effect, we consider a simple system with p-polarized light incident from vacuum onto a semi-infinite metal whose dielectric response may be described by the simple Drude model:

$$\hat{\varepsilon} = 1 - \frac{\omega_{\mathrm{P}}^2}{\omega(\omega + \mathrm{i}\omega_{\mathrm{C}})}. \tag{1}$$

Note that in the previous study of negative GH shift from such a plasma [3], damping is completely ignored with $\omega_{\mathrm{C}} = 0$ and the role of the Brewster angle is not studied. Here we shall include the damping and study in details the effect of the Brewster angle in the following. We shall also derive explicitly the conditions under which such a large negative GH shift can be observed.

As is well-known, one of the simplest (though limited) approach to the calculation of the GH shift (D) at transparent interfaces was first established by Artman in the following form [2]:

$$D = -\frac{1}{k}\frac{\mathrm{d}\phi}{\mathrm{d}\theta}, \tag{2}$$

which applies well to light beams totally reflected at angles above (but not close to) the critical angle. In recent subsequent developments, however, Eq. (2) was shown to be applicable even to absorbing surfaces, in which case the lateral (GH) shift can occur at all incident angles [4,6,10]. In Eq. (2), k and θ are the incident wave number and incident angle, respectively, while ϕ is the phase of the reflected light. Using the well-known Fresnel formula for reflection of p-polarized light incident from vacuum onto a metal with $\hat{\varepsilon} \equiv \varepsilon_{\mathrm{R}} + \mathrm{i}\varepsilon_{\mathrm{I}} = \hat{n}^2 \equiv (n + \mathrm{i}\kappa)^2$, it is not difficult to obtain an expression for the phase as follows [4]:

$$\phi = \mathrm{Im}\left[\ln\left(\frac{u-v}{u+v}\right)\right] = \tan^{-1}\left[\frac{2\mathrm{Im}(uv^*)}{|u|^2 - |v|^2}\right], \tag{3}$$

where $u = \hat{n}^2\cos\theta$, $v = \sqrt{\hat{n}^2 - \sin^2\theta}$ are complex quantities. In the limit of weakly-absorbing medium with $\kappa \ll n$ (or more precisely $\kappa \ll n/2$ so that $\varepsilon_{\mathrm{I}} \ll \varepsilon_{\mathrm{R}}$), it is straightforward to obtain from Eq. (3) the following approximate result for the phase:

$$\tan\phi \approx \frac{n\kappa\cos\theta(n^2 - 2\sin^2\theta)}{(n^2 - \sin^2\theta)^{1/2}(n^4\cos^2\theta - n^2 + \sin^2\theta)}. \tag{4}$$

By rewriting Eq. (2) in the following form:

$$D = -\frac{\cos^2\phi}{k}\frac{\mathrm{d}\tan\phi}{\mathrm{d}\theta}, \tag{5}$$

it is then easy to see that Eq. (4) will have a singularity at the Brewster angle condition defined by $\tan\theta_{\mathrm{B}} = n$, which then leads to a large positive slope for $\mathrm{d}\tan\phi/\mathrm{d}\theta$ in the vicinity of θ_{B} and hence a large negative D from Eq. (5) – a conclusion consistent with the previous observation and explanation for large negative GH shifts at Brewster angle for weakly-absorbing materials [6]. Note that Eq. (4) is applicable only for absorptive medium with small but nonzero value of κ.

Next let us consider the other extreme case with strongly-attenuating medium like a metal with its plasma frequency well-above that of the incident light. In this limit we have $n \ll \kappa$, and one can show similarly from Eq. (3) the following approximate result:

$$\tan\phi \approx \frac{2\kappa^2\cos\theta(\kappa^2 + \sin^2\theta)^{1/2}}{\kappa^4\cos^2\theta - \kappa^2 - \sin^2\theta}. \tag{6}$$

In this case the singularity will occur when

$$\sin^2\theta = \frac{\kappa^2(\kappa^2 - 1)}{\kappa^4 + 1}, \tag{7}$$

which implies a value of θ close to 90° for $\kappa \gg 1$. Hence similar to the argument above, we expect large negative values of D for close-to-grazing incidence in the case of strongly-attenuating medium like a metal. As is well-known, this condition corresponds to a large negative ε_{R} of the metal which arises when the incident frequency is far below the plasma frequency of the metal. In the previous study of a zero-damping plasma [3], this condition of grazing incidence for large negative GH shift was not pointed out, although it could have been deduced from the common GH shift formula for non-dissipative media such as that given in Eq. (25) of Ref. [3]. Our above treatment, however, can be applied even to electronic plasma with damping. Furthermore, since in this case the Brewster angle will play a very different role (see below), one will have a greater chance of observing this large negative GH shift for unlike the case studied previously with weakly-absorbing medium, the reflected light is not necessarily weak [6]. In order to illustrate this effect, we have to first comment briefly on the meaning of the Brewster angle for an absorptive medium. For a dissipative medium with absorption, there have been different propositions in the literature for the definition of the Brewster angle for p-polarized incident light. These include expressions like $\theta_{\mathrm{B}} = \tan^{-1}(\sqrt{|\varepsilon_{\mathrm{r}}|})$ for weakly-absorbing medium [6], or more generally [14], $\theta_{\mathrm{B}} = \tan^{-1}(\sqrt{|\hat{\varepsilon}|})$; where ε_{r} and $\hat{\varepsilon}$ are the real part of the dielectric constant and the whole complex dielectric constant of the medium, respectively. However, the most unambiguous definition for θ_{B} still seems to be that from referring to the dip angle in the reflectance spectrum [14].

To numerically illustrate the above negative GH shift, we have plotted in Fig. 1 the shifts D as a function of incident angle for five different wavelengths for p-polarized light. We have computed these using the exact Fresnel reflectivity into Eqs. (2) and (3). Furthermore, we have considered silver for the metal and used the data for the optical constants (n, κ) compiled in Ref. [15]. It is obvious that very large negative values of D can occur for long wavelengths at close-to-grazing incidence. This is so since the extinction coefficient becomes very large for the metal at long wavelengths (e.g. for far IR such as that at 3390 nm, $\kappa \sim 21$ with $n \sim 1.7$ for silver [15]), which in turn leads to a very large

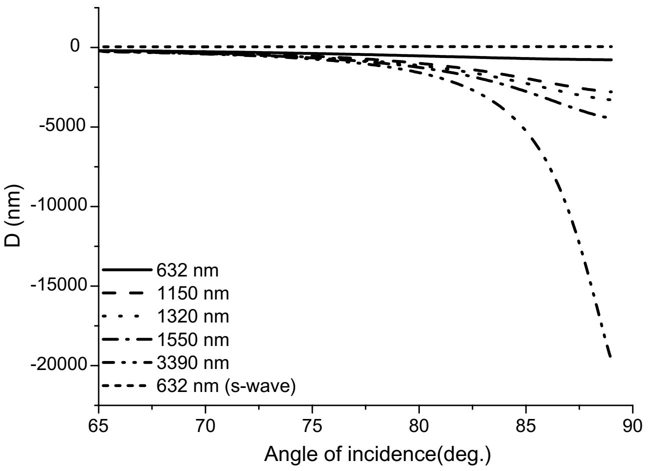

Fig. 1. Goos–Hanchen shifts as a function of incident angle for p-polarized light at various wavelengths. A typical result (at 632 nm) is also shown for s-polarized waves. The incidence is from vacuum on to a silver surface with optical constants taken from Ref. [15].

(and negative) value for ε_R. Note that the results (not shown) obtained using the simple Drude model in Eq. (1) are very similar qualitatively, with even larger negative shifts predicted (e.g. D is more negative by about 25% at 3390 nm at close to grazing incidence, with $\kappa \sim 24$ from the Drude model).

To see how close these grazing incidences are from the Brewster angle, we have plotted in Fig. 2 the reflectance spectra for the corresponding five wavelengths, using again the optical constants from [15]. It is clear that for shorter (optical) wavelengths, the Brewster dip is not sharply defined (Fig. 2) and the negative GH shift is limited (Fig. 1). As one increases towards longer wavelengths, large negative GH shifts start to take place, although the Brewster dip also starts to move towards larger values. Nevertheless, even at the "Brewster dip" for the wavelength 3390 nm, one still has over 70% of light from the reflected beam for this case with such a large attenuation. The light just does not penetrate much into the metal. Hence the negative GH shifts reported here should be relatively easy to observe compared to that studied previously for weakly-absorbing materials [4,6]. Furthermore, we notice that although these negative shifts reported here seem to bear some similarity to that observed very recently in a simulation study of such shifts from a "metal-backed dielectric film" [16], they are actually of quite different origins. That observed previously was mainly due to interference effects and will disappear as the film thickness goes to zero. On the contrary, the negative shifts observed here is from a bare metal surface in the limit of strong attenuation and reflection [17]. In addition, typical results for s-polarized light are also shown in the two figures, from which no extraordinary behavior is observed. We thus concluded that the large negative GH shift studied in the present work is unique for long wavelength p-polarized light incident on metal, at angles mostly closed to grazing incidence.

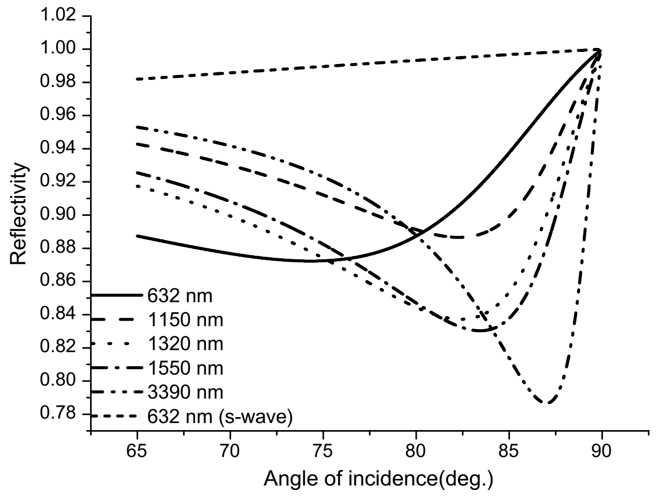

Fig. 2. Reflectivity as a function of incident angle for p-polarized light corresponding to the wavelengths and metal in Fig. 1. Typical result for s-polarized light is also shown for one wavelength (632 nm).

Acknowledgements

PTL acknowledges a research grant from Intel Corporation. This research was also partially supported by Center of Nanostorage Research, National Taiwan University, under grant number MOEA#95-EC-17-A-08-S1-0006 and the National Science Council of ROC under grant numbers NSC 95-2112-M-019-002 and NSC 95-2120-M-019-002. We also like to acknowledge the support from Center for Marine Bioscience and Biotechnology, National Taiwan Ocean University under grant numbers NTOU-AF94-05-04-01-01 and NTOU-AF94-05-04-01-02.

References

[1] F. Goos, H. Hanchen, Ann. Phys. 1 (1947) 333;
F. Goos, H. Hanchen, Ann. Phys. 5 (1949) 251.
[2] For an earlier comprehensive review: H. Lotsch, Optik 32 (1970) 116;
H. Lotsch, Optik 32 (1971) 299;
H. Lotsch, Optik 32 (1971) 553.
[3] H.M. Lai et al., Phys. Rev. E 62 (2000) 7330.
[4] W.J. Wild, C.L. Giles, Phys. Rev. A 25 (1982) 2099.
[5] O.V. Ivanov, D.I. Sementsov, Opt. Spectrosc. 89 (2000) 737;
O.V. Ivanov, D.I. Sementsov, Opt. Spectrosc. 92 (2002) 462.
[6] H.M. Lai, S.W. Chan, Opt. Lett. 27 (2002) 680;
H.M. Lai, S.W. Chan, W.H. Wong, J. Opt. Soc. Am. 23 (2006) 3208.
[7] L.G. Wang, H. Chen, S.Y. Zhu, Opt. Lett. 30 (2005) 2936.
[8] C. Bonnet et al., Opt. Lett. 26 (2001) 666.
[9] C.F. Li, Phys. Rev. Lett. 91 (2003) 133903.
[10] L.G. Wang, H. Chen, N.H. Liu, S.Y. Zhu, Opt. Lett. 31 (2006) 1124.
[11] J. He, J. Yi, S. He, Opt. Express 14 (2006) 3024.
[12] See, e.g., L.G. Wang, S.Y. Zhu, Appl. Phys. Lett. 87 (2005) 221102;
L.G. Wang, S.Y. Zhu, J. Appl. Phys. 98 (2005) 043522.
[13] A.A. Oliner, T. Tamir, J. Appl. Phys. 33 (1962) 231;
T. Tamir, A.A. Oliner, Proc. IEEE 51 (1963) 317.
[14] D. Han, X. Li, F. Wu, X. Liu, J. Zi, Appl. Phys. Lett. 88 (2006) 161110.
[15] E.D. Palik, Handbook of Optical Constants of Solids, vol. 1, Academic Press, 1985.
[16] See Fig. 4(a) in Ref. [10].
[17] For example, the imaginary part of our dielectric constant for the metal at 3390 nm is 68, compared to 0.5 used in Ref. [10] for their computation in Fig. 4(a).