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Addendum

Addendum to "Large negative Goos–Hanchen shift at metal surfaces", [Opt. Comm. 276 (2007) 206]

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In the above communication, we have investigated in details the possibility of observing a large negative lateral Goos–Hanchen (GH) shift from p-polarized light at long wavelength incident onto a bare metal surface, at angles close to grazing incidence. The shift could be up to a few wavelength (e.g. ~20 μm at a wavelength of 3390 nm onto silver) and the possible presence of a "pseudo Brewster angle" will not hinder the observability of such an effect. This effect has since been verified experimentally via reflection of IR light from a gold surface [1].

In reviewing the literature, aside from pointing out that our results were in consistency with those hinted at from previous analysis of surface backward waves [2] and of negative energy flow at interface [3], we should have also noted the first explicit calculation by Wild and Giles of such GH shifts at a silver surface which had obtained a (albeit small) negative shift in the order of one wavelength (~0.5 μm) [4].

In addition, we would like to emphasize that such large negative GH shift at a metal surface can easily be understood by examining the well-known elementary boundary conditions for the fields across an interface, as applied to the discussion of the continuity of the various components of the Poynting vector in [3].

In fact, if we let the x–z plane be the plane of incidence and apply the following boundary conditions for the normal (N) and tangential (T) field components at the vacuum–metal interface (assuming non-magnetic materials so that $B = H$ and neglecting damping):

$$E_{0\mathrm{N}} = \varepsilon E_{\mathrm{N}}, \quad E_{0\mathrm{T}} = E_{\mathrm{T}}, \quad H_{0\mathrm{N}} = H_{\mathrm{N}}, \quad H_{0\mathrm{T}} = H_{\mathrm{T}} \qquad (1)$$

we derive immediately, as in [3], the continuity of the energy flow along the interface described by the component of the Poynting vector $S_x \sim \left(\vec{E} \times \vec{H}\right)_x = E_y H_z$ for s-polarized wave; and by the quantity $\varepsilon S_x \sim -\varepsilon E_z H_y$ for p-polarized wave. Hence we conclude that while there is always a positive GH shift in the s-polarized case, S_x changes by a sign in the p-polarized case when $\varepsilon < 0$ as is the case when the incident frequency is below the plasmon frequency of the metal. This then leads to a negative GH shift [3].

Thus, following the above scheme of thought, one can easily understand how the negative GH shift in metal arises and how such shift can be manifested for p-polarized light, large incidence angle (i.e. close to grazing incidence so that E_z will be large), low incident frequency (so that ε will be more negative), and metal with high plasmon frequency (e.g. aluminum). In addition, one can also extend the above arguments to the case of meta-materials instead of metal where the magnetic permeability can also turn negative [by distinguishing the B field and H ($=B/\mu$) in (1)]. In this case, it is the continuity of $\mu S_x \sim \mu E_y H_z$ for s-polarized waves, implying that even the s-polarized light will experience negative GH shifts as has been reported in the literature [5]. Along the same line, one can even go further to design interfaces made of different combination of ordinary and meta-materials so that various positive/negative GH shifts may be generated as desired.

We believe the above remarks should help to shed some light on the recently observed negative GH shifts at a bare metal surface [1].

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T. Tamir, A.A. Oliner, Proc. IEEE 51 (1963) 317.
[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, Note that the result was somewhat overshadowed by that for a semiconductor (germanium) obtained in the same paper (~3 times the wavelength), and there was no elaboration for the possibility of observing a much larger negative shift in the metal case, without the possible hindrance by the presence of the "pseudo Brewster angle" as was clarified in our recent work.
[5] See, e.g., L.G. Wang, S.Y. Zhu, Appl. Phys. Lett. 87 (2005) 221102;
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