Direct Measurement of the Wigner Delay Associated with the Goos-Hänchen Effect

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It is shown experimentally that the nonspecular reflection of light on an interface induces a time delay, as predicted by Wigner's scattering theory. A differential femtosecond technique is used to directly isolate this delay, associated with the Goos-Hänchen spatial shift produced by a grating near a resonant Wood anomaly. A delay of 4.4 fs is observed between TE and TM pulses, in agreement with the expected Wigner delay obtained from phase shift dispersion measurements.

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Because of the existence of an evanescent wave, a beam undergoing total reflection exhibits a spatial shift, as suspected by Newton's corpuscular theory [1] and demonstrated by Goos and Hänchen [2]. This effect has since been extended to many areas of physics, such as acoustics, plasma physics, quantum mechanics [3], and surface physics and chemistry [4]. However, most of the work has been theoretical while the experimental results concerning the Goos-Hänchen (GH) effect are meager. In optics, it is only recently that a direct measurement of the GH spatial shift of a well-defined beam for a single reflection has been performed [5]. Still, only the spatial aspect of the GH shift has been investigated in stationary experiments. Yet, it was recognized very early [6] that the best quantum analysis of this effect is based on the scattering theory of Wigner [7], Smith [7], and Froissart, Goldberger, and Watson [7]. Indeed, the total reflection of light being considered a scattering process, the GH effect appears not only as a spatial shift, but also as a temporal delay which should be of the order of 10^{-14} to 10^{-15} s [8]. By the time, such a delay was clearly out of experimental reach. Now that femtosecond lasers have become a common optical source, one can wonder whether this delay may be observed in a simple way, i.e., by analyzing the reflected beams. In fact, it will be shown that, in the case of total reflection, this time delay is not directly accessible on the reflected beams, essentially because they stay in the denser medium. Fortunately, other interface structures are expected to exhibit GH spatial and temporal shifts where the beams are reflected in the *lower* index medium. A peculiar case in linear optics is the reflection of light by a metallic grating in the vicinity of a resonant Wood anomaly [9]. There, a GH spatial shift has been predicted by Tamir and Bertoni [10] on the basis of the resonant excitation of leaky-wave fields [11,12], and recent calculations have indicated that the associated delay remains of the order of a few femtoseconds [13]. Consequently, our aim in this Letter is to search experimentally for a Wigner delay in the case of a metallic grating by using a simple femtosecond technique.

Let us consider the total reflection upon a dielectric-vacuum plane interface [Fig. 1(a)]. For all values $z \leq 0$, the space is filled with a dielectric medium of index n, all values $z \geq 0$ corresponding to vacuum ($n = 1$). Then, we treat total reflection as single-channel scattering of an incoming wave packet on a potential wall at $z = 0$. The incoming wave packet crosses over into vacuum, forms an evanescent wave, and comes back into the original medium as a reflected wave packet. From Wigner's scattering theory, the corresponding elastic collision is described by a scattering matrix $S = \exp(2j\delta)$ and leads to a time delay τ given by the energy derivative of the phase shift δ:

$$\tau = j\hbar \frac{\partial S}{\partial E} S^* = -2\hbar \frac{\partial \delta}{\partial E}, \tag{1}$$

while the displacement D of any incoming orbit in a normal direction is given by the derivative of the S matrix with respect to the momentum transfer Δp in the same normal direction [7]:

$$D = 2j\hbar S^* \frac{\partial S}{\partial \Delta p} = -4\hbar \frac{\partial \delta}{\partial \Delta p}. \tag{2}$$

For a given angle of incidence i, the displacement Δx along the interface is equal to $D/\cos i$. Two different phase shifts can be explicitly calculated for the two simple cases: incoming electric field E perpendicular to the plane $y = 0$ (TE case), and E parallel to the plane $y = 0$ (TM case) [14]. This yields two different displacements Δx_{TE} and Δx_{TM} along the interface [Fig. 1(a)]. Following Ref. [8], the time delay τ is simply given by the spatial shift Δx divided by the group velocity $v_x = c/(n \sin i)$. This leads to a differential time delay $\Delta\tau = \tau_{\mathrm{TM}} - \tau_{\mathrm{TE}}$ equal to $(\Delta x_{\mathrm{TM}} - \Delta x_{\mathrm{TE}})/v_x$. Now, we analyze the differential time of arrival $\Delta\tau_d$ of the reflected wave packets onto a detector. To obtain maximal temporal resolution, the latter is placed perpendicular to the direction of propagation of the reflected wave packets. Curiously, the extra time $\Delta\tau$ spent by the TM wave packet along the interface is exactly equal to the TE wave-packet propagation time from point A to B [Fig. 1(a)] in the *denser* medium, i.e., $(n/c) \times (\Delta x_{\mathrm{TM}} - \Delta x_{\mathrm{TE}}) \times \sin i$. Therefore, the two delays compensate, and TE and TM pulses arrive in this case simultaneously onto the detector and $\Delta\tau_d = 0$ [15].

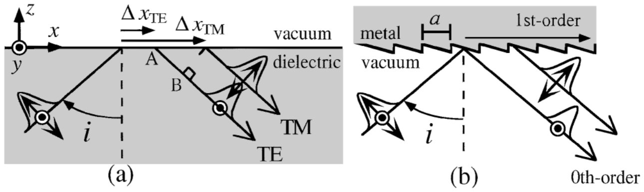

FIG. 1. (a) Total reflection of a wave packet by a dielectric-vacuum interface. (b) Reflection of a wave packet by a grating; only the zeroth and first orders of diffraction are represented.

Fortunately, other interface structures exhibit GH-like phenomena where reflection takes place in the *rarer* medium and leads to a non-null $\Delta\tau_d$. In particular, we consider now an optical beam impinging from vacuum onto a metallic grating [Fig. 1(b)]. For peculiar values of the incidence angle, a dip in the diffracted beam intensities is observed due to strong absorption of the incident beam. This phenomenon, known as Wood anomaly, occurs at an angle of incidence slightly above the so-called Rayleigh angle, for which a diffracted beam disappears at grazing emergence by passing off the edge of the grating. This anomaly has been interpreted as a forced resonant excitation of a leaky surface wave by the incident beam [11,12] which, in the case of a metallic grating, is a surface plasmon. It occurs only in TM polarization since an electric field component of the incident beam perpendicular to the grating surface is needed to create a surface density of oscillating electrons. This *resonant* Wood anomaly is accompanied by a phase shift δ for the TM zeroth-order reflected beam, which depends strongly on both the angle and the wavelength. Therefore, according to Eqs. (1) and (2), this scattering process must lead to GH-like spatial and temporal shifts.

To be more specific, let us consider a pulsed optical beam of wavelength λ diffracted by a metallic grating with a groove spacing a [Fig. 1(b)]. The Rayleigh angle associated with the disappearance of the first-order diffracted beam is

$$i_0 = \arcsin(1 - \lambda/a)\,. \tag{3}$$

For an angle of incidence i below i_0, no phase shift occurs; thus no delay is expected. Just at $i = i_0$, the energy of the disappearing first order is redistributed into the propagating orders and leads to a sharp variation of the zeroth-order efficiency. This second type of Wood anomaly is not resonant and does not lead to GH shifts. Conversely, for i just above i_0, the zeroth-order beam acquires a phase shift due to the wing of the resonant anomaly. For a small range of angles above i_0, the predominant role is played by the phase which varies strongly and hence induces spatial and temporal shifts, while the absorption by the grating remains small. Therefore, our working angle range is the wing of the resonant anomaly around i_0. As stated by Tamir and Bertoni, the GH shifts can be explained by the propagation of evanescent waves [10], just as in the case of total reflection. Indeed, a portion of the TM incident energy penetrates in the form of a leaky-wave field, progresses along the structure, and radiates back in the reflected beam direction. Because of this energy leakage, the TM reflected beam is delayed and spatially shifted with respect to the TE one, which is instantaneously and specularly reflected since it cannot excite leaky waves [Fig. 1(b)]. Therefore, we choose the differential delay between TE and TM reflected pulses as our observable.

In order to check these predictions experimentally, we send a well-collimated short pulsed optical beam at $\lambda = 800$ nm onto a commercial ruled aluminum grating with 600 grooves/mm. This grating has a blaze angle at 750 nm and is coated with a 48 nm protective layer of MgF_2. Usually, GH spatial shifts are of the order of a few microns; therefore, we can infer that the expected delays are of the order of a few femtoseconds. To observe them, we could use pulses as short as possible, ideally shorter than the delay. But the corresponding large spectrum of the pulse would average the spectral features of the Wood anomaly, leading to a dramatic decrease of the time delay. On the other hand, very long pulses would result in a lack of temporal resolution. Thus, pulses of 100 fs duration seem to constitute a good tradeoff. The incident pulse impinges on the grating with an angle of incidence i and is polarized by a Glan prism at 45° to the plane of incidence. After reflection, the TM pulse is expected to be delayed by a few femtoseconds with respect to the TE one. To detect this differential delay, we modify a commercial autocorrelator (Fig. 2). We choose to use this autocorrelator in the so-called intensity detection mode. As usual in this mode, the incident pulse is separated by a beam splitter B into two arms where translatable hollow cubes $C_{1,2}$ act as delay lines. Into each arm, we insert a sheet polarizer P, one aligned with the TE direction, and the other with the TM one. Both TE- and TM-polarized pulses are then focused onto a thin KDP nonlinear crystal Cr and a photomultiplier PM detects frequency-doubled photons.

In order to extract delays without data accumulation, the following homodyne detection is used. First, in the absence of a delay between TE and TM pulses at the input of the autocorrelator ($i < i_0 = 31.2°$ on the grating),

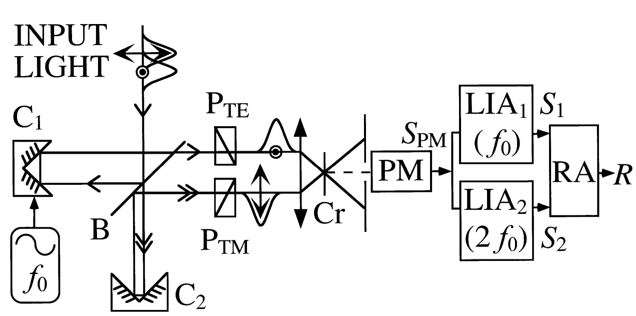

FIG. 2. Differential autocorrelator used to measure the Wigner delays.

the position of C_2 is adjusted to obtain temporal coincidence of the TE and TM pulses in the KTP crystal and thus a maximum PM signal S_{PM}. Then, the position of C_1 is sinusoidally modulated around the coincidence position at frequency $f_0 = 34$ Hz. Thus, S_{PM} is modulated at frequency $2 \times f_0$ [Fig. 3(a)]. Now, if a delay between TE and TM pulses is introduced at the entrance of the autocorrelator, the coincidence position of C_1 changes and a nonzero component at frequency f_0 appears in S_{PM}. This is clearly shown by the arrows in Fig. 3(b) where, as an illustration of the technique, a known delay $\Delta\tau = 18$ fs is induced by a quartz plate of thickness 0.65 mm inserted in front of the autocorrelator with its fast and slow axes parallel to the TE and TM axes, respectively. The f_0 component is extracted by a lock-in amplifier LIA_1 and gives a signal S_1 proportional to $\Delta\tau \times A$ for small $\Delta\tau$, where A is the amplitude of S_{PM}. Since A can vary, we extract it by demodulating S_{PM} at frequency $2 \times f_0$ with a second lock-in amplifier (signal S_2). Then the ratio $R = S_1/S_2$, solely proportional to $\Delta\tau$, is reconstructed by a ratiometer RA. R is calibrated by simply displacing C_2 of 1 μm, leading to a delay of 6.7 fs.

Let us now rotate the grating from the initial angle $i < i_0$. As expected, when the first-order diffracted beam passes off the edge of the grating ($i \approx i_0$), a delay is induced by the grating and appears as an unambiguous component at f_0 in S_{PM} [Fig. 3(c)]. Figure 4 shows the delay $\Delta\tau$ extracted from R as a function of i. Around $i = i_0$, the delay increases sharply over an angle range of 0.4°. This is due to the gradual disappearance of the first-order diffracted beam which has an angular width of 0.4°, related to the spectral width of the pulse ($\Delta\lambda = 10$ nm). A maximum temporal shift of $\Delta\tau_{max} = 4.4$ fs between TE and TM pulses is obtained. Finally, due to the increasing absorption of the TM wave by the grating, the delay decreases smoothly when i is further increased.

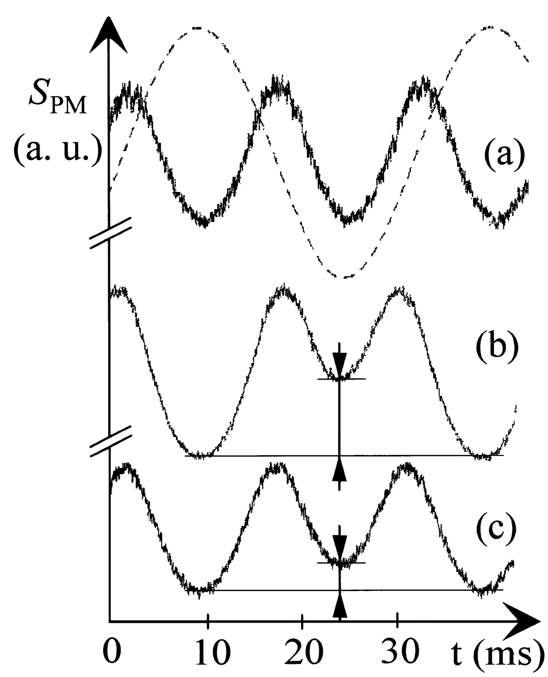

FIG. 3. Full line: signal S_{PM} of the photomultiplier versus time: (a) no delay (case $i < i_0$); (b) case $i < i_0$ with a quartz plate inserted in front of the autocorrelator; (c) case $i > i_0$ (without plate). The arrows show the appearance of the f_0 component. Dashed line: signal proportional to the displacement of C_1.

We have performed complementary experiments to confirm the fact that the observed delay can be fully interpreted in terms of a Wigner delay. With this aim in view, the phase retardance induced by the grating between TE and TM polarizations is measured with a simple polarimetric method. The same laser source is used, but run in cw mode. As previously, the laser beam is linearly polarized at 45° from the TE and TM grating axes. The zeroth-order reflected beam acquires an ellipticity which is analyzed by a second Glan prism, and the phase retardance $\delta_{TM} - \delta_{TE}$ is finally extracted. At fixed i, this retardance is measured versus λ varying from 780 to 820 nm by tuning the laser. Then, we estimate the expected value $\Delta\tau$ for this angle i according to the right-hand side of Eq. (1) averaged over the spectral width of the pulsed beam. The expected values are reported as open circles in Fig. 4 for four angles. The agreement between the measurement of $\Delta\tau$ and the expected values is quite good. Therefore, this shows unambiguously that the observed delays are Wigner delays associated with the interface.

To conclude, we have isolated a Wigner delay for an optical reflection on an interface. In the case of a grating near a resonant Wood anomaly, a delay of 4.4 fs has been observed between the TE and TM pulses reflected in the zeroth-order diffracted beam. This result lies within the same order of magnitude as the calculation of Ref. [13] performed for an idealized sinusoidal grating. Just as the GH spatial shift is well known to be given by the derivative

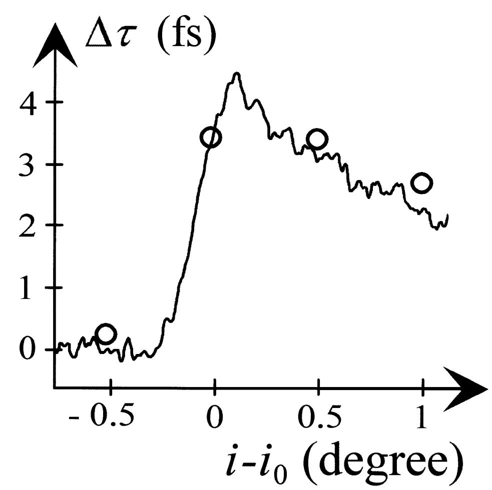

FIG. 4. Full line: measured delay $\Delta\tau$ as a function of $i - i_0$. Open circles: delays expected from phase retardance measurements. Measured and expected delays: uncertainty ± 0.4 fs.

of the phase shift with respect to the momentum transfer, we have shown experimentally that the GH delay is equal to the derivative of the phase shift with respect to energy. Since ultrashort pulsed optical experiments benefit from a high temporal resolution, it makes observable the time delay induced by a *single* reflection. Therefore, the Wigner delay on an interface could lead to applications in surface physics in a manner much easier than those suggested for the GH spatial effect. Indeed, the present method could be applied to study the delay induced by other diffractive structures [16–19] and the Wigner delay on interface could have implications in other domains such as nonlinear optics and seismology [3,20]. Depending on the considered problem, the Wigner theory thus provides complementary investigation techniques based on spatial, temporal, or ellipsometric measurements. Besides, the Wigner delay of the GH effect should be of use in the design of spatial-temporal processing techniques [21].

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[1] I. Newton, *Opticks* (Dover, New York, 1952).
[2] F. Goos and H. Hänchen, Ann. Phys. (Leipzig) **1**, 333 (1947); F. Goos and H. Lindberg-Hänchen, Ann. Phys. (Leipzig) **2**, 87 (1949).
[3] H. K. V. Lotsch, Optik **32**, 299 (1971).
[4] N. J. Harrick, Phys. Rev. Lett. **4**, 224 (1960).
[5] F. Bretenaker, A. Le Floch, and L. Dutriaux, Phys. Rev. Lett. **68**, 931 (1992).
[6] L. De Broglie and J. P. Vigier, Phys. Rev. Lett. **28**, 1001 (1972).
[7] E. P. Wigner, Phys. Rev. **98**, 145 (1955); F. T. Smith, Phys. Rev. **118**, 349 (1960); M. Froissart, M. L. Goldberger, and K. M. Watson, Phys. Rev. **131**, 2820 (1963).
[8] J. L. Agudin, Phys. Rev. **171**, 1385 (1968); K. W. Chiu and J. J. Quinn, Am. J. Phys. **40**, 1847 (1972).
[9] R. W. Wood, Philos. Mag. **4**, 396 (1902).
[10] T. Tamir and H. L. Bertoni, J. Opt. Soc. Am. **61**, 1397 (1971); S. Zhang and T. Tamir, J. Opt. Soc. Am. A **6**, 1368 (1989).
[11] U. Fano, J. Opt. Soc. Am. **31**, 213 (1941).
[12] A. Hessel and A. A. Oliner, Appl. Opt. **4**, 1275 (1965).
[13] R. Güther and B. H. Kleemann, J. Mod. Opt. **45**, 1375 (1998).
[14] M. Born and E. Wolf, *Principles of Optics* (Pergamon, Oxford, 1965), 3rd ed.
[15] The same result can be obtained by using a stationary phase model. We also note that when dispersion is taken into account, a slight differential delay $\Delta\tau_d$ occurs, although orders of magnitude smaller than $\Delta\tau$.
[16] W. J. Wild and C. L. Giles, Phys. Rev. A **25**, 2099 (1982).
[17] F. Schreier, M. Schmitz, and O. Bryngdahl, Opt. Lett. **23**, 1337 (1998).
[18] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[19] M. B. Sobnack, W. C. Tan, N. P. Wanstall, T. W. Preist, and J. R. Sambles, Phys. Rev. Lett. **80**, 5667 (1998).
[20] M. A. Breazeale and M. A. Torbett, Appl. Phys. Lett. **29**, 456 (1976).
[21] D. M. Marom, D. Panasenko, P. C. Sun, and Y. Fainman, Opt. Lett. **24**, 563 (1999).