Direct Measurement of the Optical Goos-Hänchen Effect in Lasers

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The Goos-Hänchen longitudinal shift at total reflection of an optical Gaussian beam is experimentally investigated for only one reflection. The differential experimental method uses the high sensitivity of the eigenstates of a quasi-isotropic laser to small perturbations to measure an intracavity Goos-Hänchen effect for angles of incidence both below and above the critical angle. The measurements are in good agreement with our calculations of the longitudinal shift for Gaussian laser beams.

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Since its discovery in 1947 by Goos and Hänchen [1], the beam spatial shift due to the evanescent wave at total reflection suspected by Newton's corpuscular theory [2] has been extended to many areas of physics, such as acoustics, plasma physics, quantum mechanics [3], and surface physics and chemistry [4]. It has been the subject of many controversial investigations, theoretical as well as experimental. The theoretical controversy [5] has mainly been due to the existence of stationary phase models [6], energy propagation models [7], ray models [8,9], and plane-wave beam expansion models [10–13]. More recently, the Goos-Hänchen (GH) effect has been used as an argument in the discussion of the nature of light and of the photon [14,15]. The experimental results concerning the GH effect are meager, due to the experimental difficulties. Except for nonlinear optics experiments [16], two main kinds of experiments can be distinguished. The first one consists of multiple-reflection optical experiments that amplify the small (a few wavelengths) longitudinal displacement of the beam [1,17–19]. The second one consists of single-reflection microwave experiments [20]. In the former case, no direct measurement of the dependence of the GH shift on the incidence angle has been obtained for only one reflection. On the contrary, in the latter case, the large values of the wavelength allow one to measure the GH shift directly for a single reflection. However, in this case, the quality of the beams is not very good and their transversal sizes are of the order of magnitude of the wavelength. This leads to a large distribution of wave vectors in the incident beam and consequently to an averaging of the GH shift dependence on the angle of incidence [10]. Consequently, it seems fundamental to perform an experimental measurement of the evolution of the GH shift versus the angle of incidence for a perfectly known *optical* beam in a *single-reflection experiment.* We propose here a new method to reach this goal, based on the sensitivity of the laser eigenstates to small perturbations.

Let us consider the ^{3}He-^{20}Ne laser oscillating at $\lambda_0 = 3.39$ μm shown in Fig. 1. The cavity is built with a plane mirror (reflectivity 95%) and a spherical mirror (reflectivity 64%) with radius of curvature $R = 1.2$ m. It contains a 45°-90°-45° silica prism (index of refraction $n = 1.409$) that leads to total reflection for angles of incidence i above the critical angle $i_c = 45.212°$. This reflection on the air-prism diopter leads to the existence of a GH spatial shift between the TE (perpendicular to the plane of the cavity) and the TM (parallel to the plane of the cavity) polarizations. The eigenstates of this cavity are linearly polarized TE and TM eigenstates and are *spatially separated* in one part of the cavity, i.e., between the prism and the plane mirror. Their eigenfrequencies and intensities are determined by their dephasings and reflection coefficients due to the internal reflection. Depending on the value of the angle of incidence i that governs the phase and loss anisotropies of the two eigenstates, the oscillation regime can be a one-eigenstate regime or a vectorial bistability [21] or vectorial simultaneity oscillation regime. Besides, it has been established that when a laser is made quasi-isotropic, a peculiar behavior occurs [22]. The laser becomes indeed very sensitive to very small longitudinal magnetic fields (fractions of a gauss) that induce nonreciprocal Faraday rotation in the active medium and lead to a periodic rotation of the linear polarization of the laser light. To prepare our system containing the prism to make it behave like a quasi-isotropic laser, the phase and loss anisotropies described by Fresnel's formulas [23] must be carefully com-

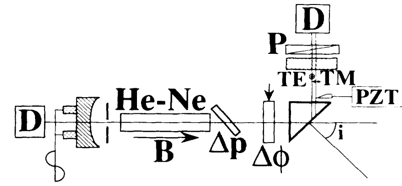

FIG. 1. Experimental setup.

pensated. A tilted silica plate is introduced inside the cavity to compensate for the extra losses undergone by the TM mode relative to the TE mode at internal reflection for angles around the critical angle. A stressed silica plate is also introduced to compensate for the phase anisotropy induced by Fresnel's laws for $i > i_c$. Once the cavity is prepared to have overall anisotropies as weak as possible, the application of a very small longitudinal magnetic field (a fraction of a gauss) on the active medium, via a solenoid, makes the polarization rotate periodically, at frequencies of the order of several tens or hundreds of kHz. If a small overall loss anisotropy is created inside the cavity, the polarization, which can be considered as linear for weak anisotropies, passes periodically from the low-loss axis to the high-loss axis, leading to a periodic modulation of the losses of the laser. Since the modulation period (a few micoseconds) is much longer than the lifetime of photons in our "bad" cavity (a few nanoseconds) and the atomic relaxation times (also a few nanoseconds), the intensity of the laser follows *adiabatically* the modulation of the losses. When our system is well prepared so that the anisotropies are carefully compensated, the residual intensity modulation is less than 0.1%.

Let us then introduce a knife edge inside the cavity where the two eigenstates are spatially separated, as shown in Fig. 1. Because of the GH spatial separation of the two eigenstates, the diffraction losses due to this knife edge are different for the TE and TM eigenstates, leading to a diffraction "loss anisotropy." When the polarization rotates, this leads to a modulation of the total intensity of the laser of a few percent, as shown in Fig. 2(a). The polarization effect is transformed into an intensity effect. Schematically, we can say that *the beam oscillates transversally with respect to the knife edge,* with an amplitude equal to the GH shift. The detection of the time evolution of the intensity detected through a polarizer shows a modulation depth very near 1, showing that the loss anisotropy is low enough to allow us to treat the polarization as a rotating linear polarization. The total intensity modulation is a direct observation of the GH spatial shift between the TE and TM eigenstate. But we need a reference to calibrate our measurements. Our knife edge is mounted on a piezoelectric transducer that provides a 60-μm peak-to-peak displacement at 5 Hz. Consequently we just have to cut the small longitudinal magnetic field and make the knife edge vibrate to know which modulation of the total intensity corresponds to a displacement of 60 μm. Such a typical calibration modulation is shown in Fig. 2(b), corresponding in this case to *a displacement of the knife edge relative to the beam.* Since the loss anisotropies introduced in both cases are small compared to the total losses of the laser, the intensity modulation depth is linear with this loss anisotropy. Moreover, since the knife edge is only very slightly introduced inside the beams, we can consider that the diffraction loss anisotropies are in both cases proportional to the peak-to-peak relative displacements of the beam and the knife edge. Consequently, the GH effect is equal to the ratio of the two modulation amplitudes multiplied by 60 μm.

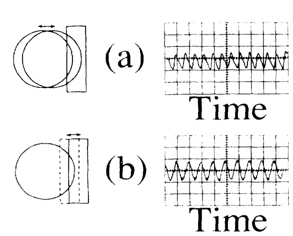

FIG. 2. Typical total intensity modulation signals due to (a) modulation of the position of the beam with respect to the knife edge (horizontal axis, 5 μs per division; vertical axis, 1.6% modulation per division) and (b) modulation of the position of the knife edge with respect to the beam (horizontal axis, 0.2 s per division; vertical axis, 3.2% modulation per division).

To compare our experimental results with theory, we extend the calculations of Ref. [12]. We consider the GH effect as being the result of interferences between the differently reflected Fourier components of the given incident beam. The incident beam inside the prism can be written as

$$E^i = \frac{1}{\sqrt{q}} \exp\left\{ -\frac{2j\pi}{\lambda}(x \sin i - z \cos i \right\} \times \exp\left\{ -\frac{2j\pi}{q} \frac{(x \cos i + z \sin i)^2}{2\lambda} \right\}, \quad (1)$$

where x, y, and i are defined in Fig. 3, $\lambda = \lambda_0/n$ is the wavelength inside the denser medium, and the complex beam parameter q is

$$q = nd + x \sin i - z \cos i + j\pi w_0^2/\lambda , \quad (2)$$

where w_0 is the beam waist on the plane mirror and d is the distance from the beam waist. The Fourier components of the beam incident on the interface are given by

$$A^i(u) = \int_{-\infty}^{+\infty} e^{jkux} E^i(x, z=0) dx , \quad (3)$$

with $k = 2\pi/\lambda$. The Fourier components of the reflected

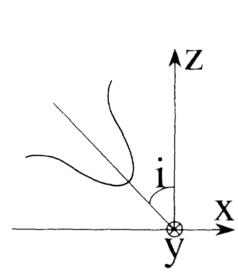

FIG. 3. Gaussian beam incident on a diopter with angle of incidence i.

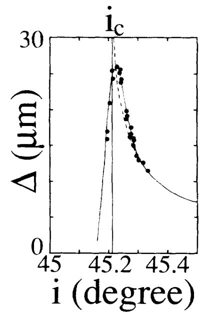

FIG. 4. Difference between the TE and TM GH shifts vs the angle of incidence. Solid line, theory; dotted line, Artmann's formulas; points, our measurements.

beam are then given by

$$A^r(u) = R[\arcsin(u)]A^i(u)\,, \tag{4}$$

with R given by Fresnel's laws for each polarization [23]. The GH shift can then be given by the mean abscissa of the output intensity:

$$x^r = \frac{\int_{-\infty}^{+\infty} E^r(r) x E^{r*}(r)dx}{\int_{-\infty}^{+\infty} E^r(r) E^{r*}(r)dx} = -\frac{j}{k}\frac{\int_{-\infty}^{+\infty}(dA^r/du)A^{r*}du}{\int_{-\infty}^{+\infty}A^r A^{r*}du}\,. \tag{5}$$

The quantity that we must compare with our experimental results is $\Delta = (x^r_{\mathrm{TM}} - x^r_{\mathrm{TE}})\cos i$, i.e., the difference between the TM and TE GH shifts. This comparison is shown in Fig. 4 with $w_0 = 800$ μm and $n = 1.409$, corresponding to our experimental conditions. A good agreement is shown between theory and experiments. The corresponding calculations with Artmann's formulas [6] are shown by the dotted line, showing that these formulas are valid when $i - i_c$ is larger than the divergence of the beam, i.e., when all the Fourier components of the beam are totally reflected.

In conclusion, we have shown that our experimental method based on the sensitivity of laser eigenstates to small perturbations allows one to isolate small surface effects. This method has been applied to the direct measurement of the GH spatial shift for a single reflection of a Gaussian beam. Good agreement has been found between our plane-wave beam expansion model calculations and experiments both below and above the critical angle. This method can have other applications, such as measurements of the still smaller transversal spatial shift for the circularly polarized beam investigated by Fedorov [24] and Imbert [25] or the determination of surface properties of optically transparent materials like semiconductors [3].

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