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Transverse displacement at total reflection near the grazing angle: a way to discriminate between theories

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ABSTRACT The transverse shift is observed and precisely measured at total internal reflection on a dielectric interface for a circularly polarized light beam when the incident angle is scanned from the critical angle up to the grazing angle close to 90°. The experimental results show with no doubt that the transverse displacement exists far away from the critical angle and only vanishes at grazing angle. A comparison with theories also allows a discrimination between the most different theoretical models traditionally used to interpret physically this effect.

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1 Introduction

Longitudinal and lateral spatial shifts of a light beam at total reflection on an interface between two dielectric media of high and low refractive indexes have been largely discussed in the past [1, 2]. These effects are attributed to the evanescent wave propagating into the lower index medium near the interface and depend on the incident angle as well as on the incident polarization state of the beam. In the case of an elliptically polarized beam, the spatial shift can be discomposed into two components, a longitudinal one called the Goos–Hänchen (GH) shift [3–5] which corresponds to a displacement in the plane of incidence and a transverse shift [6–8] which is perpendicular to the plane of incidence.

On the one hand, the experimental observation and the measurement of the Goos–Hänchen effect have been reported many times despite the fact that the displacement is only a few λ near the critical angle. Several techniques have been used to measure such a displacement. A first solution consists to amplify the longitudinal displacement by using multiple reflections [3]. Another way is to use an electromagnetic wave in the microwave domain [9]. Recently, a very elegant technique was proposed by using a quasi-isotropic laser containing an intracavity prism on which the total reflection appears [10].

On the other hand, the transverse displacement, initially predicted by Fedorov [6], has been first experimentally investigated by Imbert, also using multiple reflections in a prismatic structure [8, 11]. Despite the fact that many authors have reported on the transverse shift [12, 13] (and see references in [8]), we should call the transverse displacement as the "Imbert–Fedorov" (IF) shift. Very recently, our group has developed a highly sensitive technique to detect simultaneously the GH and IF shifts [14]. This experimental set-up allowed us to measure for the first time the transverse displacement after a single total reflection close to the critical angle [15].

Nevertheless, from the theoretical point of view, most of the models used to describe the Imbert–Fedorov shift predict that the transverse displacement should be observable far away from the critical angle contrary to the Goos–Hänchen shift which decreases very quickly versus the angle of incidence. However, this prediction has never been confirmed experimentally.

The goal of the present paper is thus to investigate this transverse shift far away from the critical angle up to the grazing angle. Moreover, different models used to explain the Imbert–Fedorov effect at total reflection disagree when the incident angle is close to 90° [16, 17]. Therefore, the experimental measurements are compared with two of the most common models usually used to interpret the transverse shift. The comparison is done to determine if the experimental measurements allow a possible discrimination between at least the most contradictory theories.

2 Experimental set-up

The schematic of the experimental set-up used to determine the transverse displacement at grazing angle is illustrated in Fig. 1 and has been described in a previous paper [15]. A collimated optical beam is emitted by a Spectra Diode Laboratories laser diode (Model 6702 H1; $\lambda = 1.083$ µm) driven by a SDL 800 power supply. The incident linear polarization is periodically switched at a frequency $f = 1$ kHz between TE and TM polarization states thanks to the Liquid Crystal Valve (LCV). A Quarter Wave Plate (QWP) is added

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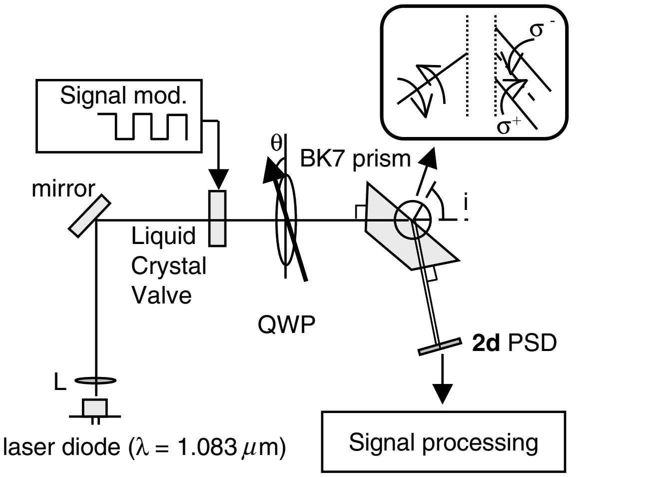

FIGURE 1 Schematic representation of the experimental set-up viewed in the incident plane; the insert shown above illustrates both the longitudinal and the transverse shifts in the transverse plane

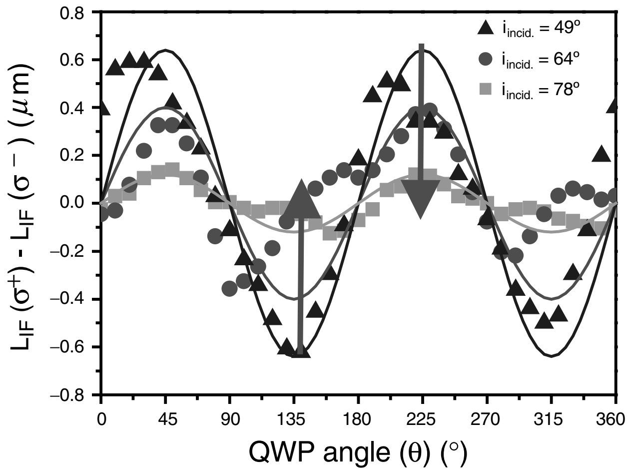

FIGURE 2 Transverse shifts measured versus the orientation of the *QWP* for three incident angles i (s: 49°; l: 62°; n: 78°; *solid line*: theory). The *arrows* just show the evolution for the displacement as the incident angle increases

after the LCV in order to generate adjustable polarization state. Let us assume θ the angular orientation of the wave plate axes with respect to the linear polarization states emerging from the LCV (for example TE and TM states). If the angle θ is set to 45°, the polarization of the incident wave is periodically switched between right-circular σ^+ and left-circular σ^- polarization states. Under these conditions, the relationship between spatial shifts of both polarization states is: $L_{\mathrm{IF}}(\sigma^+) = -L_{\mathrm{IF}}(\sigma^-)$ where $L_{\mathrm{IF}}(\sigma^{+(-)})$ represents the Imbert–Fedorov displacement for a $\sigma^{+(-)}$ incident polarized beam. To keep similar experimental conditions when the incident angle varies from the critical angle ($i = 41.6°$) up to grazing angles, three different BK7 prisms have been successively used to perform the experiment (a right-angle prism for i around 45°, an equilateral prism for i around 60° (Fig. 1) and a specially shaped prism for the experiments around $i = 80°$). It results that the entrance angle on the prism is always close to 0°. When this entrance angle went away from 0°, a parasitic signal would have appeared because of the difference between the transmission coefficients in amplitude for both orthogonal polarized states. The position of the laser beam after total reflection is then detected on a 2d-PSD (AME UDT-Model FIL-C4DG) which is perpendicular to the reflected beam. The signal processing using a lock-in amplifier (Standford Research System, Model SR810) locked to the reference signal at frequency f directly provides $\Delta L_{\mathrm{IF}}(\sigma^+/\sigma^-) = L_{\mathrm{IF}}(\sigma^+) - L_{\mathrm{IF}}(\sigma^-) = 2L_{\mathrm{IF}}(\sigma^+)$.

3 Results and analysis

Experimental results are obtained when the optical axis of the QWP is rotated. The transverse displacement is maximum when $\theta = 45°$ whereas this shift vanishes for linear incident polarization states ($\theta = 0°$ or 90°). Figure 2 shows the evolution of the transverse displacement versus the angular orientation of the QWP. The three graphs present a similar periodic evolution versus the angular orientation of the QWP whatever the incident angle is close or far away from the critical angle ($i = 49°$, 64° and 78°). As theoretically predicted, these variations show an angular period equal to $\Delta\theta = 180°$ which clearly confirm that the beam displacements observed can be attributed to the Imbert–Fedorov effect. Moreover, the experimental displacement progressively decreases when the angle of incidence i on the interface increases and approaches 90°. Using such a curve, it becomes possible to represent $\Delta L_{\mathrm{IF}}(\sigma^+/\sigma^-)$ or $L_{\mathrm{IF}}(\sigma^{+(-)})$ versus the incident angle as shown in Fig. 3. The experimental points correspond to three set of experimental points measured respectively with the three different prisms around 45°, 60° and 80°. In this figure, error bars are deduced from measurements obtained when the QWP is replaced by a half wave plate (HWP). In this case, a small parasitic signal is obtained when the HWP is rotated. The error signal presents an angular period $\Delta\theta = 90°$ which corroborates the fact that in this case it can not be attributed to the transverse displacement and is just due to parasitic effects.

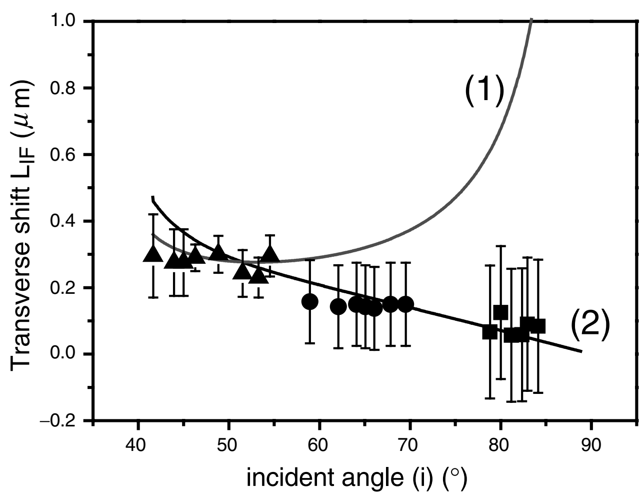

FIGURE 3 Transverse displacement (L_{IF}) versus the angle of incidence i on the interface n_1/n_2; solid line are theoretical and *(1)* is relative to Hugonin and Petit formula whereas *(2)* is relative to the conservation energy model

From a theoretical point of view, different expressions of the relative transverse spatial shift $\Delta L_{\mathrm{IF}}(\sigma^+/\sigma^-)$ can be calculated depending on the approach used. Unfortunately, these expressions could be in total controversy. For example, from Hugonin and Petit (Eq. 74 in [16]), we can deduce:

$$\Delta L^1_{\mathrm{IF}}(\sigma^+/\sigma^-) = 2 \cdot \frac{\lambda}{\pi} \cdot \frac{1+\cos^2 i}{2\sin i \cdot \cos i} \cdot \frac{\frac{n_1}{n_2}}{\left(\frac{n_1}{n_2}\right)^2 - 1} \cdot \frac{\left(\cos^2 i + \frac{n_1^2}{n_2^2}\sin^2 i - 1\right)^2}{\cos^2 i + \frac{n_1^4}{n_2^4}\sin^2 i - \frac{n_1^2}{n_2^2}} \quad (1)$$

whereas, for the same incident conditions, the model based on the energy flux conservation argument [8, 17] provides:

$$\Delta L^2_{\mathrm{IF}}(\sigma^+/\sigma^-) = 2 \cdot \frac{\delta}{2} \cdot \tan i \cdot \sqrt{\frac{n_1^2}{n_2^2}\sin^2 i - 1} \cdot \mathrm{Re}(t_{/\!/} t_\perp^*) \quad (2)$$

- δ is the penetration depth of the evanescent wave and can be expressed as follow:
$$\delta = \frac{\lambda}{2\pi \cdot \sqrt{n_1^2 \sin^2 i - n_2^2}};$$
- $t_{/\!/}$ and $t_\perp$ are the transmission coefficients in amplitude associated (respectively) with the TE (Transverse Electric) and TM (Transverse Magnetic) polarization states [18];
- n_1 is the refractive index of the incident medium and n_2 is the refractive index of the low index medium after the interface.

Evolutions of $\Delta L^1_{\mathrm{IF}}(\sigma^+/\sigma^-)$ and $\Delta L^2_{\mathrm{IF}}(\sigma^+/\sigma^-)$ are represented in Fig. 3 with $n_1 = 1.506$ (refractive index of a BK7 prism at $\lambda = 1.083$ µm) and $n_2 = 1$ (refractive index of air) which corresponds to the experimental conditions in our set-up.

The two expressions provide lateral shifts of same order of magnitude near the critical angle. However, the first one [16] predicts that the transverse displacement tends toward infinity when the incident angle i approaches the grazing angles whereas the energy conservation model [8, 17] predicts that the lateral shift vanishes when i is close to 90°. Compared to the experiments, it clearly appears that the model developed by Renard in Ref. [17] seems to be in a better agreement than the models based on Hugonin's formula, which completely failed to predict the transverse shift near the grazing angle. A comparison between the Renard's theory and the experimental results is also presented in Fig. 2 and again shows a good overlap between our measurements and the theoretical curve. It shows that our experimental technique is sufficiently sensitive to measure precisely the transverse displacement near the grazing angle and allows discriminating at least between the most opposite models.

4 Conclusion

In conclusion, we have extended our measurement of the small transverse shift observed after a single total internal reflection to the case of incidence angles scanned from critical angle up to grazing angle (angle called i in Fig. 1). It confirms that the transverse shift still appears for angles far away from the critical angle and vanishes only at 90°. Moreover, the results become useful as they allow discriminating between some theories. The experimental measurements well overlap with those calculated using the energy flux method developed initially by Renard and, at least, are sufficient to invalidate expression deduced from [16].

However it would be interesting to understand why models based on stationary phase method or deformation beam disagree with the experimental results and which hypothesis are invalid in these models. Among the vast bibliography about theoretical description of transverse displacements, some discussions were centred on the role of the intensity distribution in the observed shift. In the present experiment, the optical beam was simply collimated. Some experiments with our experimental set-up could be done with special shapes of the incident beam on the interface in order to show the importance of this parameter on the longitudinal and lateral shifts. These complementary experiments could then be used to really understand the existence of the transverse displacement and the most sensitive parameters that could influence the amplitude of the spatial displacement at total internal reflection.

REFERENCES

1 H.K. Lotsch, JOSA **58**, 551 (1968)
2 C. Imbert, Nouv. Rev. Opt. Appl. **3**, 199 (1972)
3 F. Goos, H. Hänchen, Ann. Phys. (Leipzig) **1**, 333 (1947)
4 K. Artmann, Ann. Phys. (Leipzig) **2**, 87 (1948)
5 H.K.V. Lotsch, Optik **32**, 116 (1970)
6 F.I. Fedorov, Dokl. Akad. Nauk SSR **105**, 465 (1955)
7 H. Schilling, Ann. Phys. **16**, 122 (1965)
8 C. Imbert, Phys. Rev. D **5**, 787 (1972)
9 J.J. Cowan, B. Anicin, J. Opt. Soc. Am. **67**, 1307 (1977)
10 F. Bretenaker, A. Le Floch, L. Dutriaux, Phys. Rev. Lett. **68**, 931 (1992)
11 Y. Levy, C. Imbert, Opt. Commun. **13**, 43 (1975)
12 B.R. Horowitz, T. Tamir, JOSA **61**, 586 (1971)
13 L. Dutriaux, A. Le Floch, F. Bretenaker, Europhys. Lett. **24**, 345 (1993)
14 H. Gilles, S. Girard, J. Hamel, Opt. Lett. **27**, 1421 (2002)
15 F. Pillon, H. Gilles, S. Girard, Appl. Opt. **43**, 1863 (2004)
16 J.P. Hugonin, R. Petit, J. Opt. **8**, 73 (1977)
17 R.H. Renard, JOSA **54**, 1190 (1964)
18 M. Born, E. Wolf, *Principles of Optics*, 7th edn. (Cambridge University Press, Cambridge, 1999)