Frustrated total internal reflection: the Newton experiment revisited

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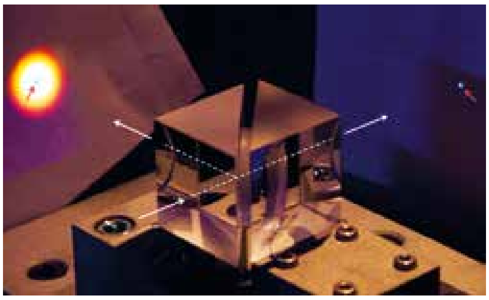

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Three centuries ago, Isaac Newton reported the experimental observation of the tunnelling of a light ray between two prisms separated by a small gap once one of them was shinned in total internal reflection. This article describes a modern revisit of this seminal Newton's experiment, generally known as the Frustrated Total Internal Reflection. This experiment was created in the framework of a series of lectures about near-field optics and nanophotonics for Master students. During a 4h lab work session, the students are running the experiment to evidence and quantify the evanescent wave on top of a glass prism once illuminated above the critical angle.

Any bachelor student who studies optics and electromagnetism at University knows that illuminating a prism under total internal reflection results in the generation of an evanescent wave on top of it. Near field optics, which refers to the research field on evanescent waves and their related applications, has grown amazingly since 30 years thanks to the rapid progress of nanotechnologies. Primarily restricted to the applications in subwavelength imaging by scanning probe microscopy in the late 90s and earlier in evanescent couplers for waveguide optics, evanescent waves have widely spread to the field of nanophotonics and plasmonics where they contribute to create the original properties of artificial optical materials such as metamaterials, metasurfaces or photonic crystals. Nowadays, numbers of active and passive optical systems are taking benefits of these evanescent waves such as for fingerprint recognition, tactile screens and promising cutting edge new technologies for AR/VR vision which will reach the market in a near future.

The first direct description of an optical experiment involving an evanescent wave is attributed to Isaac Newton in his seminal book *"Opticks: or, a treatise of the reflections, refractions, inflections and colours of light"* [1]. In this so-called "Frustrated" [2] Total Internal Reflection (FTIR) experiment, Newton considered two glass prisms brought together so that they do not fully touch, one of them being illuminated under total internal reflection and he wrote in Book 3: *"For the Light which falls upon the farther surface of the first Glass where the Interval between the Glasses is not above the ten hundred thousandth Part of an Inch (2.54µm), will go through that Surface, and through the Air or Vacuum between the Glasses, and enter into the second Glass"*. The theoretical background to explain this phenomenon was missing when Newton did these observations and it has been explored later on both experimentally and theoretically by Fresnel and many others. More details on attempts and advances on this subject throughout history are available in an article written by E. Hall [2] in 1902 which provides references to related works in the XVIIIth and XIXth centuries, and also in a review paper by Zhu and coworkers [3] in 1986 which makes the link to the XXth century. Because FTIR appears for very small distances • • •

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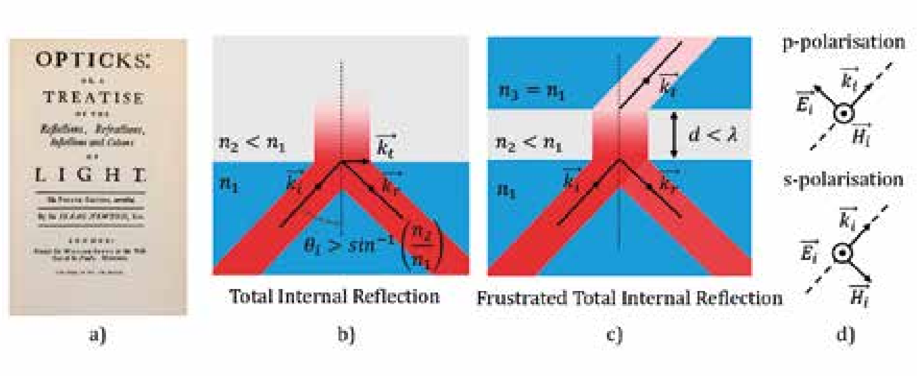


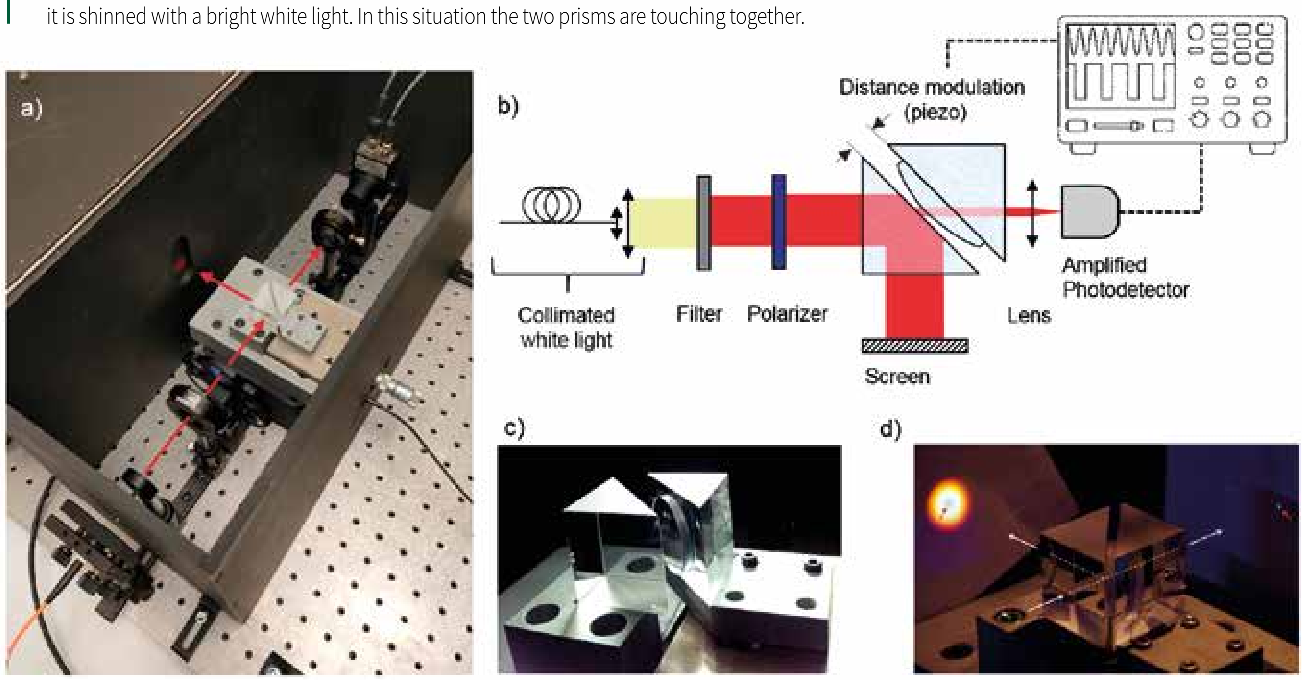
Figure 1. a) Cover of Isaac Newton's book. 4th edition 1730. b) Illustration of the total internal reflection between a prism and air for an incident angle larger than the critical angle. c) Illustration of the frustrated total internal reflection by bringing a second prism in the near-field of the first one. d) s- and p- polarizations of the incident field.

between the prisms, addressing it experimentally and achieving a quantitative relationship between the prisms distance and the overall transmitted light has been a longstanding challenge. The experiment described hereafter provides such a relationship under various illumination conditions (polarization, wavelength) in a friendly-user setup that has been used by more than two hundred students over the past 10 years.

The Newton experiment as a labwork for Master students

In the framework of our lectures to the Master students at Université Bourgogne Franche-Comté (International Master on Physics, Photonics and Nanotechnologies), we created 10 years ago a set of turn-key experiments illustrating some important effects arising in Near-field Optics and Nanophotonics and the revisited Newton experiment described in this article is one of them. All the elements of this experimental setup are available commercially and we have intentionally limited the cost of each of them to achieve a setup with a reasonable price of less than 5,000€. As shown in Figure 2, it consists of an optical bench mounted on a damped breadboard and including a set of two prisms mimicking the Newton experiment. The optical source for illumination consists of a blackbody lamp coupled to a multimode fiber which is free-space collimated into a large beam to create a pseudo plane wave around the optical axis. The source is filtered spectrally with a band-pass colored filter around 633nm and is linearly polarized to set the illumination to s- or p-polarization (see Figure 1 d). The first prism is a right-angle prism to achieve a total internal reflection at θ_i=45° on its outer face. The second prism is also a right-angle prism. It is mounted in front of the first one and its accurate positioning is controlled by a piezoelectric stage. To bypass the tricky task to align the

Figure 2. a) Picture of the turn-key setup for evidencing the frustrated total internal reflection. b) Schematic drawing of the experiment. c) Picture of the two prisms with the high radius of curvature lens glued on top of. d) Smartphone picture of the operating experiment once it is shinned with a bright white light. In this situation the two prisms are touching together.



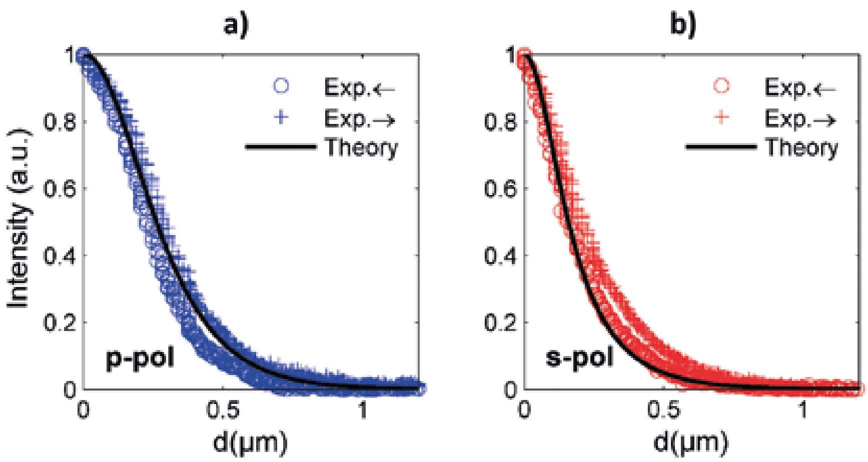


Figure 3 . Experimental measurements and theoretical predictions of the Frustrated Total Internal Reflection for a) a p-polarized and b) a s-polarized illumination at λ=633nm.
The transmitted intensity is plotted versus the distance between the two prisms. The approach (circles) and the retraction (crosses) of the second prism are separated in the experimental graphs to highlight the hysteresis of the piezoelectric effect used for positioning the second prism.

parallelism between the faces of the two prims facing each other, we used a plano-convex lens glued (with an optical UV glue!) on the inner face of the second prism (Figure 2c). In this configuration, the top of the convex face defines the contact point between the two prisms. As the radius of curvature of the lens is very large (400mm) compared to the characteristic distance between prisms at which FTIR occurs (<1μm), we consider in this experiment that the apex of the lens in the near field of the first prism acts as a flat glass surface placed at a given distance from it. As it will be seen below, the relatively good quantitative agreement between experiment and theory confirms that this is a reasonable assumption.
The contact between the prisms is identified manually and visually by the experimentalist under white light illumination. It appears as a dark spot in the middle of the totally internal reflected beam and as a small bright beam transmitted through the two prisms which is clearly visible to the naked eye (Figure 1d). This latter transmitted beam is collected by a lens and focused onto an amplified silicon photodetector. Finally the distance is modulated over few microns by the piezoelectric stage hosting the second prism and the transmitted light intensity is recorded synchronously, mimicking the approach-retraction measurements which are commonly performed in scanning probe microscopy. The experiment is placed on a conventional table and it is remarkably stable provided there is no external mechanical perturbation while it is running, for example a student touching the table.

Results

The typical measurements obtained by this setup are shown in Figure 3 for both s- and p-polarizations. As expected, the transmitted intensity increases exponentially once the distance between the prisms is decreased down to 500nm and then reaches a plateau as they touch together. A single measurement also provides the outgoing light intensity both for the approach and the retraction of the outer prism. As visible on the Figure, these two measurements are not perfectly overlapping which results in a slight hysteresis cycle. This is a common feature of cheap piezoelectric stages whose absolute positioning is not corrected by a position sensor and a closed-loop. As this issue does not interfere with the FTIR observation, we have intentionally kept this piezoelectric stage and this observation is used as a pretext to discuss the piezoelectric effect and related applications and issues in scanning probe microscopy techniques.

These FTIR experiments can be described analytically from Fresnel relations which connect the incident, reflected and transmitted amplitudes of the different fields at both sides of the interfaces between the two prisms and the gap medium (air). The complete algebraic manipulations giving the analytical relations for FTIR are described for a general case in [4], and, in our situation depicted in Figure 1c) where the two prisms have the same refractive index n_1 and are separated by air ($n_2 = 1$), the transmission of a monochromatic planewave is reduced to :

$T = 1/(a sinh^2 \rho + 1)$
with $\rho = (2\pi d/\lambda)\sqrt{n_1^2 sin^2\theta_i - 1}$
and
$a = a_s = \left[(n_1^2 - 1)/2n_1\right]^2\left\{1/\left[\cos^2\theta_i(n_1^2 sin^2\theta_i - 1)\right]\right\}$ for s- polarization,
$a = a_p = a_s\left[(n_1^2 + 1)sin^2\theta_i - 1\right]^2$
for p-polarization,

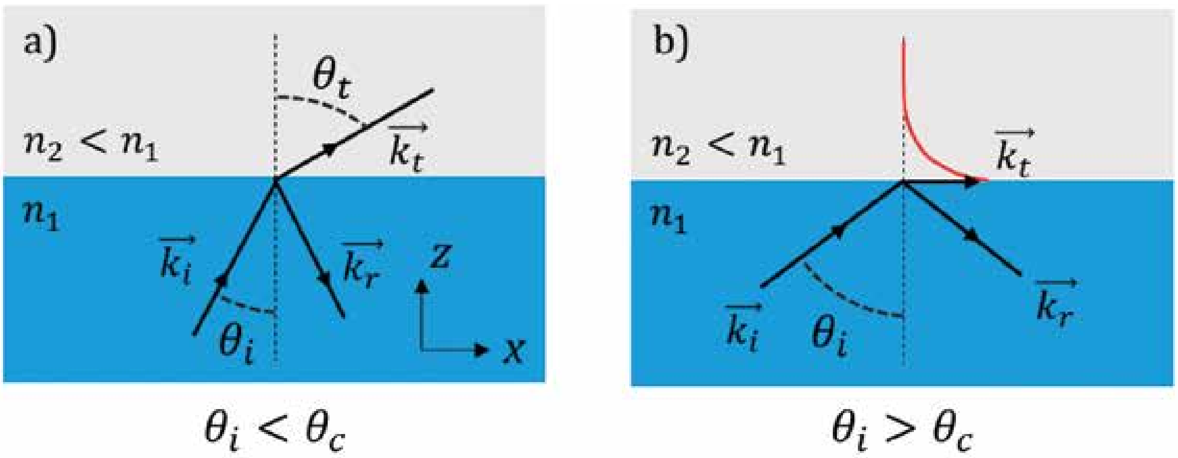
This theoretical transmission under FTIR conditions for both polarizations is shown together with the experimental results in Figure 3. A relatively good quantitative agreement is achieved despite the uncertainties related to the piezoelectric stage motion. In this version of the setup, it is worthnoting that such an agreement is only achieved for a narrow colored filter with a central wavelength matching the factory

EVANESCENT WAVE GENERATION UNDER TOTAL INTERNAL REFLECTION ILLUMINATION

Once the illumination of an interface between two dielectric media is carried out by a monochromatic plane wave with a wavelength λ, the relationship between the angle of incidence θ_i, and the angle of refraction, θ_t, is given by the momentum conservation of the wavevectors component parallel to the interface. Hence, using the expression $k_{t,x}^2 + k_{t,y}^2 + k_{t,z}^2 = k_t^2 = \left(\frac{2\pi}{\lambda}n_2\right)^2$, the transmitted wavevector is:

$$\vec{k}_t = \begin{cases} k_{t,x} = \frac{2\pi}{\lambda} n_2 sin\theta_t = \frac{2\pi}{\lambda} n_1 sin\theta_i = k_{i,x} \\ k_{t,y} = 0 \\ k_{t,z} = \frac{2\pi}{\lambda}\sqrt{n_2^2 - n_1^2 sin^2\theta_i} \end{cases}$$

Figure a) Reflection and transmission at an optical interface for an oblique incidence below the critical angle.
Figure b) Surface wave generation for an oblique incidence above the critical angle.



For any incident wave with θ smaller than the critical angle $\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$, this provides the well-known Snell Descartes law $n_1 sin\theta_i = n_2 sin\theta_t$ between the incident and the transmitted waves. For higher angles of incidence, $k_{t,z}$ becomes imaginary since the argument of the square root is negative, and is written as $k_{t,z} = j\tilde{K}$ with $\tilde{K} = \frac{2\pi}{\lambda}\sqrt{n_1^2 sin^2\theta_i - n_2^2}$. For an incident plane wave $\vec{E}_{i,s}$ (for s-polarized light here), the electric field in the second medium is $E_{t,s}(\vec{x}, z, t) = t.E_{i,s}\exp[j(\omega t - k_{t,x})].exp(-\tilde{K}z)\vec{e}_y$ with t the Fresnel complex transmittance. Hence, in the second medium, the transmitted wave is a surface wave which decays exponentially along z with a penetration depth $d_p = 1/\tilde{K}$ while it propagates along x.

alignment wavelength of the fiber collimator (633 nm here). Indeed, changing the filter wavelength without changing the collimator accordingly results in a slight divergence of the incident beam. Thus, it introduces an additional uncertainty on the angle of incidence which rapidly moves the experimental measurement away from the theoretical calculations. In other versions of the setup, for instance using lasers with different wavelengths, this artefact vanishes but we decided to keep it as it is for pedagogic reasons and to motivate discussions with the Master students at the end of the labwork.

Conclusion

We have presented in this paper a modern revisit to Newton's frustrated total internal reflection experiment. The setup described here is a turnkey automated experiment that provides a quantitative measurement of the evanescent wave excited at the top of a glass prism during total internal reflection illumination. As part of the courses on Near-field optics and Nanophotonics, more than 200 Master students from the EIPHI Graduate School in Bourgogne Franche-Comté have been carrying out this experiment in a 4-hours labwork for the past 10 years. They perform the experiment themselves, compare their results with the theory in a report in which they also provide their own observations and comments. This experiment is the first of a series of four other home-made labworks developed to illustrate some key features in nanophotonics, including surface plasmon resonance, microfibre pulling and evanescent coupling to whispering gallery mode resonators, optical trapping of nanoparticles and absorption molecular spectroscopy. All these experiments are available as pedagogical resources on the SMARTLIGHT platform at the Laboratoire Interdisciplinaire Carnot de Bourgogne (France). ●

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