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# What Everyone Needs to Know About Evanescent Fields

Almost four hundred years ago, Newton used a prism to bend light by total internal reflection. During one experiment, he brought a convex lens into contact with the reflecting face of the prism. To his surprise, light came through the back of the prism across an area larger than the contact area between the two pieces of glass. Somehow, light was propagating a short distance beyond the plane of total internal reflection. Newton had discovered evanescent electromagnetic fields, fields that fade out exponentially within a few wavelengths.

As the study of electricity and magnetism developed in the 19th century, theoretical tools explained the existence of exponentially decaying electromagnetic fields. At this time, optical experiments on evanescent fields were impractical. The fields die out within a few wavelengths, and precision on that length scale was inaccessible by the technology of the day. When centimeter-wave sources were developed in the 1890s, scientists could probe evanescent fields with subwavelength precision [Fornel, 2000]. With the newly available centimeter scale electromagnetic waves, Bose rigorously studied the same sort of frustrated internal reflection that Newton had observed centuries earlier.

Today, with increasing ability and desire to probe with nanometer resolution, optical evanescent fields are becoming ever more relevant in research. We will explore the basic theory behind the evanescent fields created by total internal reflection. Then we will describe some of the current applications of evanescent fields in areas ranging from atomic optics to microscopy to biosensors.

**Total internal reflection theory**

From Maxwell's equations, we know that the component of the electric field tangent to the interface of two dielectrics must be continuous across that interface. For a plane wave moving from one dielectric to another,

$$k_i \, \mathrm{Sin}[\theta_i] = k_t \, \mathrm{Sin}[\theta_t]$$

where k is the wave vector, theta is the angle between the wave propagation and the interface normal, and subscripts i and t stand for incident and transmitted wave fronts, respectively.

The frequency of the wave is identical on either side of the interface, so we have Snell's law:

$$n_i \, \mathrm{Sin}[\theta_i] = n_t \, \mathrm{Sin}[\theta_t]$$

with n the index of refraction of each of the media.

At incoming angles equal to and above the critical angle

$$\theta_c = \text{ArcSin}\left[\frac{n_t}{n_i}\right]$$

The reflectance is 1, the transmittance is 0, and all energy is reflected back to the incoming side of the interface. However, as electric fields impinge on our uncharged dielectric interface, the boundary conditions due to Maxwell's equations and the conservation of momentum demand that there be a matching field on the far side. The component of $k_t$ parallel to the interface is still equal to the component of $k_i$ to obey the boundary conditions.

We have an incoming plane wave

$$E_i[r, t] = \mathcal{E}_i \, e^{(i\,(k_{ix}\,\hat{x} + k_{iz}\,\hat{z} - \omega\, t))}$$

With amplitude *E*i, wave vector k and frequency w. The z direction is normal to the plane of interface of two dielectrics, and the x direction is chosen so that the wave vector lies entirely in the xz plane.

Likewise, the transmitted wave is

$$E_t[r, t] = \frac{1}{2} E_{0\,t} \, e^{(i\,(k_t \cdot r - \omega\, t))}$$

where

$$k_{tz} = k_t \,\text{Cos}[\theta_t] = \pm k_t \sqrt{1 - \text{Sin}^2[\theta_t]}$$

$$= \pm k_t \sqrt{1 - \frac{\text{Sin}^2[\theta_i]}{(n_t / n_i)^2}}$$

The second line is thanks to Snell's law, and is an imaginary quantity for $\theta_i > \theta_c$.

Thus, the transmitted wave can be rewritten:

$$E_t[r, t] = \frac{1}{2} E_{0\,t} \, e^{(i\,(k_t \cdot r - \omega\, t))}$$

d is the positive, real, evanescent penetration depth.

$$d = \frac{\lambda}{2\pi \sqrt{n_i^2 \,\text{Sin}^2[\theta_i] - n_t^2}}$$

The positive exponential d z is unphysical if the second medium is semi-infinite.

We have demonstrated the existence of an exponentially decaying evanescent field on the far side of a totally internally reflecting interface. For a theoretical treatment of the polarization of the incoming and transmitted fields, see [Voigt, 2000] or [Fornel, 2000].

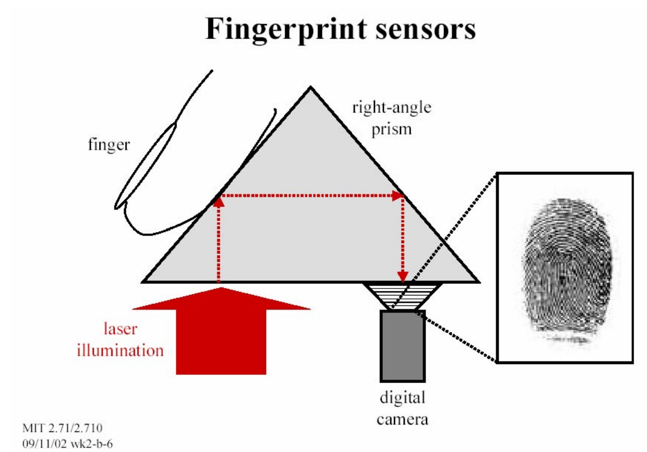
Frustrated total internal reflection (FTIR) occurs when we a third medium of high refractive index bring into the evanescent field. To produce FTIR, the third medium must have an index of refraction such that the wave vector $k_i$ would not undergo total internal reflection if media one and three were in direct contact. The evanescent field in the second medium is then able to excite propagating fields in the third medium, and perturb the total internal reflection of the first medium.

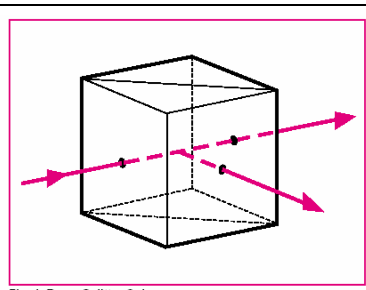
The mathematics of an exact description of FTIR are beyond the scope of this paper, although they are not hard to describe qualitatively. Simply place another slice of dielectric in the positive z region where the evanescent field lies, and solve the wave equations in all three media with appropriate boundary conditions.

**Applications of evanescent fields generated by total internal reflection**

The property of total internal reflection that allows a small evanescent field to leak through the back side of the reflecting medium and the resulting phenomenon of FTIR has a wide range of applications.

One device that uses FTIR in a very simple way is the fingerprint scanner. [Barbastathis, 2002] Fingertip ridges that touch the surface of a prism frustrate the total internal reflection of incident light on the prism surface, sending a negative image of the contact region to a detector.



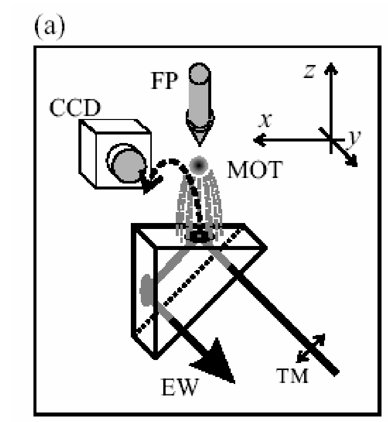

beam splitter cube, Oriel instruments
http://www.oriel.com/down/pdf/13013.pdf

By far the most important and most common use of FTIR is in beamsplitters and fiber optic couplers. Each long distance phone call that is placed, and much of the data sent across the internet makes its way through a series of optical fibers. These fibers are coupled to each other, to repeaters, and to opto-electronics. Many of these optical components make use of evanescent fields to split or combine beams. It is possible to split optical signals into arbitrary proportions by controlling the thickness of a low index coating, and thus the evanescent field coupling, between two prisms.

Elements for atomic optics under development also use evanescent fields [Fornel, 2000]. An atom with an electronic transition frequency $w_{at}$ in an electric field is subject to a radiation pressure of potential U:

$$U = \hbar \frac{\omega_1 - \omega_{at}}{2} \mathrm{Log}\left[1 + \frac{I / I_{sat}}{1 + 4\,(\omega_1 - \omega_{at})^2 / \Gamma^2}\right]$$

where I is the electric field intensity, Isat is the saturation intensity, $w_1$ is the laser frequency, and $G$ is the transition line width. An evanescent field can provide a repulsive potential to the atom, allowing the fabrication of atom mirrors, beam splitters, etc. from optical prisms.



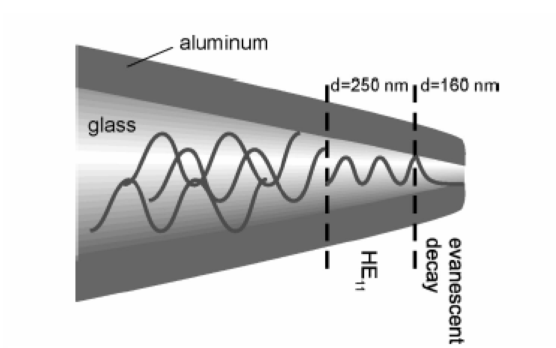

Evanescent wave atomic mirror, [Voigt, 2000]

Integrated optical structures offer the intriguing potential of compact, reproducible waveguide arrays, rings, Y junctions, etc., that could be used to design evanescent field traps to transport, store, and interact atoms in networks as complicated as any integrated optical waveguide circuit. [Burke et Al, 2002]

New chemical and biological sensors are beginning to use evanescent fields to detect low concentrations of reagent. [Maseeh, 2002]. The evanescent field that occurs outside of a totally internally reflecting prism is sensitive to refractive index changes on the surface of the prism. When an analyte adsorbs to the chemically or biologically active layer on the surface of the prism, it changes the index of refraction of the surface layer, frustrating the total internal reflection to a certain degree, changing the amplitude of the reflected light. [Fornel, 2000] These sensors offer high sensitivity, low cost, possible large scale integration, and are beginning to appear on the commercial market . [Maseeh, 2002].

Certain dark field microscopes employ evanescent fields. Instead of directly illuminating a sample a conventional bright field optical microscope condenser does, a dark field microscope uses a condenser that illuminates the sample at high incidence angle or totally internally reflects light just below the sample. [Fornel, 2000] In the case of a totally internally reflecting condenser, the sample perturbs the evanescent field, sending propagating fields out to the microscope objective. Dark field microscopy features improved contrast over bright field microscopy. Sub-wavelength objects are easily visible as they scatter incident radiation.

A whole slew of scanning near field optical microscopes (SNOMs) have been developed by researchers over the past 15 years. These microscopes smash the diffraction limit of far field microscopes, potentially achieving resolution an order of magnitude better than a standard confocal microscope [Hect 2000]. One such SNOM is the scanning tunneling optical microscope. This microscope uses a sharp glass tip to locally frustrate total internal reflection below a surface, indirectly imaging features on that surface at high spatial resolution. Aperture based SNOMs are more common and more practical. [Hect 2000] They produce an evanescent field by forcing light through a small aperture (see figure). The evanescent field locally illuminates the sample. Once free of the aperture, the field is no longer evanescent, and it expands in the far field to be picked up by a detector. To achieve high resolution, the aperture must be small, and close to the sample surface so the field is tightly confined when it interacts with the sample. Full analysis of the field-sample interaction of a SNOM is a difficult or impossible undertaking, but the data produced can yield important and detailed information about a sample surface.



Evanescent fields produced by the tapered tip of a SNOM. [Hect, 2000]

We have described the theory behind evanescence as well as a wide range of devices that use evanescent fields. Many of these devices are just beginning to move out of the laboratory and into the commercial sector. Evanescent fields are a powerful tool for probing the nanoscale world. As demand grows for sensitive optical, chemical, and biological information at very high resolution, the applications of evanescent fields will certainly become more visible.

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