Photon Scanning Tunneling Microscope: Detection of Evanescent Waves

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Abstract:
We report the formation of a standing evanescent wave formed by total internal reflection (TIR) of two counter propagating plane waves using a 532nm laser beam at a glass-air interface. Using a fiber probe as a collection device for our photon scanning tunneling microscope (PSTM) we measure the decay length of the evanescent field and the standing wave pattern present on the surface of a glass prism.

Keywords: evanescent wave, total internal reflection (TIR), photon scanning tunneling microscope (PSTM)

Introduction:
Photon scanning tunneling microscopy was initially conceived some 75 years ago by E. H. Synge, [1] and was experimental demonstrated nearly 50 years later in the microwave regime [2] and as recently as 1991 in the optical regime [3].

Ref [4] serves as the basis for the work contained in this report, where the reader will find a more detailed account of the experimental arrangement. Appendix A details the mathematical foundations of the work contained herein. Our experimental configuration replicates that used by Meixner et al [4]. Theoretical calculations and our experimental conclusions are compared with [4] and explanations for any differences given in terms experimental parameters and detection probe geometry.

Principles:
Fig. 1. shows the experimental configuration of our PSTM system. The standing evanescent wave is produced by two counter propagating waves both of which are formed by TIR at the glass-air boundary of a 90° glass (BK7) prism. We use a 532nm line from a diode laser polarized in the plane of incidence.

The first evanescent wave is formed by the field transmitted through the transparent face of the prism, whereas the second evanescent field is formed, again at the glass-air interface, having been reflected from the metal coated prism face, (see Figure 1).

Figure 1 - Schematic diagram of the experimental set up

Drawing not to scale
By raster scanning a dielectric probe (produced via a chemical etching technique [5] and held by means of a controlled feedback mechanism [6]) over the surface of the prism we are able to effectively couple the decaying evanescent field and produce a propagating mode in the fiber, which we detect with a photon multiplier tube (PMT) detector, positioned at the output end of the fiber probe.

This coupling of evanescent field to fiber can be explained in two ways. A quantum mechanical explanation involves excitation of the atoms in the fiber probe by the evanescent field. The atoms in the fiber probe re-emit this radiation, either into the fiber forming the propagating mode, or out of the fiber as a reflected wave. A more classical explanation involves conservation of momentum. Since there is a traveling wave with momentum along the surface of the prism, this wave is scattered by the probe. Part of this wave is reflected and part of this wave, to balance momentum, is transmitted down the length of the fiber.

Theory:

Equation 1 (see Appendix A) describes the electric field strength of an unperturbed evanescent field at a distance z from a glass-air interface [4]. The first interesting parameter is the decay constant d, which characterizes the 1/e decay length of the electric field from the glass-air interface. Upon substitution of the known physical values we calculate the intensity decay length to be \( d/2 = 120 \text{nm} \).

The second interesting parameter related to this study is the period of the standing-evanescent wave, (see Equation 2, Appendix A). Calculations show that for the given experimental set up the period of the evanescent wave is \( \Lambda(\theta=45^\circ) = 248 \text{nm} \).

Results:

The standing wave pattern recorded is shown in Figure 2. The 4x4μm scan area was obtained by raster scanning a fiber probe (tip diameter = \( \Phi = 150 \text{nm} \)) over the prism surface at a constant tip-surface distance as described earlier. We observed bright and dark bands representing the intensity maxima and minima respectively of the standing wave pattern at the air-glass interface. Our data show 10 \( \frac{1}{4} \) maxima and minima. This corresponds to \( \Lambda = 390 \text{ nm} \), roughly 1.5 larger than the theoretically predicted value. We rule out that this difference is due to angle error because theoretically we calculated \( \Lambda(\theta=41.3^\circ) = 266 \text{nm} \) and \( \Lambda(\theta=50^\circ) = 229 \text{nm} \).

Figure 2 - Experimental standing wave pattern

We also noticed variation in contrast between the maxima and minima. One possible explanation is the width of the fiber probe. The fiber probe used had a tip diameter of 150nm, which is approximately 1.5 times smaller than the standing wave period. Using a probe with a diameter less than 100nm it should be possible to obtain a clearer distinction between the intensity maxima and minima. Two other prominent features are the diagonal nature of the contour lines and a series of low contrast horizontal dark and bright bands superimposed on the standing wave. This is probably due to drift in the fiber probe, variation in the incident angle \( \theta \), misalignment of the prism, variation in the prism flatness, and poor impedance matching in the electronics.

The decaying evanescent field shown in Figure 3 was obtained using a digital oscilloscope with the Y input recording photon counts (as a voltage) and the X input (also as a voltage) monitoring the distance of the probe from the prism surface. Our experimental results reveal a measured intensity decay length (1/e value) of approximately 45-50nm, a factor of roughly 2.5 times smaller than the theoretical value. We speculate that the discrepancy may be explained in part by the calibration of the z-piezo, i.e. \( nm/volt \), variations in the impedance matching of the
electronics, saturation of the photomultiplier tube with photon count, and the effect of the probe on the evanescent wave trapped in the near field.

Photon counts from our PMT varied from $10^5$ to $10^6$, depending on the proximity of the tip at the prism surface. A theoretical calculation (see Appendix B) gives a photon counts on the order of $10^7$. The discrepancy here is most likely due to the uncertainty in the tip diameter and the effective area of the tip.

Figure 3 - Experimental decaying field

Conclusions:

The results contained herein demonstrate the feasibility and ease by which one can extract and probe information, namely the evanescent field produced by TIR at a glass-air interface, exclusively contained in the near-field. Differences in the theoretical predictions and experimental results can be explained by considering the physical parameters of the experiment, such as probe geometry and size, z-piezo calibration and also by the perturbation of the evanescent field by our fiber probe.

References:

Appendix A: Mathematical formulas and experimental parameters

Mathematical description of an unperturbed electric field of an evanescent wave at position \((x, z)\) at a glass-air interface is given by [4], [9]:

\[
E(x, z) = E_0 e^{-\frac{z}{d}} e^{-ikx},
\]

(1)

where:

\[
|E_0|^2 = \frac{4(n_1/n_2)^2}{1 + (n_1/n_2)^4 \gamma^2} |E_i|^2
\]

\[
\gamma = \frac{\sqrt{n_1^2 \sin^2 \theta - n_2^2}}{n_1 \cos \theta}
\]

\[
\lambda = \frac{\lambda_0}{n_1 \sin \theta}
\]

\[
d = \frac{\lambda_0 / n_2}{2\pi \sqrt{(n_1/n_2)^2 - 1}}
\]

\[
\Lambda = \frac{\lambda_0}{(2n_1 \sin \theta)}
\]

(2)

\(E_0\), \(\lambda_0\), and \(\theta\) represent the amplitude of the incident field, the vacuum wavelength and the angle of incidence. \(n_1\) and \(n_2\) are the refractive indicies of the prism and of air respectively. The period of the standing evanescent wave is given by equation 2 below.

For the experimental arrangement (see Figure 1) the following values were assigned: \(\lambda_0 = 532\,\text{nm}\), \(\theta = 45^\circ \pm 3^\circ\), \(n_1 = 1.515\), \(n_2 = 1.000\) and \(r^2 = 0.9\).
Appendix B: Coupling efficiency (Mean power collected by fiber probe)

The transmission function for the fiber tip of diameter \( \Phi \) is given by [4], [7], [8], [9],

\[
T(z) = \frac{1 - (1 - \frac{2}{\alpha_\parallel})}{\cosh(\frac{2z}{d}) - (1 - \frac{2}{\alpha_\parallel})}
\]

\( \alpha_\parallel = \alpha_\perp \left\{ \left[ \left( \frac{n_1}{n_2} \right)^2 + 1 \right] \sin^2 \theta - 1 \right\}^2 \)

\[
\alpha_\perp = \frac{\left( \frac{n_1}{n_2} \right)^2 - 1}{4\left( \frac{n_1}{n_2} \right)^2 \cos^2 \theta \left[ \left( \frac{n_1}{n_2} \right)^2 \sin^2 \theta - 1 \right]}
\]

The mean power collected by the tip perpendicular to its effective aperture area \( \sigma \) is then,

\[
P(z) = I_\| \cos \theta (1 + r^2) \sigma T(z)
\]

For the experimental arrangement the following values were assigned: \( I_\| = 2 \text{mW/m}^2 \), \( \Phi \) (measured with an SEM) = 150nm, \( \sigma = 235.6 \text{nm}^2 \), \( \theta = 45^\circ \), and \( r^2 = 0.9 \). A theoretical graph of photon counts versus \( z \) (at \( \lambda = 532 \text{nm} \)) is shown below.