Index of Refraction Sensors: Virtually Unlimited Sensing Power at Critical Angle

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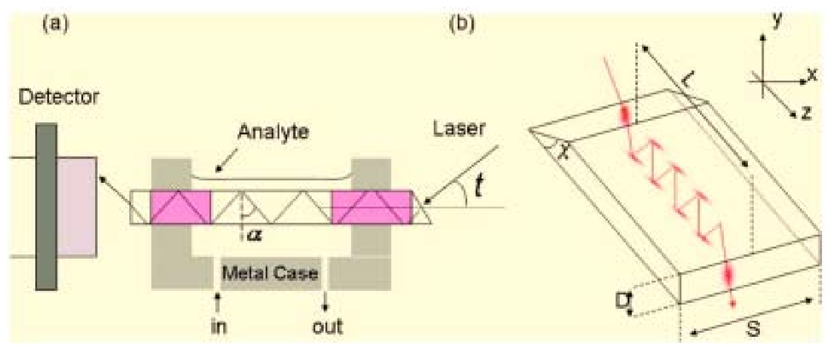
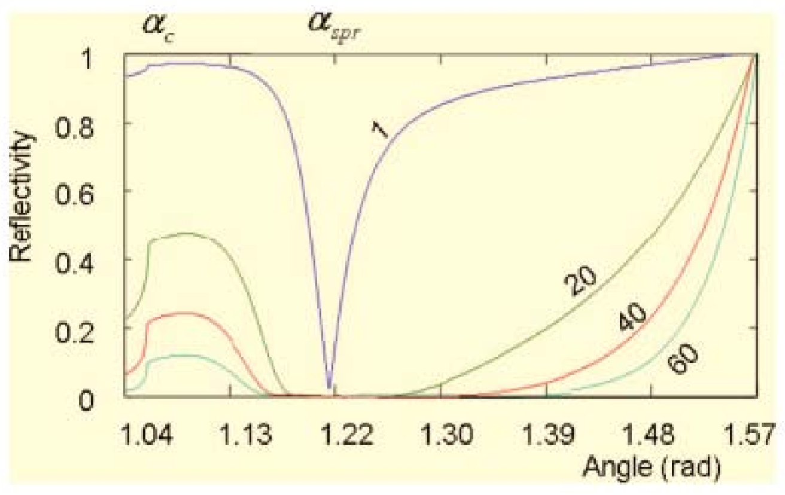
We demonstrate analytically that discontinuity at critical angle can be used to reach extremely high sensitivities against any optical properties that modify this angular value. To test in practice the approach we fabricated cheap and basic sensors by which we could demonstrate extremely high index of refraction discrimination ability in the range of one part over a million.

To test in practice this theoretical insight, we compared the refraction index sensitivity to the one of a conventional SPR (surface Plasmon sensor). Also we constructed a similar apparatus to detect in a very simple and low-cost manner nanometer scale mechanical vibrations. Also in this case we obtained very high sensitivity, tiny vibrations of 2.4nm were resolved, this correspond to an angular shift of about 50 ∗ 10−6 deg, as far as we know the best angular sensitivity recorded so far. The critical angle detection method discussed in this poster is applicable generally to any optical system and may pave the way for next generation optical sensing devices.

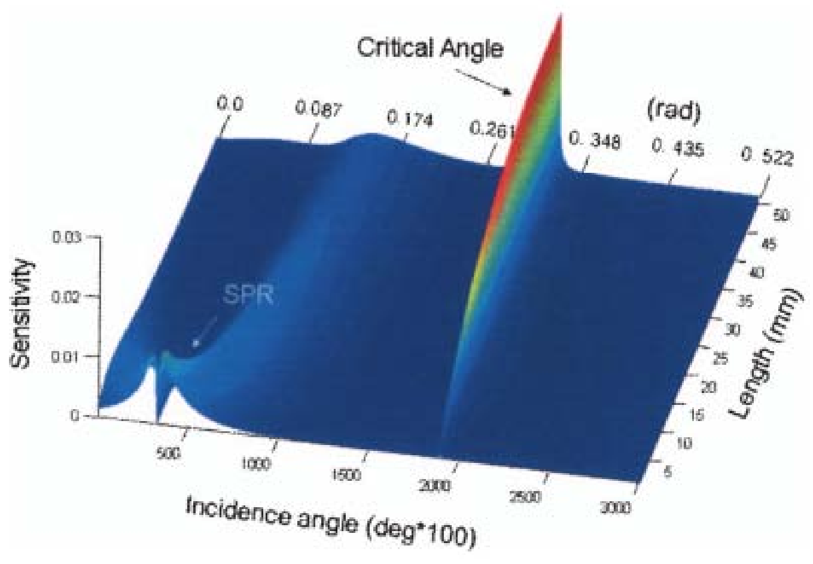




$$r_{ms} = (k_{mz}\epsilon_s - k_{sz}\epsilon_m)/(k_{mz}\epsilon_s + k_{sz}\epsilon_m)$$

$$r_{pm} = (k_{pz}\epsilon_m - k_{mz}\epsilon_p)/(k_{pz}\epsilon_m + k_{mz}\epsilon_p)$$

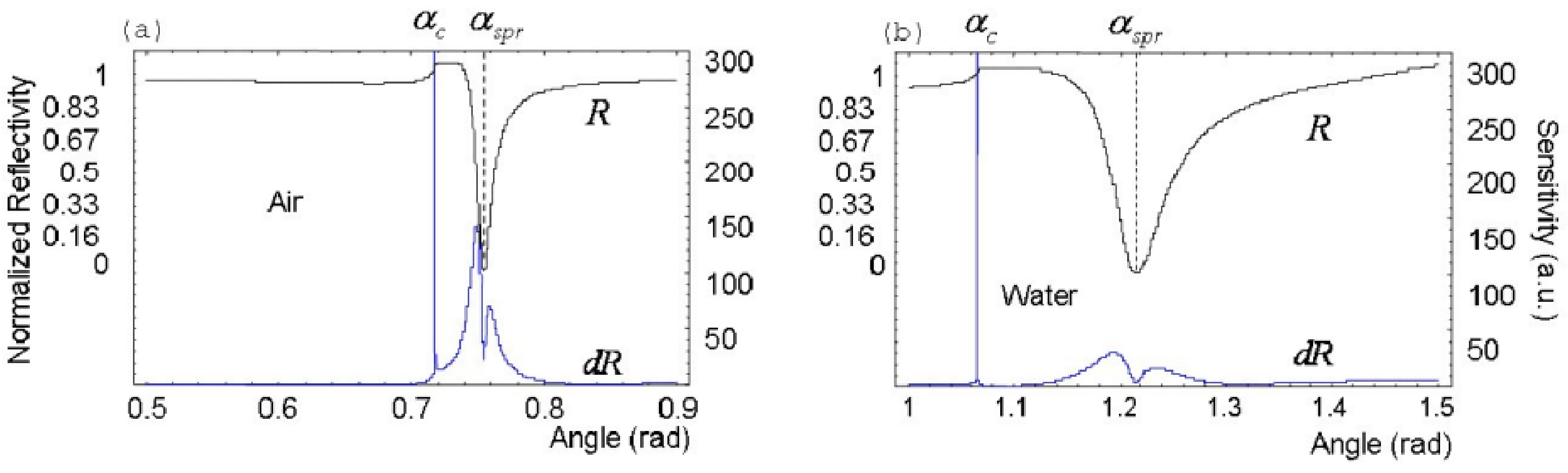
$$R = \left| \frac{r_{pm} + r_{ms}\exp(i2k_{mz}d)}{1 + r_{pm}r_{ms}\exp(i2k_{mz}d)} \right|^2$$



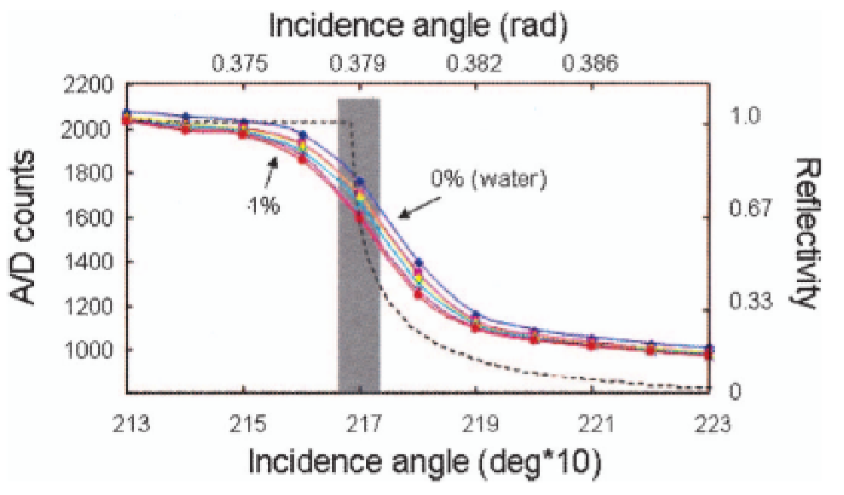
$$k_{jz} = [\epsilon_j(\omega/c)^2 - k_x^2]^{1/2}$$

$$k_x = (\omega/c)\sqrt{\epsilon_p}\,\sin\alpha$$

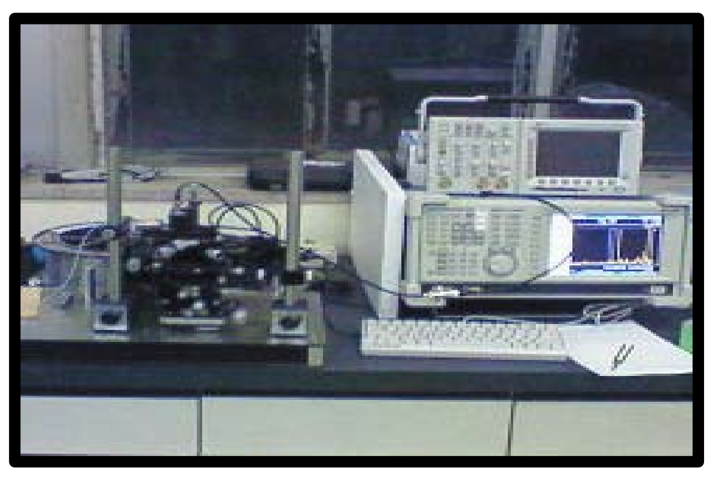
The critical angle discontinuity is proved theoretically better than SPR sensing. Also, we demonstrated experimentally by a multiple reflection refractometer that at critical angle we could resolved better than 50*10^(-6)

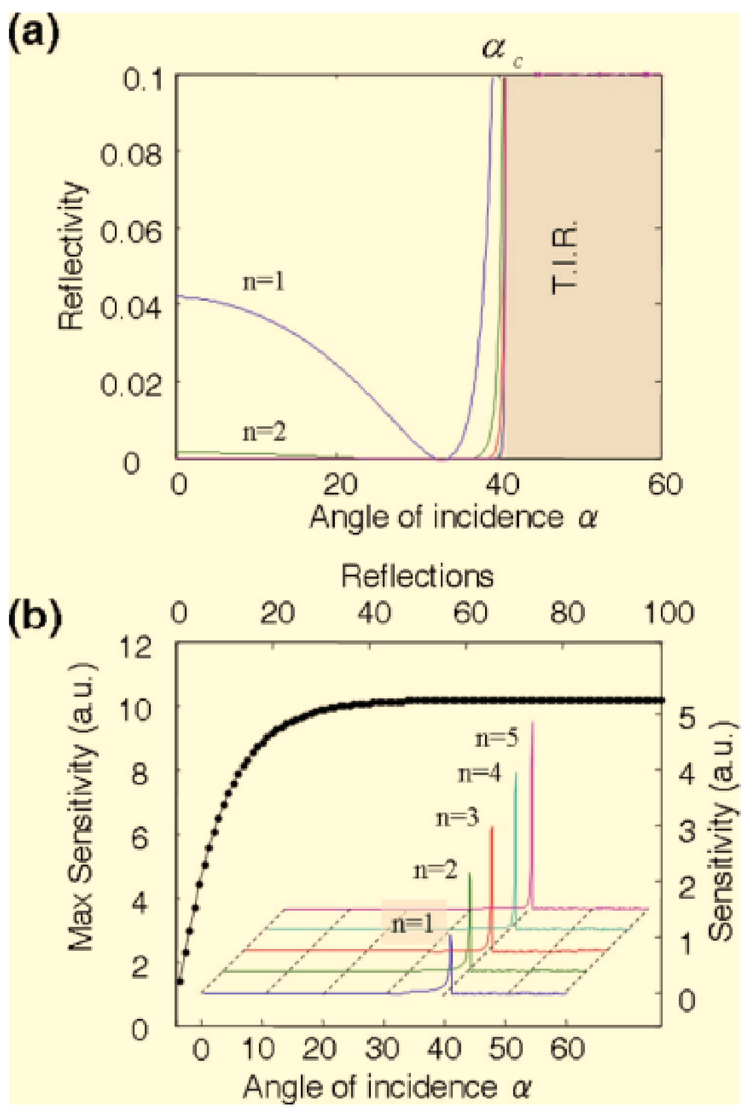


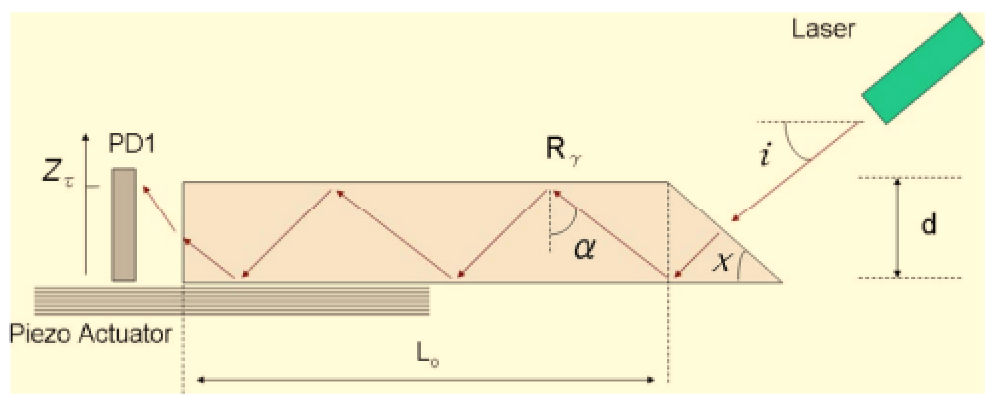
Sensitivity curve for a Kretschmann three layer system. Calculations are including Surface Plasmon Resonance effect for comparison between critical angle and SPR sensitivity peaks. R is the Reflectivity in function of angle α (rad). The SPR dip is visible at α_{spr} , together with a small shoulder at critical angle α_c. The curve dR is the numerical derivative of R, a very sharp and narrow peak is evident at critical angle. These plots are obtained from a three layer Fresnel planar model under illumination of $\lambda = 670$ nm. Materials are glass ($n_p = 1.52$), a Gold ($\omega_p = 1.3610^{16}$, $\omega_t = 1.4510^{14}$, $\varepsilon_i = 9.75$) layer $d = 52$ nm thick and water ($n_s = 1.33$) or air ($n_s = 1$) as sample materials. The SPR peak deteriorates to increased index of refraction, whereas sensitivity peak at α_c appears extremely sharp and unchanged.



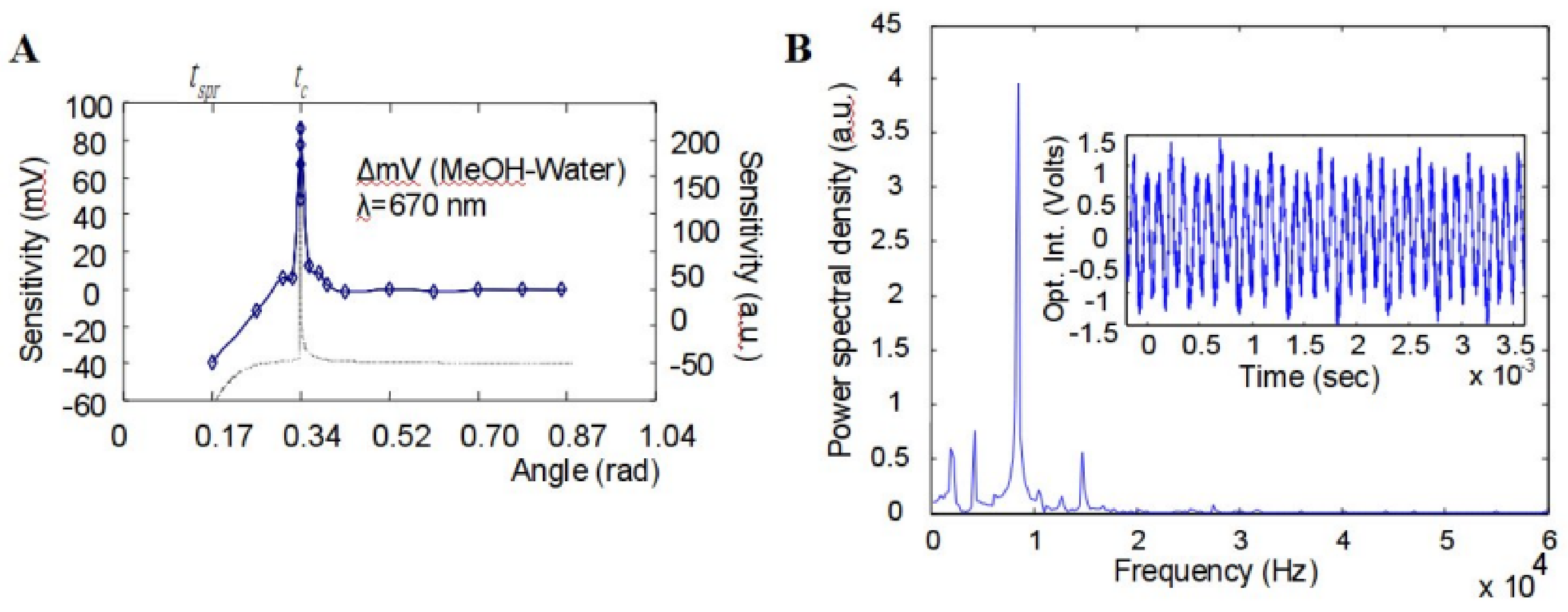
Experimental data with a highly diluted ethanol sample. The theoretical behavior is represented by the dashed curve. The top curve is pure water at (0% ethanol). Less reflective curves are solutions of water and ethanol, 0.2%, 0.4%, 0.6%, 0.8%, and 1% in volume concentration. The A/D converter is 8 bit; data angular resolution is 0.1°, corresponding to the degrees ×10 horizontal scale.







Principle of operation of the sensor is illustrated: light is launched in a planar glass waveguide, after a number of total internal reflections it is collected on the opposite side by the photodetector PD1. A piezoactuator is placed under the waveguide to induce calibrated nanometer displacements along the axis Z. Contact between piezo and glass is minimized to avoid reflection coefficient changes. The working angle is centered on the critical angle so that any small vibration will result in large signal variations amplified by the multiple reflection configuration. See text for details.



Panel A: Test on sensitivity measured as response difference between water and methanol. Sharp sensitivity peak at critical angle is evident, theoretical curve is also shown. Panel B: The power spectrum of a calibrated 240nm, 8KHz vibration applied to the sensor, the inset shows the signal detected at the optical detector.

Theoretical behavior of the system: (a) The reflectivity curve is plotted for the first five reflections; the first two are labeled. The well known Fresnel behavior degenerates to a steplike curve centered on critical angle α_c. (b) The sensitivity of the system is proportional to the numerical derivative of the reflectivity; the surface represents this sensitivity (right axis) as a function of the angle (bottom axis) and the number of reflections from 1 to 5, as indicated. An evident peak increasing with the number of reflections is noticeable. Superimposed is the plot of the maximum sensitivity for the first 100 reflections (top axis).

Conclusions

We presented a new simple approach to **index of refraction sensing**, we proved analytically that sensitivity is unlimited and we tested experimentally the promising behavior reaching index of refraction discrimination in the order of 10−6 with a **simple home made planar detector**. While detection of local plasma perturbation in the vicinity of metal coating is reserved to the sole SPR operation mode, we demonstrated that sensitivity to the index of refraction is higher at **α_c** . Moreover, we have shown that the concept of **critical angle sensing** can be extended to other kind of sensors, presenting a simple vibration sensor with excellent performances based on the same principle. Critical angle sensing realize a **virtually unbounded sensitivity** value, so instrumental constraints are the only limitation to various possible devices. We believe this approach can be useful to realize extremely sensitive systems for next generation detectors

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