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# Surface Plasmon-like Effect on POF Sensors for Refractive Index Measurements

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**Abstract**

Our group has been investigating a surface plasmon resonance (SPR) sensor based on Polymeric Optical Fibre (POF) technology. Side-polished Poly-Metil-Metacrilate (PMMA) POFs were coated with a 50 nm thickness Pd thin film. The experimental set-up was used to measure small refractive index variation of ethanol/water solution. A sensitivity of +83.0 dB/RIU (Refraction Index Unit) and ~$10^{-4}$ RIU resolution in the range of 1.333-1.358 were achieved.

## Introduction

After a long experience in developing silica fibre sensors for industrial (electric power, oil & gas), biochemical and biomedical applications, the Photonics and Instrumentation Laboratory of the Federal University of Rio de Janeiro (LIF/COPPE/UFRJ) began in 1999 to investigate the use of POFs for sensing [1] as well. Such interest rises from some useful advantages of POFs comparing to silica fibres. One can name its easy of handling, sturdy structure, safety and potentially low cost for disposable units, for some applications.

Previously, LIF had developed a refractometer based on the side-polishing technique, achieving good results on this device [2]. In order to improve the sensor sensitivity, we began to investigate the SPR technique on PMMA POFs.

It is well known that the bulk or fibre optical sensor based on SPR at a metal-dielectric interface can provide a very high degree of sensitivity to small changes in refractive index for many applications. Such phenomena may be used to build optical fibre passive and active devices such as an electro-optical modulator, polariser, polarisation selective couplers and allow an improvement on the efficiency of a number of sensors and non-linear devices [3]. It can be used to measure the refractive index of chemical samples or thin film chemical transducer layers. Such sensors include the following: immunoassay, liquid, gas and thin film sensors, real-time monitoring of laser-ablation processes and temperature sensing [4-7]. The commercial implementation of this type of sensor has been limited mainly to large expensive bulk optical designs [8,9].

## Sensor Fabrication and Experimental Procedure

The sensing elements are manufactured by embedding a slightly bent piece of PMMA POF in a polyester resin block. This way the POF structure remains tangent with the block face. In order to access the evanescent field, such face is polished out up to the fibre diameter with a very fine lapping film (emery), reducing it to one half of the original diameter. The achieved sensor element is placed in a vacuum chamber evaporator in order to be coated with a Pd thin film. Both silver and gold are traditionally used to excite SPR in the visible or near infrared range, but in this work we used a Pd thin film only due to the convenience. Such metal layer is about 50 nm thick and approximately 10 mm long. A cuvette is positioned around this region in order to hold the liquid solution under test (SUT) in contact with the sensing region. The SUT is a mixture of ethanol and water in nine different relative concentrations (10%-90%). The refraction index of the SUT is independently measured by the Abbè refractometer technique. After the measurement of each sample, a syringe removes the SUT, and a final evaporation is performed with compressed air jet. In all experiments, a light from a HeNe laser (633 nm) is launched in the POF entrance with 0° angle thus exciting the SPR. After the interaction with the SUT an optical power meter measures the transmitted light at the other end of the POF.

## Results

Figure 1 shows the measured results for the refractive index varying from 1.333 to 1.358. Notice at curve A, a linear response from 1.339 to 1.355, giving a total variation of 0.0174 RIU. Such range corresponds to approximately + 83.0 dB/RIU of the device sensitivity after performing a least-square calculation and ~$10^{-4}$ RIU resolution.

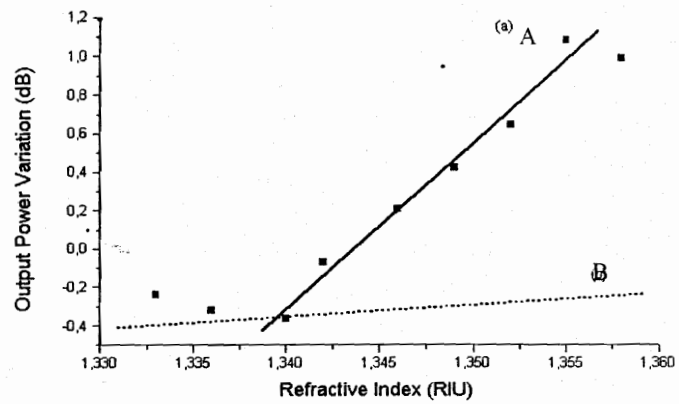


Figure 1 – Optical output for different concentration of ethanol/water solution. A - Surface plasmon resonance POF sensor. B - Bare POF sensor.

Curve B corresponds to the results obtained using a bare POF sensor. Such POF sensor is prepared by side-polishing technique, using a course lapping film, but without metal deposition [5]. These results were obtained using a sucrose solution, since the use of ethanol could chemically damage the POF sensing element. A sensitivity of about +7.5 dB/RIU is achieved for the same refraction index range. By comparing curves A and B one can see that the SPR technique greatly enhances the sensitivity of the POF sensor for refraction index measurements. An increase of about 76.5 dB in the sensor sensitivity, obtained as a result.

Surface plasmon waves (SPW) are excited at the interface between a thin metal and a sample by coupling through a high refractive-index substrate (as PMMA). The coupling between the SPR and the guided modes of a fibre can be established through the

vanescent field interaction in structures that contain an optical fibre with locally removed cladding and a metal overlayer. SPW are transverse waves that can be supported by the metal-dielectric interface with collective oscillations of the free electrons at the metal surfaces where the oscillating electric field is normal to the surface (TM waves). The field vectors of SPW reach their maximum at the metal boundary and strongly decay toward the superstrate (SUT). When the wave vector of the radiation in the surface normal is made to match the SPR condition by a specific combination of wavelength, incidence angle and refractive index, a surface plasmon is excited, which results in energy loss from the reflected intensity, and then the transmitted light exiting the POF drops out [8]. The rays propagating at $\theta > \theta_{critical}$ in the fibre can undergo reflection at the metal/dielectric interface with the SPR coupling angle $\phi_{SP}$. When the propagation modes of the (multimode) POF enter the interaction region of the structure, they excite a SPW at the outer boundary of the metal layer if the two waves are closely phase matched. As the SPW is strongly lossy the coupling results in damping of the fibre mode. The strength of the interaction and consequently the fibre mode attenuation is highly sensitive to optical properties of the materials involved (mainly to those of the metal layer and the superstrate) and to a wavelength. At this specific angle $\phi_{SP}$ the transmitted optical power is attenuated as a result of the incident optical energy transferred to the SPR charge-density waves. Light is attenuated due to the coupling of incident light energy to SPW at the Pd/liquid sample interface. The refractive index of the dielectric medium surrounding the fibre can be determined from the optical power measurements after a suitable calibration.

Our results can be compared with $5 \times 10^{-4}$ RIU resolution and –194,4 dB/RIU at 730 nm as achieved with a silica singlemode optical fibre and $10^{-4}$ RIU resolution and –93,3 dB/RIU at 670 nm with a silica multimode optical fibre. Both are plasmon sensors, but the latter with a launch angle selected of monochromatic light [10,11].

Although we are using a laser source (narrow bandwidth), theoretical analysis of SPR excitation by light sources of wider bandwidth as LEDs used in POF technology indicates that even at bandwidth around 50 nm is capable of yielding high level of SPR excitation [8]. Usually the plasmon sensor is not very sensitive to temperature variations, i. e. < 0.01 dB/°C at room temperature that limits our resolution at ~ $10^{-4}$ RIU [8,12].

We have also performed another measurement that presented the temporal POF-plasmon sensor response. Such behaviour is important in some applications, as for instance in biochemical area, where the sensor time response can be determinant for its use. In measuring the sensor rise time, the photo-detector output is connected to a storage oscilloscope. Figure 2 shows the temporal response of the POF-plasmon sensor as acquired from the oscilloscope. The time base and vertical scale were adjusted to 20 s/div and 100 mV/div sensitivities respectively. A rise time response of approximately 25 seconds was measured.

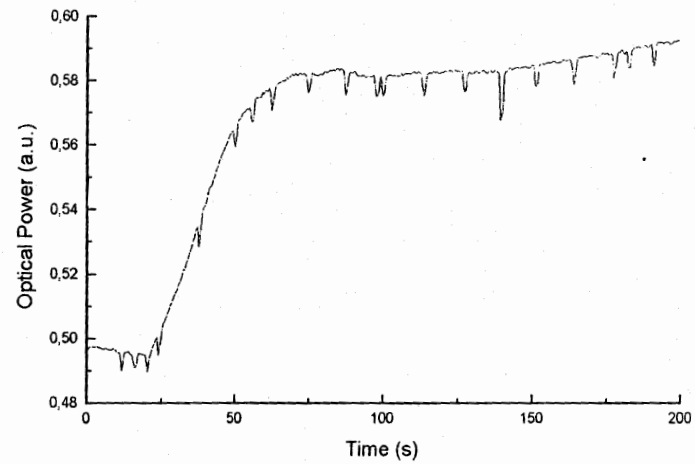


Figure 2 – Temporal response of surface plasmon-like POF sensor.

Other investigators have shown that after pouring water + isopropanol into the plasmon sensor, a slow temporal response of ~ 30s was observed [8]. Such behaviour is similar to our findings.

## Concluding remarks

The POF-plasmon sensor presented here, although in its earlier stage of development, is easy to build and its cost is potentially low. The sensor is able to detect small refractive-index variation in the range of 1.333-1.358 of the dielectric liquid surrounding the fibre. On the other hand, our configuration can be used as a refractometer after a suitable calibration. The POF-plasmon sensor does not require complex or expensive optical components or equipment, nor a stable optical bench is necessary. The advantage of metal deposition for protecting the POF surface from chemical damage due to the SUT composition has also been demonstrated. This can broaden the applicability of POF sensors, as polymeric material for harsh environment (except for high temperatures), as well as maintaining all intrinsic advantages characteristic of the fibre optical sensors. Further investigations are under development in our laboratories.

## Acknowledgement

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