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Low-Cost Sensing with Plastic Optical Fibers—From Turbidity and Refractive Index to Chemical Sensing †

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Abstract: This manuscript presents low-cost sensing systems for the monitoring of liquids, namely water and beverages quality assessment, with remote and in-site monitoring capabilities. The collaboration with several research groups allowed the development of smart optical platforms and low-cost sensors based on plastic optical fibers for the measurement of turbidity, color, refractive index and water contaminants.

Keywords: optical fiber sensors (OFSs); plastic optical fibers (POFs); low-cost sensing; intensity modulation; turbidity; color; refractive index (RI); chemical sensing; data fusion algorithm; remote sensing;

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1. Introduction

The availability of low-cost sensing systems able to give a reliable output is urgently needed in day-to-day lives. The capability to bring high level technology to the ground level of common users, with no need for specialized knowledge and with simple instruments would be a great advance in the synergy between science and population. This can be accomplished with low-cost sensing systems which will be presented in this manuscript.

This research team works on the development of low-cost, smart optical platforms for in-line and real-time measurement of liquid properties and/or chemical contaminants, based in optical fiber technology using plastic optical fibers (POFs). With the collaboration of national and international research groups, the development of low-cost sensors for the measurement of turbidity, color, refractive index and water contaminants was possible. An online cloud platform was also developed which allows to store, analyze and display the infield sensors' data using wireless connectivity.

Sensors' principle of operation relies on the light intensity modulation-based sensing using both intrinsic and extrinsic configurations designed to have dependence to the parameter to measure. The presence of contaminants in water can be detected through the interaction of target analytes with selective layers that are deposited on the POFs, therefore acting as selective coatings. The binding between the target analyte and these selective coatings causes a variation in the refractive index of the layer which allows the detection and monitoring of the target contaminant(s).

2. Optical Sensing Configurations

The developed sensors are based in intensity modulation, which means that the variation in the light intensity that reaches the detector after passing and interacting with the medium to be analyzed was used as sensing mechanism. This allowed to measure turbidity, color as well as refractive index variations using different optical configurations and taking advantage of the interaction of light and matter.

Optical fiber sensors can be based in intrinsic and extrinsic configurations. An POF extrinsic sensor means that the POF only allows the light to travel to and from the medium to be analyzed, only acting as a waveguide, whereas an intrinsic POF sensor means that the light interacts with the sensing medium while travelling in the POF. The turbidity and color sensors are based in extrinsic configurations, while the refractive index and chemical sensors are based in intrinsic configurations where the POF acts as a waveguide and a transducer.

The sensors allow low-cost sensing once LED's are used as light sources and photodiodes are used as detectors. The developed sensing systems allow for remote and real-time measurements with the capability for data treatment and visualization in the developed online cloud platform.

3. POF Sensors

3.1. Turbidity and Color POF Sensors

The turbidity sensor, used for the measurement of the total suspended particles in a solution, was a concept developed by Bilro et al. since 2010 [1]. It requires a direct interaction with the external medium from which it pretends to measure. To accomplish this, an air gap fiber to fiber transmission scheme between two perfectly aligned fibers and submerged in the liquid is used. Light exiting from one of the fibers will interact with suspended particles and phenomena of scattering or absorption of light will occur. The remaining light will be captured by the other fiber and detected in a photodiode. Higher concentrations of particles will diminish the light detected in the other side following the Beer-Lambert law. Adding to this measurement scheme, a 90° fiber is placed longitudinal 2 mm from the emitter fiber that will provide the capability to measure the scattering light in this angle. Higher particle concentration will promote higher scattering light and therefore higher intensity will be detected. The developed POF turbidity sensors allowed to estimate the concentration of sediments and organic matter [2–5].

A single LED can be used to provide the light for the emitting fiber, being infrared (IR) light the best solution to avoid color influence. However, by using an array of colored LEDs, namely in the red, green and blue wavelength, added to the IR one, it is possible to have a color measurement simultaneously with the turbidity measurement. This approach was developed in 2013 by Ferreira et al. [6,7] and developed further [8–10]. To increase the accuracy and resolution of the turbidity and color measuring, Duarte et al. developed a Data Fusion algorithm capable of combining information from the multiple wavelength sources and schemes of measurement by extracting the best features of each one to the best result possible [11,12].

3.2. Refractive Index POF Sensors

Low-cost POF-RI sensors were designed and developed based in D-shape and straight POF configurations. The sensing region of the POF sensors is in contact with the liquid to be measured and the principle of operation is based on the variation of the transmitted light through the modified section of the fiber due to RI variations of the liquid being monitored. The low-cost sensing system allows real time monitoring through Bluetooth technology and the data is saved through a LabVIEW application, which can be further analyzed, allowing for remote sensing and in-site monitoring.

D-shaped POF sensors were developed in collaboration with researchers from the University of Aveiro, University of Pavia and University of Campania Luigi Vanvitelli, allowing the measurement of RI variations with resolution of 10^{-3} RIU [13–16]. These sensors are produced by side-polishing the POF with sandpapers of known grit size after embedding the POF in a planar platform. Several studies were performed which showed that the length and roughness of the sensing region are important parameters that will determine the performance of the sensors, namely sensitivity and resolution. POF sensors with straight configuration were also developed in collaboration with researchers from University of Aveiro and University of Campania Luigi Vanvitelli. In this case the sensors were produced by exposing the POF's core and modifying the roughness of the sensing region through polishing with sandpapers of known grit size, allowing to measure refractive index variations with a resolution of 10^{-4} RIU [17,18].

3.3. Chemical POF Sensors

D-shaped POF chemical sensors based on molecularly imprinted polymers (MIPs) were developed through an international cooperation (University of Campania Luigi Vanvitelli and Copernico S.r.l). An MIP was deposited in the surface of D-shaped POFs for the selective detection of Perfluorinated Alkylated Substances (PFASs) in water [19–21]. The obtained results revealed that this platform is suitable for low-cost chemical sensing although the performance of the sensors can still be improved.

Preliminary studies related with the coating of straight POFs with proteins was performed through a national collaboration (UCIBIO, Universidade NOVA de Lisboa). The success of the coating was easily confirmed at naked eye [22]. Future work aims the deposition of modified selective proteins for chemical sensing in water.

4. Conclusions

Several POF sensors were developed and tested for the measurement of liquid properties – turbidity, color, refractive index and presence of contaminants. The developed sensors allow for remote and real-time measurements, with low-cost sensing systems.

Further developments aim new POF sensors configurations, with higher performance as well as the coating of POF's with different types of selective coatings contributing to the development of low-cost POF chemical sensors and biosensors for water and beverages quality assessment.

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