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Surface Plasmon Resonance Sensor Based on Inkjet 3D Printing †

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Abstract: A novel surface plasmon (SPR) sensor was designed, manufactured and experimentally tested. A novel approach was followed to fabricate the sensor. It is based on a combination of both the inkjet 3D printing process and the use of optical adhesives, which were used as an alternative solution to the use of plastic optical fibers (POFs). The obtained experimental results showed good performances, at least in terms of figure of merit (FOM), for the 3D-printed sensor, which were quite similar to those gained by an SPR–POF configuration. Next, through a cost analysis, the possibility of manufacturing the SPR sensor at a low cost was demonstrated, thus being economically advantageous towards conventional sensors.

Keywords: 3D printing; additive manufacturing; photocurable resin; plasmonic sensor

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1. Introduction

In the last few years, the continuous demand for sensitive sensors operating in diverse application fields has led to developing innovative platforms based on different working principles [1–3]. Among them, the surface plasmon resonance (SPR) technique is commonly used as a detection method [4]. In particular, the SPR working principle relies on the refractive index discrepancy at the interface between a dielectric medium and a metallic nanofilm. This family of sensors can be used to analyze different substances, such as pollutants, pesticides, toxic metals, viruses and other molecules. As an alternative to silicon-based technologies, SPR sensors could be fabricated by means of a novel technique relying on inkjet 3D printing. One of the most remarkable advantages of using 3D printing technologies resides in the possibility to realize more complex geometries, different from basic cylindrical fibers [5–7], and obtain a freedom design approach. An additional benefit of developing organic optoelectronic devices is their low cost compared to silicon-based ones [8] as clean rooms are not needed, unlike microelectronics industries.

With regard to 3D-printed plasmonic sensors, despite several approaches having recently been presented [9], one of the common downsides is represented by the necessity of polishing the printed surfaces before gold sputtering in order to obtain the required SPR performance [10]. For complex designs with restricted access to all surfaces, this strategy can be a limiting factor. In addition, several strategies involve the use of expensive resin [5], which increases the total cost of the developed sensor.

In order to overcome the above-mentioned issues, in this work, a novel SPR sensor has been designed and manufactured via an inkjet 3D printing process combined with

optical adhesive use. The developed SPR sensor is easy to fabricate since no further surface modifications (i.e., lapping procedures) are required. This approach was previously adopted as a substitute to plastic optical fibers (POFs) [11] but with no reference to SPR phenomena. The numerical and experimental results have been presented as well. Eventually, through a cost analysis, it has been demonstrated that the 3D-printed sensor is economically advantageous.

2. 3D-Printed Surface Plasmon Resonance Sensor

2.1. SPR Sensor Design and Fabrication

The SPR sensor has been designed disassembled and is composed of four different parts by using Autodesk® Fusion 360 (Figure 1), and then the STL (Standard Triangle Language) files were generated. The latter is a de facto standard file that describes the external closed surfaces of the original CAD model and forms the basis for the slicing procedure. Next, the G-Code instructions for the 3D printer were realized via the software Objet Studio™. Finally, the sensor construction was performed by using the PolyJet 3D printer Stratasys Objet260 Connex 1 (Stratasys, Los Angeles, CA, USA). The used material was a liquid photopolymer ink (VeroClear RGD810). Once the SPR sensor parts construction was completed (Figure 2), the waveguide core of the 3D-printed optical device was fabricated. Thus, the UV photopolymer adhesive (NOA88, Edmund Optics, Nether Poppleton, York, UK) was microinjected into the sensor channel and cured for 10 min by means of a lamp bulb with UVA emission at 365 nm, as shown in Figure 3.

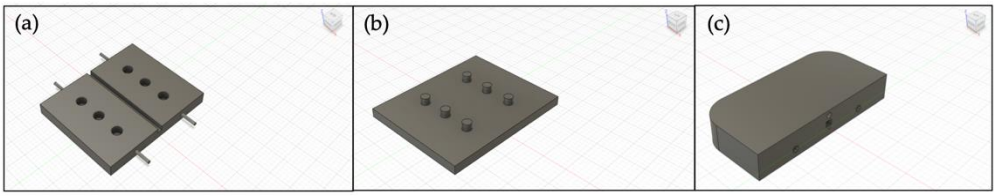


Figure 1. Disassembled parts of the surface plasmon resonance (SPR) sensor designed on Autodesk® Fusion 360. (**a**) Substrate having the functionality of cladding for the waveguide core; (**b**) cover as cladding for the upper part of the waveguide core; (**c**) support for fitting with 1 mm POF waveguides.

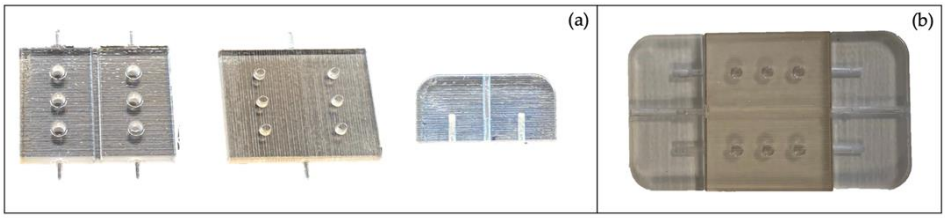


Figure 2. (**a**) SPR sensor's 3D-printed disassembled parts. (**b**) Assembled SPR sensor.

Next, to generate the SPR phenomenon, the cured core, without any further surface modification, was gold-sputtered with a coater (Bal-Tec SCD 500, Schalksmühle, Germany) in such a way as to present a noble metal nanofilm. The thickness of the sputtered gold was about 60 nm.

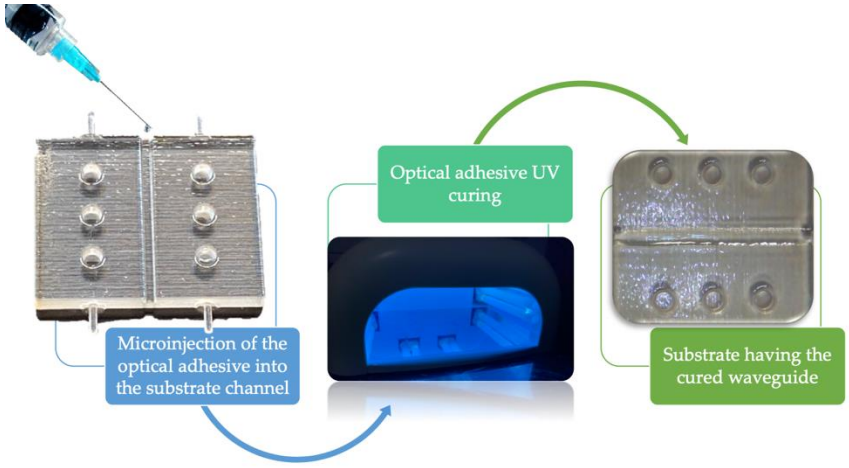


Figure 3. Waveguide core made of cured optical adhesive (NOA88) fabrication.

2.2. Experimental Setup

To monitor the developed plasmonic sensor, a simple experimental setup has been used, as shown in Figure 4, to carry out a low-cost sensor system. In particular, it comprises a halogen lamp, used as a white light source (HL-2000LL, Ocean Optics, Dunedin, FL, USA), two POF patches (1 mm total diameter) to couple and collect the light into the 3D-printed plasmonic sensor and a spectrometer (FLAME-S-VIS-NIR-ES, Ocean Optics, Dunedin, FL, USA) with a detection range from 350 nm to 1023 nm.

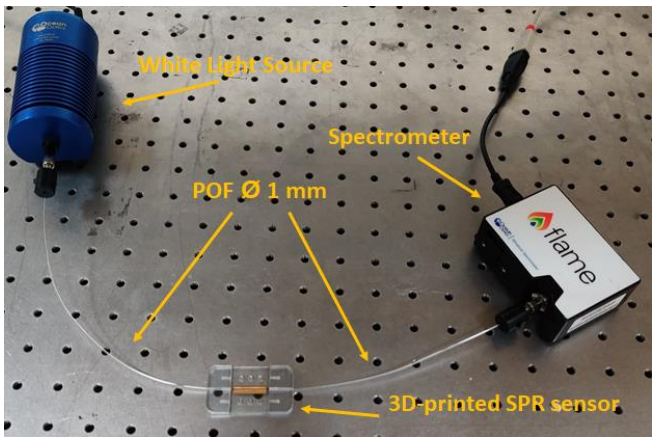


Figure 4. Experimental setup used to test the developed 3D-printed SPR sensor.

3. Results

3.1. Experimental Results

The experimental measurements have been obtained by exploiting the experimental setup reported in Figure 4. In particular, several water–glycerin solutions, whose refractive index ranges from 1.332 to 1.382, have been used to test the sensor performances. Figure 5 reports the normalized SPR transmitted spectra obtained using these water–glycerin solutions in contact with the gold sensing surface.

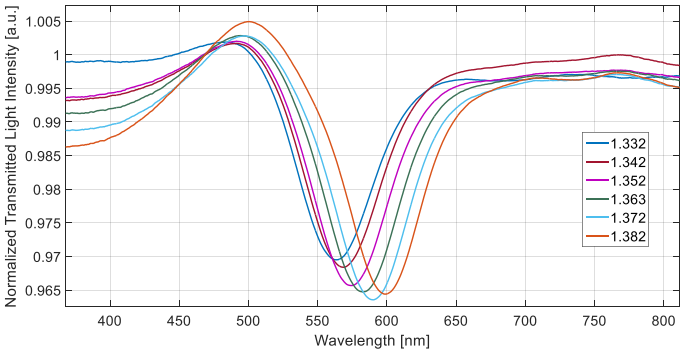


Figure 5. SPR spectra obtained at different refractive indices (from 1.332 to 1.382).

For the proposed 3D-printed SPR sensor, the obtained results have shown a good sensitivity, equal to about 710 nm/RIU (in the considered refractive index range). This value has been calculated by considering a linear sensor response [12]. Moreover, the 3D-printed SPR sensor has also denoted a figure of merit (FOM) equal to 13.6 RIU^{-1} [12], and this value is very similar to the one obtained with another low-cost SPR sensor based on D-shaped POFs [13]. The best improvement with respect to Ref. [13] is related to an approximate 40% improvement in the signal to noise ratio (SNR) [12,13].

3.2. Cost Analysis

By categorizing the cost parameters as process, material and machine, the cost needed to fabricate the SPR sensor was modeled. Focusing on the raw material cost, it was modeled by considering the raw material cost (393.11 €/kg for the model material VeroClear RGD810, 126.74 €/kg for the support material FullCure705, 2.50 €/ml for the optical adhesive NOA88) and the quantity needed to manufacture the model (i.e., 0.017 kg of VeroClear RGD810, 0.006 kg of FullCure705 and 1 ml of NOA88). Next, with the purchase, installation and maintenance costs of the 3D printing machine used being known, the cost model even considered the depreciation of the machine itself. To complete this operation, input parameters were used for the model both in terms of the depreciation cost (i.e., 10 €/h) and the printing time needed to manufacture the sensor (equal to 0.47 h in this case). In conclusion, the last input parameter considered was related to the power cost. In this case, the power requirements for the instrument used during the 3D printing process were considered. In detail, in the model, the power cost (0.10 €/kWh) and the printing time (0.47 h), which correspond to the usage of the machine in terms of time, were taken into account.

The resulting cost allocation is shown in Figure 6. The raw materials cost (model material VeroClear RGD810 393.11 €/kg, support material FullCure705 126.74 €/kg, optical adhesive NOA88 2.50 €/mL) had the greatest impact (equal to 66%) since the 3D printer employed only uses proprietary materials. As a result, the determined price for one sensor was ∼15 €, which resulted to be much cheaper than a traditional sensor. The costs can be further reduced in the future by using new vat-photopolymerization printers that are being developed and that use more low-price materials (i.e., 50 €/kg).

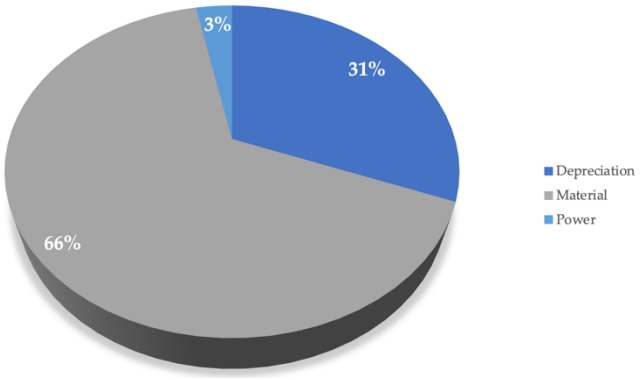


Figure 6. Cost allocation pie chart.

4. Conclusions

Once a CAD model was accomplished, by using the inkjet 3D printing technology, a cheap SPR sensor was manufactured. It is an innovative approach to obtain sensors in a fast way for mass production. The manufacturing cost resulted to be a very low-price (∼15 €), making the proposed approach very cost-effective. Moreover, the total cost for this device could be further decreased by using cheaper resins through the LCD printing.

The experimental analysis performed showed good performances for the SPR sensor fabricated. Indeed, the test run showed a figure of merit quite similar to the POF-based SPR sensor, while the sensitivity resulted to be somewhat minor. It is important to underline that, in order to improve the sensor's performances, other photocurable resins could be used in the fabrication process. In fact, by changing the waveguide core material, i.e., its refractive index, it will be possible to tune the SPR sensitivity, making it possible to obtain an improved sensor configuration.

For all these reasons, the fabricated sensor could represent the starting point for developing a new class of plasmonic biochemical sensors for several applications where high sensitivity and real-time, label-free detection are strictly required. Moreover, with the versatility of the proposed sensing approach, it could also be possible to include these kinds of sensors in a "smart city" environment, for instance, to monitor air pollutants and water quality, in view of the so-called "internet of things".

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