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Femtosecond laser writing of near-surface waveguides for refractive-index sensing

Alain Abou Khalil, [1,2] **Philippe Lalanne,** [3] **Jean-Philippe Bérubé,** [2] **Sylvain Danto,** [4] **Thierry Cardinal,** [4] **Yannick Petit,** [1,4] **Réal Vallée** [2] **and Lionel Canioni** [1]

[1]*Université de Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33405 Talence, France*
[2]*Centre d'optique, Photonique et Laser (COPL), 2375 Rue de la Terrasse, Université Laval, Québec G1V A06, Canada*
[3]*Laboratoire Photonique, Numérique et Nanosciences (LP2N), IOGS, Université de Bordeaux, CNRS, 33400 Talence cedex, France*
[4]*Université de Bordeaux, CNRS, ICMCB, UPR 9048, F-33608 Pessac, France*
alain.abou-khalil@u-bordeaux.fr

Abstract: Using femtosecond laser writing technique, near-surface waveguides with no need for additional processing were written in silver-containing glasses. An ultra-sensitive refractive index sensor exhibiting a novel double-wing feature is manufactured in a 1 cm glass chip.

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1. Introduction

Femtosecond laser writing (fs LW) is a well-established technique for the creation of 3D optical components in transparent substrates such as glasses. However, most of the written optical components were embedded inside the glasses and only few works have been reported for writing waveguides near the glass surface which is due to the glass ablation that occurs when reaching the glass surface [1]. Up to now, this has prohibited mostly the interaction of light with the outside medium and limited the sensing applications. In this paper, taking advantage of the low pulse energy regime below the ablation threshold [2], we report the ability to write silver-based "*type A*" [2,3] near-surface waveguides with no additional processing (which is not the case for the well-known *type I* modification) as well as the creation of an ultra-sensitive refractive index in a 1 cm glass chip. Finally, we also report a new theoretical approach to simulate the behavior of such refractive index (RI) sensor.

2. Results

2.1 Near-surface waveguides

Following a stair pattern, series of 1 cm near-surface waveguides at different depths from the surface (Fig. 1.a) in silver containing glass were written using fs LW technique. The S-shaped waveguides were composed of 5 mm length neighboring the glass surface and acting as a sensing region as shown in Fig. 1.b. The exit facet of the glass under white light illumination shows the side view of the near-surface waveguides at different depths (Fig. 1.c.). All the near-surface waveguides exhibit a smooth writing process (typical of *type A* morphology [2,3]) where no ablation nor cracks of the glass were observed from both the side and the top view, as compared to the well embedded waveguide inscribed 32 µm below the glass surface acting as a reference as show in Fig. 1.c.

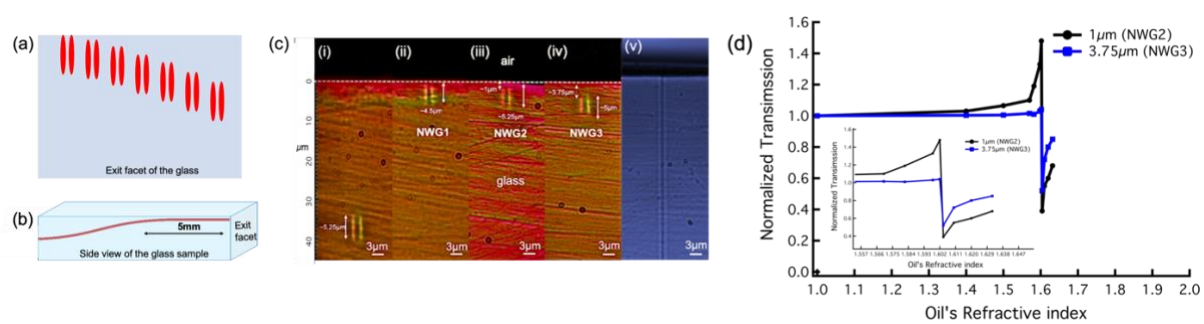

Fig. 1. (a) Schematic presentation of the stair pattern fs LW process. (b) Side view of the sample following fs LW of a rising near-surface waveguide. (c) Exit facet bright field images for (i) well embedded waveguide inscribed 32 µm below the surface (ii) NWG1, waveguide written on the glass surface (iii) NWG2, waveguide 1 µm below the glass surface (iv) NWG3, waveguide 3.75µm below the glass surface (v) Top view of a near-surface waveguide portion. (d) Normalized transmission of experimental values following the deposition of 4 mm oil droplets exhibiting different refractive indices for the NWG2 near-surface waveguide (black curve) 1 µm away from the surface, and NWG3 3.75 µm away from the surface (blue curve). NWG2 exhibits a non-standard original response with a two wing-feature. Inset: Close-up of the double-wing feature.

2.2 Refractive index sensor and theoretical results

Based on the near-surface waveguides, a refractive index (RI) sensor is created in a 1 cm glass chip. Two waveguides NWG2 and NWG3 were considered, exhibiting distances from the surface of 1 and 3.75 µm respectively. To investigate the sensitivity of such waveguides, different index matching oils were deposited on top of the glass covering 4 mm of the near-surface portions of the waveguide. Surprisingly, the NWG2 waveguide exhibited an unexpected double-wing feature characterized by an increase of the transmission of ~50% for an oil RI of 1.602 that is followed by a sudden decrease of the transmission of ~63% for an oil RI of 1.604 that matches the effective index of the propagating mode, as shown in Fig. 1.d. This behavior was not observed for deeper waveguides which highlights the effect of proximity from the surface on the sensing behavior (Fig. 1.d). Finally, a theoretical model based on full Maxwell equations solution for the propagation of the electromagnetic field was proposed. It is able to simulate for the first time the double-wing feature i.e. the increase and the decrease in the transmission as shown in Fig. 2 which was not possible using previously reported models [4,5].

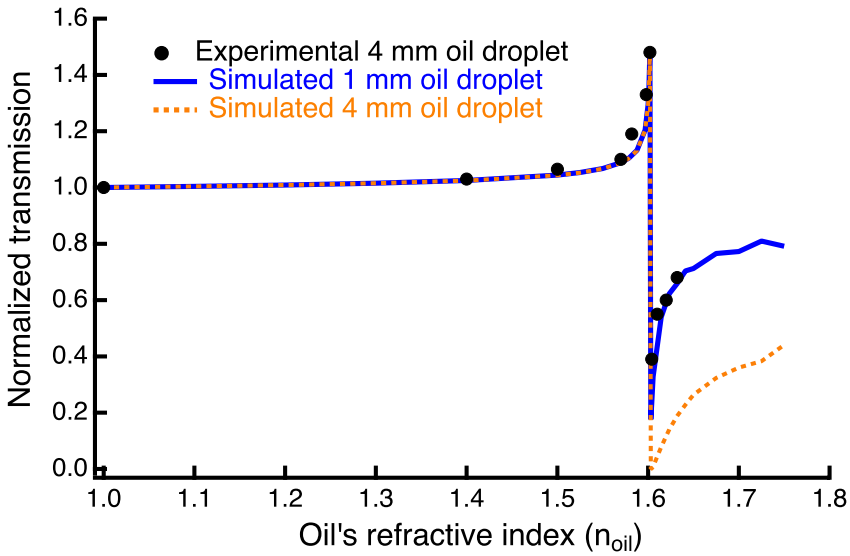

Fig. 2. Simulated (blue and orange respectively for 1 and 4 mm oil droplet) and experimental (black dots) normalized transmission of the refractive index sensor for different oil's refractive indices. The theoretical method simulates well the behavior of our refractive index sensor with the increase and decrease of the transmission.

3. Conclusion

Taking advantage of the low pulse energy regime to trigger *type A* modification, near-surface waveguides were written in silver containing glass with no need for additional processing while it is the case of the standard *type I* modification in glasses. Based on that, an ultra-sensitive refractive index sensor was created that exhibits an unusual double-wing feature allowing an extended range of sensing for indices from 1.4 to 1.7. A new theoretical approach based on the variation of the spatial mode profile propagating inside the waveguide is proposed. This approach is able to simulate for the first time the behavior of such refractive index sensor.

4. References

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