Bloch surface wave resonances generated with dielectric stack of high refractive index contrast deposited on a D-shaped optical fiber for sensing applications

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Abstract: A 5-layer stack composed of TiO_2 and Al_2O_3, two materials with a high refractive index contrast, was deposited on a D-shaped fiber to generate Bloch surface wave resonances with an improved figure of merit. © 2022 The Author(s)

1. Introduction

Electromagnetic resonances show a great potential for sensing applications. In addition, remarkable progress in nanodeposition techniques, such as sputtering, dip coating, layer-by-layer, and atomic layer deposition, has made it possible to underpin these phenomena in optical fiber sensors[1].

In Urrutia et al.[2] the performance of multiple optical fiber sensing structures is analyzed in terms of figure of merit (FoM), being the FoM the ratio between the sensitivity to refractive index (RI) and the full width at half minimum (FWHm) of the resonance. Among the structures analyzed in that work, two examples of combining electromagnetic resonances and optical fibers must be highlighted. The first one is tilted fiber Bragg gratings (TFBGs), where the application of metal thin films [3] has permitted to boost the performance of these structures to FoMs exceeding 1000. The second one is the lossy mode resonance (LMR), which is based on the deposition of a high refractive index dielectric material, typically a metallic oxide[4,5] . The best structure to explore this phenomenon is D-shaped fiber, where the TE and TM component can be separated using a polarization maintaining fiber[6] or an in-line polarizer and a polarization controller[7]. This setup permits to obtain sensitivities reaching thousands of nm per RI unit in water and a FoM of around 2000 for the latter case.

However, in some works the FoM is considered as the sensitivity divided by the full width at half maximum (FWHM)[8,9], which leads to lower values of the FoM in the structures analyzed or to the situation where the FoM cannot be calculated because the resonance exceeds the limit of the optical spectrum analyzer, as it is the case for the LMRs in[7]. This indicates that an improvement of the resonance width must be studied in order to attain higher resolution, and hence high performance devices[10]. Recently, we have demonstrated the deposition of a stack of layers deposited on a D-shaped fiber[9], which is a structure with many degrees of freedom compared to the simple deposition of a thin film. Alternating thin layers of tin oxide (SnO_2) and copper oxide (CuO) that exhibit a moderate RI contrast, close to 0.3 at the near infrared region, it was possible to obtain Bloch surface wave resonances (BSWR) with FWHM of 104.5 nm, 73.5 nm, and 52.5 nm, for 3-, 5- and 6-layer structures and sensitivities of 491 nm RIU^{-1}, 327 nm RIU^{-1}, and 322 nm RIU^{-1}, respectively[9]. The FoM is rather low and reaches 5, but it was the first demonstration of this structure.

In this work, thin film materials, such as stack of TiO_2 and Al_2O_3 with a high RI contrast reaching 0.8, have been applied to generate BSWRs. These materials have already been applied for optical fiber sensing purposes[11]. In addition to the high contrast, the imaginary part of RI of both the materials is low, which gives a possibility to obtain a resonance with a low FWHM and a high FoM. The performance of the device will be analyzed both as an RI sensor and as a device sensitive to formation of a thin coating to identify the capability of the device to serve as label-free chemical sensor or a biosensor.

2. Materials and Methods

Fig. 1a shows the cross section of the D-shaped fiber deposited with a a stack of 5 layers, where the first and the last one are TiO_2. For the sake of simplicity, the first four layers present the same thickness of 260 nm; this value was selected on the basis of the dispersion curves in the photonic bandgap analyzed by means of the transfer matrix method[12], as shown in Fig. 1b. The last layer thickness defines the position of the BSWR, and, in this case, it was calculated as 74 nm in order to locate the BSWR in the wavelength range of the optical spectrum analyzer (1250-1750 nm).

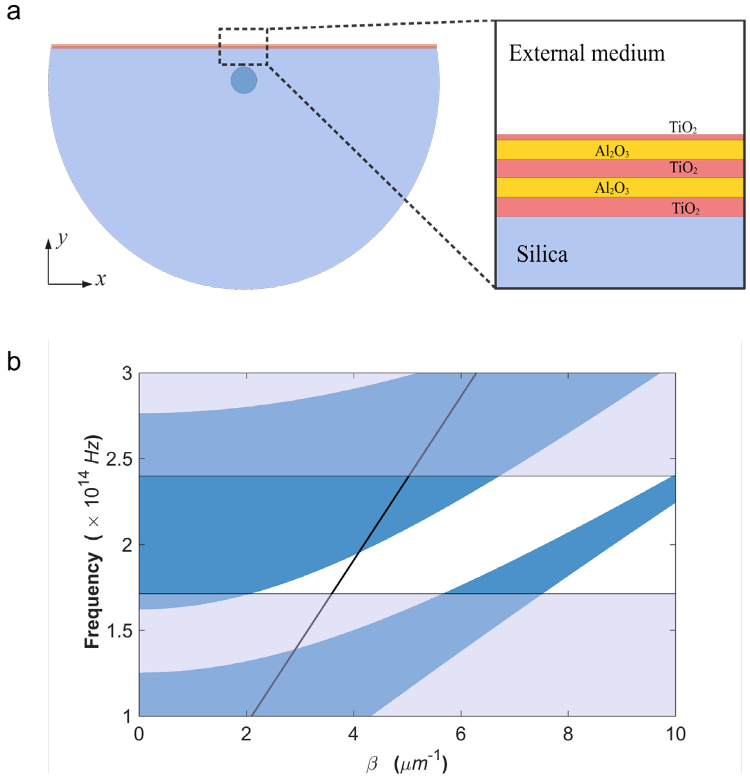

Fig. 1. (a) Cross section of the optical fiber structure and (b) bandgap diagram for the TE polarization.

In order to obtain the structure, an Oxford Plasmalab 400 reactive magnetron sputtering system supported with high purity 8-inch Al and Ti targets was used. The deposition conditions have been specified in[11]. Additional Al_2O_3 coating aiming to identify sensitivity of the device to formation of a layer has been deposited using Veeco Savannah S100 atomic layer deposition setup following the procedure described in[13]. Reference TiO_2 and Al_2O_3 coatings deposited on Si wafers were characterized using Horiba Jobin-Yvon UVISEL spectroscopic ellipsometer (see the results in Fig. 2). There it is evident the great contrast between both materials in a broad wavelength range that includes the operating range of the ellipsometer[13].

After the manufacturing process, the optical fiber structure was connected by one end to a multi-SLD light source (FJORD-X3-1330-1650, Pyroistech) and by the other end to an optical spectrum analyzer (OSA) MS9740A from Anritsu. In addition, it was immersed in various solutions of glycerol in water at different concentrations: 0 (milli-Q water), 10, 20, 30, 40, 50, 60 and 70 % W/V, which corresponds to RI in the range from 1.333 to 1.429. The same process was followed after the deposition of a 64 nm coating of Al_2O_3 on top of the 5-layer structure and repeated once again after the etching of the Al_2O_3 layer by immersion in NaOH 0.1 M.

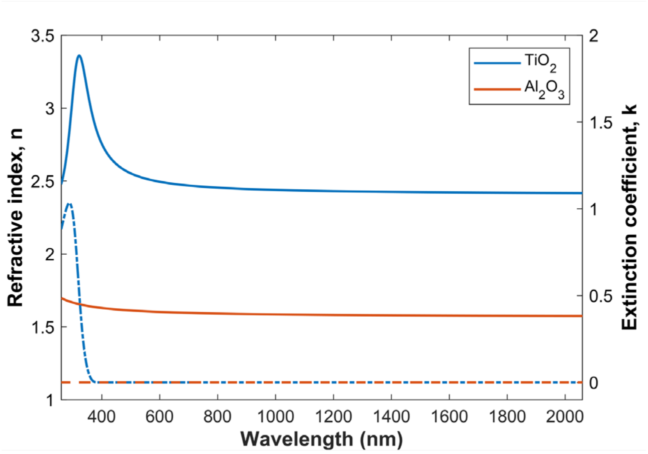

Fig. 2. Refractive index, n (solid lines) and extinction coefficient, k (dashed lines) of the TiO_2 and Al_2O_3 thin films.

3. Results and Discussion

Fig. 3a shows the transmission spectra obtained with the structure without additional Al_2O_3 layer for the considered refractive indices. Fig. 3b shows the spectra corresponding to the structure with the additional Al_2O_3 layer, where the BSWR is located at longer wavelengths due to the increase in thickness of the structure deposited on the D-shaped fiber, according to what is observed in other works[7,9].

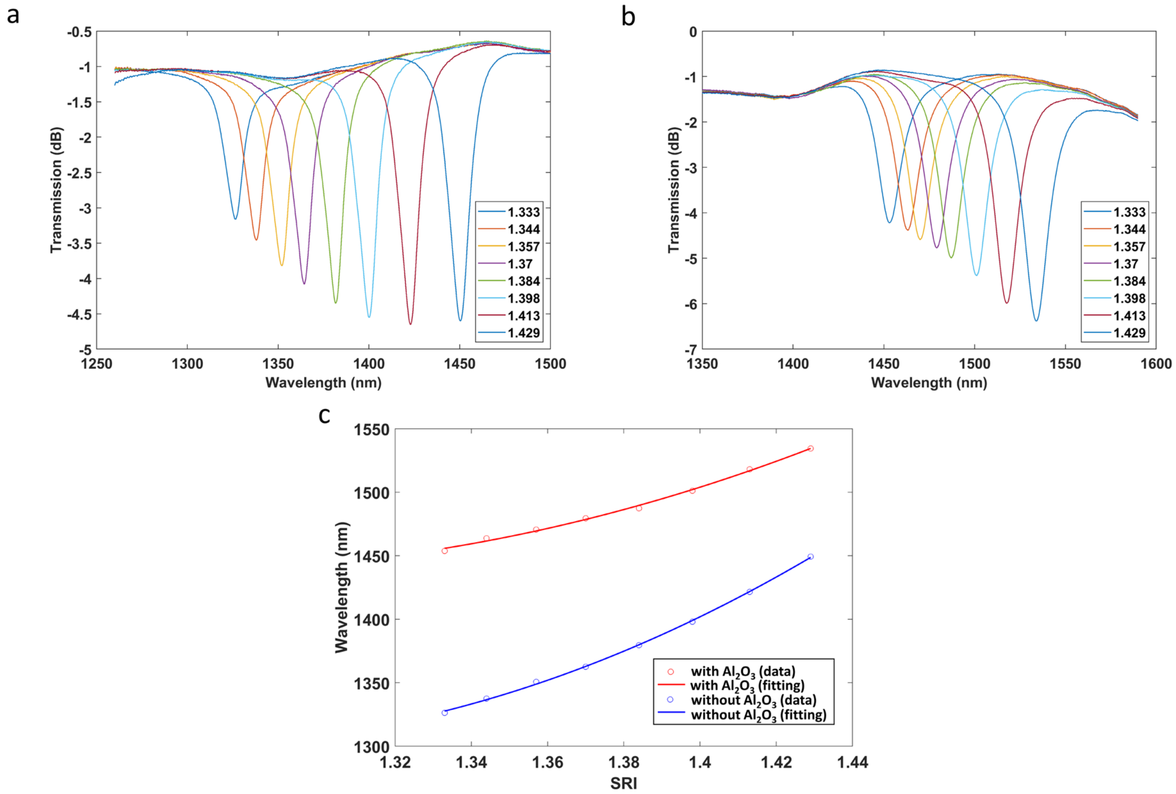

Fig. 3. Transmission spectra for refractive indices ranging from 1.333 to 1.429: (a) 5 layer structure and (b) 5 layer structure + 64 nm Al_2O_3 layer. (c) Sensitivity of both structures

In addition, Fig. 3c shows that the sensitivity is 1281.2 nm RIU^{-1} without Al_2O_3 layer and 835.5 nm RIU^{-1} with Al_2O_3 layer. The FoM also decreases from 256 to 60. The reduction of performances (both sensitivity and FoM) with the Al_2O_3 layer is something expected because an additional low RI layer leads to a reduction in the evanescent field of the wave in the external medium, compared to the case without additional low RI layer.

4. Conclusions

To conclude, it has been experimentally demonstrated that the FoM of 5 attained in the BSWRs generated with a stack of layers of SnO_2 and CuO, with refractive index contrast 0.3 [9], can be increased by using Al_2O_3 and TiO_2, with higher contrast and lower absorption. This has permitted to multiply the FoM by 50 in one of the two cases analyzed opening the path to obtaining structures with an improved performance compared to the single application of a thin film. The degrees of freedom of the proposed structure are numerous, as it is demonstrated here with the deposition of a final layer of Al_2O_3, which leads to a decrease in sensitivity. This confirms the idea explored in[9] that the material and the thickness of the last layer is critical for the performance of the device. The last layer tunes the position of the resonance and at the same time rules the sensitivity. Therefore, monitoring the wavelength shift of the resonance during the deposition of the last layer will the next step to follow in the path towards optimizing this type of structures and use them in challenging domains, such as chemical sensors and biosensors.

5. Acknowledgements

This work was supported by the National Science Centre (NCN), Poland, OPUS program, project No. 2019/35/B/ST7/04388, and the National Centre for Research and Development (NCBiR), Poland, as a part of TECHMATSTRATEG-III/0042/2019 project. Support received from Mr. Tomasz Gabler within ALD experiments is also acknowledged. The authors also acknowledge the support of the Spanish Ministerio de Ciencia e Innovación (PID2019-106231RB-I00 and PDI2019-104276RB-I00), the FPI program grant, the Universidad Nacional de Colombia–Sede Medellín through the Postdoctoral Internship Program (Hermes code 53395) and the Instituto Tecnológico Metropolitano (project P20212).

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