Bimodal waveguide sensors enabled by subwavelength grating structures

Luis Torrijos-Morán, Amadeu Griol and Jaime García-Rupérez
Nanophotonics Technology Center, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
jaigarru@ntc.upv.es

Abstract: A subwavelength grating sensor based on a bimodal waveguide configuration is presented for continuous in-flow measurements of refractive index variations. An experimental bulk sensitivity of 1350nm/RIU and a limit of detection of $2x10^{-5}$RIU is obtained in a single-channel refractive index sensor. Author(s) [10-point type, centered]
OCIS codes: 000.0000, 999.9999. [8-pt. type] For codes, see http://www.osapublishing.org/submit/ocis/

1. Introduction

Subwavelength grating (SWG) waveguides have attracted considerable research effort from the scientific community over the last years. They are composed by a periodic arrange of dielectric elements with a lattice constant smaller than the wavelength of light, which propagates without losses through the structure as if it were an homogeneous medium. Compared to conventional waveguides, SWG waveguides present a stronger field interaction with the cladding and additional dispersive properties [1,2]. This fact has been extensively exploited in the literature to develop refractive index sensors such as SWG ring resonators, for instance [3]. On the other hand, bimodal interferometric waveguides have also been reported for several biosensing purposes, carrying out the sensing operation as a result of the effective index difference existing between the first two modes supported by an uniform waveguide, one acting as a reference and the other as a sensing signal [4,5].

Within this context, we propose a new sensor concept taking advantage from the inherent dispersion obtained in a SWG bimodal waveguide working near the Bragg reflection regime [6,7]. As a result, we obtained an ultra-sensitive single-channel refractive index sensor for spectral-based interrogations systems. Here, we present the characterization of the sensing performance of a SWG bimodal waveguide for continuous in-flow measurements of refractive index variations using ethanol dilutions in deionized water (DIW). The bimodal SWG sensor design is studied and experimentally demonstrated for high-sensitivity bulk refractive index sensing.

2. Sensor concept

The sketch of the design is shown in Fig. 1(a) where a single-mode input and output waveguides supporting the fundamental transverse-electric (TE) mode are disposed in the interface with the bimodal SWG waveguide. Due to symmetry conditions, the first two even and odd modes of the same polarization are excited within the periodic elements, creating an interference pattern at the exit as a result of the different propagation constants obtained. The designing parameters are periodic pitch Λ=280nm, element width w_i=180nm, length w_e=1400nm, single-mode waveguide width w_s=450nm displaced a distance of 350nm from the x=0 point, and height h=220nm. Since we are working in a dispersive region of the SWG waveguide, the phase shift between both modes remain almost constant for a wide range of wavelengths, as it is explained in [6]. This effect has been used in other SWG designs to develop, for example, broadband beamsplitters where a uniform beat length is obtained for a large operation bandwidth [8]. For sensing purposes, we can also benefit from this phenomenon by measuring the spectral shift of a given spectral fringe in the transmission spectrum. Since there is a flat phase shift response between both modes, large spectral shifts will be obtained for changes in the refractive index of the cladding, therefore drastically increasing the bulk sensitivity of the sensor.

3. Results and conclusions

The complete design has been fully etched in a Silicon-on-insulator (SOI) substrate of 220nm silicon height with a buried silica layer of 2 microns. Electron beam lithography has been employed in the exposure process on a HSQ negative resist, and an inductively coupled plasma etching has been used to transfer the resist patterns into the wafer. To carry out the experiments, the photonic sample has been placed on a metal holder fixed with vacuum. Light has been vertically coupled into the chip by using grating couplers and a tunable laser (Keysight 81980) synchronized with a power meter (Keysight 81636B) to measure the transmitted power at the output. A polydimethylsiloxane (PDMS) cell and a pump has been used to flow the ethanol in DIW dilutions at 20µl/min rate over the sample, see Fig. 1 (b).

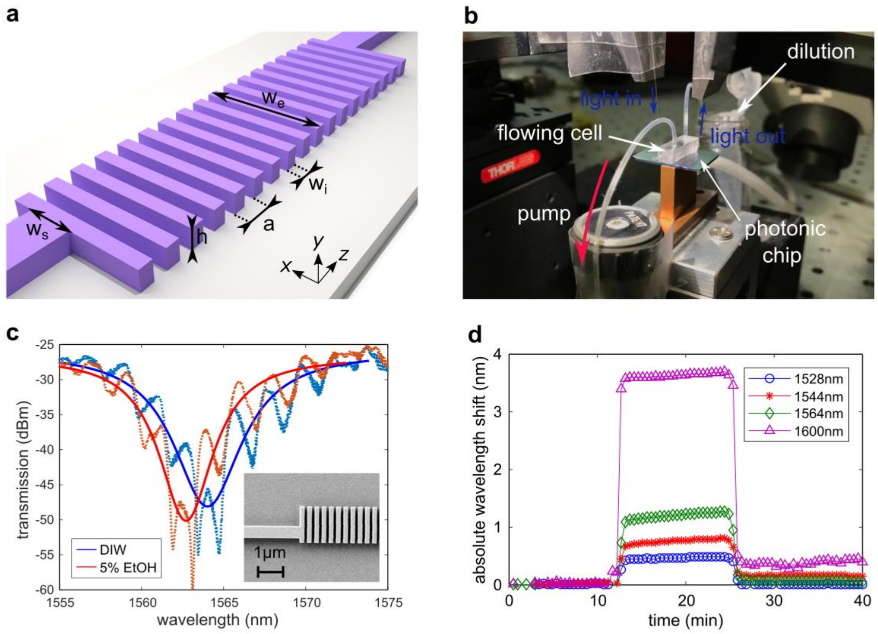

Fig. 1 (a) Sketch of the bimodal SWG sensor presented. (b) Setup used for the experimental measurements, involving the optical characterization and the flowing system. (c) Spectra for pure DIW and 5% of ethanol dilution and the Lorentzian fitting applied. The inset shows the SEM image of the fabricated structure (d) Optical wavelength shift of the spectral fringes for a 5% of ethanol in DIW dilution over 40 minutes time. First 10 minutes of pure DIW, 15 minutes of 5% ethanol in DIW and DIW again for the last 15 minutes.

Figure 1(c) inset shows a scanning electron microscope (SEM) image of the fabricated structure. In order to carry out the refractive index experiments, continuous data of the transmission spectra have been recorded by a LabVIEW software. A Lorentzian fitting has been processed on the destructive spectral fringes and the minima points have been monitored. In Fig. 1(c) we can see the spectra shift towards lower wavelengths under an increment of the cladding refractive index by introducing the ethanol in DIW dilution. Figure 1 (d) depicts the results of the wavelength shifts obtained for four different spectral fringes placed at 1528nm, 1544nm 1564nm and 1600nm, when flowing 5% of ethanol in DIW at minute 10 for 10 minutes. As it can be seen, the wavelength shift increases with wavelength, since those spectral features are located at a flatter phase shift region in the spectra. Consequently, the higher spectral shift is obtained for the 1600nm fringe, corresponding to a measured bulk sensitivity of 1350nm/RIU. Considering the measured noise in the experiment as the standard deviation of the baseline wavelength shift, we obtain a limit of detection of $2x10^{-5}$ RIU.

To summarize, continuous in-flow measurements of ethanol dilutions in DIW have been presented by using a bimodal SWG sensor. Due to the dispersion characteristics of SWG structures, high bulk experimental sensitivities and low limit of detection are presented, which validates these kinds of sensors for future biosensing applications.

4. References

1. P. Cheben, R. Halir, J. H. Schmid, H. A. Atwater, and D. R. Smith, "Subwavelength integrated photonics," Nature **560**(7720), 565–572 (2018).
2. J. G. Wangüemert-Pérez, A. Hadij-ElHouati, A. Sánchez-Postigo, J. Leuermann, D. X. Xu, P. Cheben, A. Ortega-Moñux, R. Halir, and Í. Molina-Fernández, "Subwavelength structures for silicon photonics biosensing," Opt. Laser Technol. **109**, 437–448 (2019).
3. J. Flueckiger, S. Schmidt, V. Donzella, A. Sherwali, D. M. Ratner, L. Chrostowski, and K. C. Cheung, "Sub-wavelength grating for enhanced ring resonator biosensor," Opt. Express **24**(14), 15672–15686 (2016).
4. K. E. Zinoviev, A. B. González-Guerrero, C. Domínguez, and L. M. Lechuga, "Integrated bimodal waveguide interferometric biosensor for label-free analysis," J. Light. Technol. **29**(13), 1926–1930 (2011).
5. D. Duval, A. B. González-Guerrero, S. Dante, J. Osmond, R. Monge, L. J. Fernández, K. E. Zinoviev, C. Domínguez, and L. M. Lechuga, "Nanophotonic lab-on-a-chip platforms including novel bimodal interferometers, microfluidics and grating couplers," Lab Chip **12**(11), 1987–1994 (2012).
6. L. Torrijos-Morán and J. García-Rupérez, "Single-channel bimodal interferometric sensor using subwavelength structures," Opt. Express **27**(6), 8168–8179 (2019).
7. L. Torrijos-Morán, A. Griol, and J. García-Rupérez, "Experimental study of subwavelength grating bimodal waveguides as ultrasensitive interferometric sensors," Opt. Lett. **44**(1), 4702–4705 (2019).
8. R. Halir, P. Cheben, J. M. Luque-González, J. D. Sarmiento-Merenguel, J. H. Schmid, G. Wangüemert-Pérez, D. X. Xu, S. Wang, A. Ortega-Moñux, and Í. Molina-Fernández, "Ultra-broadband nanophotonic beamsplitter using an anisotropic sub-wavelength metamaterial," Laser Photonics Rev. **10**(6), 1039–1046 (2016).