ÓPTICA PURA Y APLICADA
www.sedoptica.es

Type: REVIEW PAPER
Section: SENSORS AND PHOTONICS DEVICES

Fiber optics - A new route to surface wave sensors with ultra-wide refractive index sensing range and ultra-high figure of merit

Fibras ópticas - Una nueva ruta hacia los sensores de ondas superficiales con un rango de detección de índice de refracción ultra amplio y una figura de mérito ultra alta

Esteban Gonzalez-Valencia[1,2*], Pedro Torres[1]

1. Escuela de Física, Universidad Nacional de Colombia - Sede Medellín, A.A. 3840 Medellín, Colombia.

2. Department of Electronic and Telecommunications Engineering, Instituto Tecnológico Metropolitano, Medellín, Colombia.

(*) E-mail: egonzalv@unal.edu.co

Received: 10/29/2021 Accepted: 22/01/2022
DOI: 10.7149/OPA.55.1.51074

ABSTRACT:

Bloch surface waves (BSWs) exploit the bandgap of a photonic crystal to obtain guiding of a surface wave, resulting in a surface-sensitive evanescent field that offers new opportunities for controlling the light propagation and has many applications in areas of the physical and biological sciences. Most of the applications based on BSW excitation exploit the prism-based Kretschmann-Raether configuration, which is often bulky and difficult for integration due to the use of prism. The integration of fiber optics with micro/nano-technology has given the opportunity to develop novel sensing schemes for real applications. In this paper, we present our more recent results on the design and realization of fiber optic configurations to excite BSWs. We aim to provide an overview of the results achieved with each configuration, as a proof of the versatility and great potential of this technology.

Key words: Surface waves; Bloch surface waves; Photonic crystal; Fiber design and fabrication; Fiber optic sensors

RESUMEN:

Las ondas de superficie de Bloch (BSW) aprovechan la banda prohibida de un cristal fotónico para lograr el guiado de una onda de superficie, lo que da como resultado un campo evanescente sensible a la superficie que ofrece nuevas oportunidades para controlar la propagación de la luz y tiene muchas aplicaciones en áreas de las ciencias físicas y biológicas. La mayoría de las aplicaciones basadas en la excitación de las BSW explotan la configuración de Kretschmann-Raether basada en prismas, que a menudo es voluminosa y difícil de integrar debido al uso de prismas. La integración de la fibra óptica con micro/nanotecnología ha brindado la oportunidad de desarrollar nuevos esquemas de sensado para aplicaciones reales. En este artículo, presentamos los resultados más recientes que hemos conseguido en el diseño y realización de configuraciones de fibra óptica para excitar BSW. Nuestro objetivo es ofrecer una visión general de los resultados obtenidos con cada configuración, como prueba de la versatilidad y el gran potencial de esta tecnología.

Palabras clave: Ondas de superficie; ondas de superficie de Bloch; cristales fotónicos; diseño y fabricación de fibra óptica; sensores de fibra óptica

REFERENCES AND LINKS / REFERENCIAS Y ENLACES

[1] A. K. Sharma, R. Jha, and B. D. Gupta, "Fiber-Optic Sensors Based on Surface Plasmon Resonance: A Comprehensive Review," Sensors Journal, IEEE **7**(8), 1118–1129 (2007).

[2] J. a. Polo, T. G. Mackay, and A. Lakhtakia, *Electromagnetic Surface Waves: A Modern Perspective*, 1st ed. (Elsevier, 2013).
[3] P. Berini, "Long-range surface plasmon polaritons," Adv. Opt. Photonics **1**(3), 484 (2009).
[4] N. Gomez-Cardona, E. Reyes-Vera, and P. Torres, "High sensitivity refractive index sensor based on the excitation of long-range surface plasmon polaritons in H-shaped optical fiber," Sensors **20**, 11 (2020).
[5] J. Dostálek, A. Kasry, and W. Knoll, "Long range surface plasmons for observation of biomolecular binding events at metallic surfaces," Plasmonics **2**(3), 97–106 (2007).
[6] Y. Xu, P. Bai, X. Zhou, Y. Akimov, C. E. Png, L. K. Ang, W. Knoll, and L. Wu, "Optical Refractive Index Sensors with Plasmonic and Photonic Structures: Promising and Inconvenient Truth," Adv. Opt. Mater. **7**(9), (2019).
[7] D. J. J. Hu, H. P. Ho, and R. M. Day, "Recent advances in plasmonic photonic crystal fibers: design, fabrication and applications," Adv. Opt. Photonics **9**(2), 257–314 (2017).
[8] E. Gonzalez-Valencia, I. Del Villar, and P. Torres, "Novel Bloch wave excitation platform based on few-layer photonic crystal deposited on D-shaped optical fiber," Sci. Rep. **11**(1), 1–11 (2021).
[9] R. Alonso, F. Villuendas, J. Tornos, and J. Pelayo, "New "in-line" optical-fibre sensor based on surface plasmon excitation," Sensors Actuators A. Phys. **37–38**(C), 187–192 (1993).
[10] Q. Xie, Y. Chen, X. Li, Z. Yin, L. Wang, Y. Geng, and X. Hong, "Characteristics of D-shaped photonic crystal fiber surface plasmon resonance sensors with different side-polished lengths," Appl. Opt. **56**(5), 1550 (2017).
[11] A. T. Andreev, B. S. Zafirova, E. I. Karakoleva, A. O. Dikovska, and P. A. Atanasov, "Highly sensitive refractometers based on a side-polished single-mode fibre coupled with a metal oxide thin-film planar waveguide," J. Opt. A Pure Appl. Opt. **10**(3), 035303 (2008).
[12] R. Jha, R. K. Verma, and B. D. Gupta, "Surface plasmon resonance-based tapered fiber optic sensor: Sensitivity enhancement by introducing a teflon layer between core and metal layer," Plasmonics **3**(4), 151–156 (2008).
[13] A. B. Socorro, I. Del Villar, J. M. Corres, F. J. Arregui, and I. R. Matias, "Tapered single-mode optical fiber pH sensor based on lossy mode resonances generated by a polymeric thin-film," IEEE Sens. J. **12**(8), 2598–2603 (2012).
[14] T. Tu, F. Pang, S. Zhu, J. Cheng, H. Liu, J. Wen, and T. Wang, "Excitation of Bloch surface wave on tapered fiber coated with one-dimensional photonic crystal for refractive index sensing," Opt. Express **25**(8), 9019–9027 (2017).
[15] C. Vandenbem, "Electromagnetic surface waves of multilayer stacks: coupling between guided modes and Bloch modes," Opt. Lett. **33**(19), 2260 (2008).
[16] E. Descrovi, T. Sfez, L. Dominici, W. Nakagawa, F. Michelotti, F. Giorgis, and H.-P. Herzig, "Near-field imaging of Bloch surface waves on silicon nitride one-dimensional photonic crystals," Opt. Express **16**(8), 5453–5464 (2008).
[17] M. Ballarini, F. Frascella, F. Michelotti, G. Digregorio, P. Rivolo, V. Paeder, V. Musi, F. Giorgis, and E. Descrovi, "Bloch surface waves-controlled emission of organic dyes grafted on a one-dimensional photonic crystal," Appl. Phys. Lett. **99**(4), 043302 (2011).
[18] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the Flow of Light*, 2nd ed. (Princeton University Press, 2008).
[19] S. Pirotta, M. Patrini, M. Liscidini, M. Galli, G. Dacarro, G. Canazza, G. Guizzetti, D. Comoretto, and D. Bajoni, "Strong coupling between excitons in organic semiconductors and Bloch surface waves," Appl. Phys. Lett. **104**(5), 13–16 (2014).
[20] K. V. Sreekanth, S. Zeng, J. Shang, K.-T. Yong, and T. Yu, "Excitation of surface electromagnetic waves in a graphene-based Bragg grating," Sci. Rep. **2**(1), 737 (2012).
[21] P. Yeh, A. Yariv, and C.-S. Hong, "Electromagnetic propagation in periodic stratified media. I. General theory," J. Opt. Soc. Am. **67**(4), 423–438 (1977).
[22] P. Yeh, A. Yariv, and A. Y. Cho, "Optical surface waves in periodic layered media," Appl. Phys. Lett. **32**(2), 104–105 (1978).
[23] E. Gonzalez-Valencia, R. Acuna Herrera, and P. Torres, "Bloch surface wave resonance in photonic crystal fibers: towards ultra-wide range refractive index sensors," Opt. Express **27**(6), 8236–8245 (2019).
[24] A. Sinibaldi, N. Danz, E. Descrovi, P. Munzert, U. Schulz, F. Sonntag, L. Dominici, and F. Michelotti, "Direct comparison of the performance of Bloch surface wave and surface plasmon polariton sensors," Sensors Actuators, B Chem. **174**, 292–298 (2012).
[25] A. L. Lereu, M. Zerrad, A. Passian, and C. Amra, "Surface plasmons and Bloch surface waves: Towards optimized ultra-sensitive optical sensors," Appl. Phys. Lett. **111**(1), (2017).
[26] M. Gryga, D. Ciprian, and P. Hlubina, "Bloch surface wave resonance based sensors as an alternative to surface plasmon resonance sensors," Sensors (Switzerland) **20**(18), 1–16 (2020).
[27] J. Homola, S. S. Yee, and G. Gauglitz, "Surface plasmon resonance sensors: review," Sensors Actuators B Chem. **54**(1), 3–15 (1999).
[28] S. Li, J. Liu, Z. Zheng, Y. Wan, W. Kong, and Y. Sun, "Highly Sensitive, Bloch Surface Wave D-Type Fiber Sensor," IEEE Sens. J. **16**(5), 1200–1204 (2016).
[29] X.-J. Tan and X.-S. Zhu, "Optical fiber sensor based on Bloch surface wave in photonic crystals," Opt. Express **24**(14), 16016–16026 (2016).
[30] M. Scaravilli, A. Micco, G. Castaldi, G. Coppola, M. Gioffrè, M. Iodice, V. La Ferrara, V. Galdi, and A. Cusano, "Excitation of Bloch Surface Waves on an Optical Fiber Tip," Adv. Opt. Mater. **6**(19), 1–10 (2018).

[31] P. Russell, "Photonic Crystal Fibers," Science (80-.). **299**(5605), 358–362 (2003).
[32] E. Gonzalez-Valencia, I. Del Villar, and P. Torres, "Bloch waves at the surface of a single-layer coating D-shaped photonic crystal fiber," Opt. Lett. **45**(9), 2547–2550 (2020).
[33] V. Zamora, A. Díez, M. V. Andrés, and B. Gimeno, "Cylindrical optical microcavities: Basic properties and sensor applications," Photonics Nanostructures - Fundam. Appl. **9**(2), 149–158 (2011).
[34] P. Jia and J. Yang, "A plasmonic optical fiber patterned by template transfer as a high-performance flexible nanoprobe for real-time biosensing," Nanoscale **6**(15), 8836–8843 (2014).
[35] R. Tabassum and B. D. Gupta, "Influence of Oxide Overlayer on the Performance of a Fiber Optic SPR Sensor with Al/Cu Layers," IEEE J. Sel. Top. Quantum Electron. **23**(2), 81–88 (2017).
[36] Z. Li, T. Chen, Z. Zhang, Y. Zhou, D. Li, and Z. Xie, "Highly sensitive surface plasmon resonance sensor utilizing a long period grating with photosensitive cladding," Appl. Opt. **55**(6), 1470 (2016).
[37] X. Qiu, X. Chen, F. Liu, B. O. Guan, and T. Guo, "Plasmonic Fiber-Optic Refractometers Based on a High Q-Factor Amplitude Interrogation," IEEE Sens. J. **16**(15), 5974–5978 (2016).
[38] I. Del Villar, P. Zubiate, C. R. Zamarreño, F. J. Arregui, and I. R. Matias, "Optimization in nanocoated D-shaped optical fiber sensors," Opt. Express **25**(10), 10743–10756 (2017).
[39] P. Zubiate, C. R. Zamarreño, I. Del Villar, I. R. Matias, and F. J. Arregui, "High sensitive refractometers based on lossy mode resonances (LMRs) supported by ITO coated D-shaped optical fibers," Opt. Express **23**(6), 8045 (2015).
[40] A. Urrutia, I. Del Villar, P. Zubiate, and C. R. Zamarreño, "A Comprehensive Review of Optical Fiber Refractometers: Toward a Standard Comparative Criterion," Laser Photonics Rev. **13**(11), 1–32 (2019).
[41] A. Ozcariz, C. R. Zamarreño, P. Zubiate, and F. J. Arregui, "Is there a frontier in sensitivity with Lossy mode resonance (LMR) based refractometers?," Sci. Rep. **7**(1), 1–7 (2017).

1. Introduction

Electromagnetic surface waves (ESWs) are a specific type of wave that are confined at the interface between two different media and decay exponentially into the neighbouring media, which are widely studied due to their potential applications in photonic devices and sensing applications in areas such as biology, chemistry, physics, among others [1]. The first observed ESWs were the surface plasmon polaritons (SPPs), which are surface waves located at the interface between a metal film and a dielectric medium. SPPs are characterized by a strong absorption of the metal layer [1,2], which leads to the broadening of resonance band and reduction in surface evanescent enhancement, thereby posing an upper limit to the overall figure of merit (FoM) and limits the scalability of such structures to short propagation lengths. Long-range surface plasmons (LRSPs) were proposed as a way to improve the performance of SPPs, making use of their longer propagation length and narrower resonances [3,4]. However, coupling for LRSP is strongly dependent on a refractive index (RI) symmetry requirement of media surrounding the thin metal film, which might limit the range of usable buffer solutions for analyte detection [5]. Therefore, there is a high interest in surface waves between two dielectric media, since the ESWs can propagate at the interface with minimum losses, whereby the ESW resonances appear much narrower than those observed for surface plasmons, with an expected increase of device performance.

At the same time, most of the proposed applications based on ESW excitation exploit the well know Kretschmann-Raether configuration, employing a high RI prism coated on its base by a thin metallic film/dielectric structure, and the ESWs are excited in the interface between the surface thin film and its surrounding medium by the attenuated total reflection (ATR) mechanism. Metallic grating structures have also been exploited to excite ESWs [6]. However, ESW excitation in optical fibers is considered a more compact, lightweight, and robust alternative, with potential for remote and live monitoring applications, and for "lab-on-fiber" platforms that can be applied for communication and sensing purposes [7,8]. The interest on this topic has started growing in recent years, as witnessed by theoretical and experimental studies of ESW sensors based on the use of metal/dielectric-coated side-polished fibers [8–11], also known as D-shaped fibers, and tapered fibers [12–14]. In both cases, ESW excitation is achieved when the evanescent field of the core-guided light resonates with a surface mode in the deposited thin film, whose excitation conditions strongly depend on the surrounding medium.

In this paper, we present our more recent results on fiber optic configurations to excite Bloch surface waves (BSW), also called surface states of photonic crystals [15], which are ESWs confined at the interface between a homogeneous dielectric medium and an abruptly terminated photonic crystal (PC). BSWs offer several possible advantages compared to SPP. First, due to the use of dielectric materials the losses are very low, allowing for sharper resonances and longer propagation lengths. The use of a PC provides greater freedom in the operating wavelengths than SPP, which is limited to a narrow range of metal dependent wavelengths. The PC can be designed to sustain both TE and TM polarized BSW, a condition that cannot be achieved with SPP as they are only TM polarized. Additionally, PC based BSW sensors are more chemically robust since the dielectric layers are intrinsically inert to the ambient chemicals. With this same platform, sensors with improved characteristics for biosensing can be developed by suitably changing the geometry and materials of the PC. In this case, to study the sensing performance, both sensitivity and figure of merit are typically evaluated, defined as $S_n=\partial\lambda/\partial n_s$ and FoM=S_n/FWHM, respectively, where, on the one hand, λ and n_s are the BSW resonant wavelength and the surrounding RI, respectively, and FWHM, on the other hand, is full width at half-maximum of the resonance peak.

2. BSW excitation

The optical properties of the two media determine the nature of the ESW that can be sustained. One of the most relevant ESWs in dielectric interfaces are the BSWs [16], which consists of electromagnetic waves that propagate at the interface between two dielectric media, where at least one of them is a PC. In the simplest case, the PC consists of alternating layers of different RI media, also called one-dimensional photonic crystal (1DPC) or Bragg reflector [16,17]. The surface confinement is due to total internal reflection from the side of the homogeneous dielectric and to the photonic bandgap in the PC [18,19]. Additionally, the design of the PC is wavelength scalable and may be designed to sustain TE- and/ or TM-polarized BSWs at a broad range of wavelengths from near UV to IR [20].

BSWs were first reported theoretically and later observed experimentally in the 1970s [21, 22]. However, recent advances in thin film deposition allowed to increase the design possibilities and renovate the interest in ESWs in dielectric interfaces [23]. BSW excitation using the prism-based Kretschmann-Raether configuration has been used in applications such as BSW based sensors, guided optical applications based on BSW, and BSW-controlled fluorescence [23]. In recent years, there appear a few experimental and theoretical comparison studies between SPP- and BSW-based sensors [24–26]. For example, a direct experimental comparison of the sensing performance for SPP- and BSW-based biosensors was reported by Sinibaldi et al. [24] in 2012. Recently, a numerical study on comparing BSW and SPP sensors has shown that SPP has higher angular sensitivity, but lower FoM as compared to BSW sensor [25]. More recently, SPP and BSW resonances were resolved in the Kretschmann-Raether configuration when the wavelength interrogation method is utilized [26], demonstrating that the BSW based sensor has a similar sensitivity as the SPP based sensor, but outperforms it in the FoM.

3. Fiber-coupled BSW

Optical waveguide coupled ESW sensors should reach similar sensitivity as those prism-coupled configurations [27]. In an optical fiber waveguide, light is strongly confined in the fiber core, therefore, for sensing applications, some modifications must be made to the optical fibers for the access of the core-guided light and the coupling to ESW. The first fiber optic BSW-based sensor design was proposed in 2016 [28], where 1DPC has been deposited on the flat surface of a D-shaped single-mode fiber polished to the fiber core. Furthermore, designs of 1DPCs deposited on omnidirectional one-dimensional multi-mode optical fiber [29], on a tapered fiber [14], and at the tip of a single-mode fiber [30] have been considered. As shown in Fig. 1, all these proposed structures have in common that the fiber core acts as the prism in the Kretschmann-Raether configuration, they have a large number of layers [28–30] with a very high RI contrast [14, 28, 29].

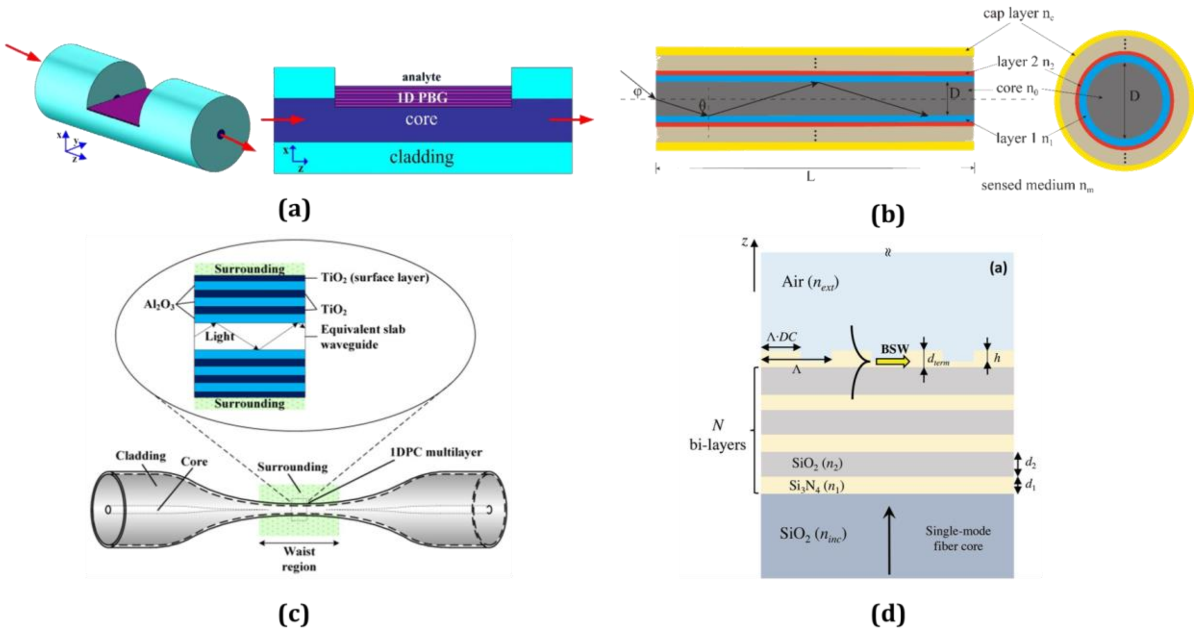

Fig.1. Fiber optic BSW sensors where the fiber core acts as the prism in the Kretschmann-Raether configuration: (a) D-shaped standard fiber polished to the fiber core [28], (b) omnidirectional fiber [29], (c) tapered fiber [14], and (d) fiber tip [30]. (a) Adapted with permission from [28] © IEEE; (b) reprinted with permission from [29] © The Optical Society; (c) reprinted with permission from [14] © The Optical Society; (d) reprinted with permission from [30] © The Optical Society.

The fiber-based BSW can be efficiently excited as long as the effective index of the core-guided mode coincides with that of the BSW. This is known as the resonance or phase matching condition. We recently reported the first experimental observation of BSW excitation in commercial D-shaped optical fiber with few-layer 1DPC deposited on its flat surface using alternating thin layers of SnO_2 (300 nm) and CuO (200 nm) [8]; see Fig. 2a-b. The fiber–optic-based platform enhances the light-matter interaction in a strong way compared to other optical platforms, resulting in a more compact, lightweight, and robust alternative compared to the Kretschmann-Raether prism-based configuration. Although most of the BSW excitation platforms require a large number of layers or materials with a large RI contrast, we demonstrated that even a 3-layer stack on the fiber-based excitation platform can sustain TE-polarized BSWs using a 1DPC consisting of materials that have a small difference in RI, close to 0.3 at the near-infrared region, and relatively low extinction coefficient values. The top layer material and thickness depend on the number of coating layers. The evanescent field of the core-guided mode excites BSW modes on the multilayer structure, which supports the fundamental and higher-order BSW modes, as shown in Fig. 2c.

We also demonstrated the suitability of this platform as refractometer. When the surrounding medium is changed, the evanescent field of the BSW will be affected, and, thereby, the phase matching condition will be altered. For example, the 6-layer structure achieved a sensitivity of 508 nm/RIU, as shown in Fig. 3. The sensitivity of this structure is comparable to other surface-wave-based sensing structures, including some BSW-based structures, paving the way for the development of chemical sensors or biosensors. The designed structure is easy to manufacture and could be adapted to a wide range of applications in the fields of telecommunications, environment, health, and material characterization [8].

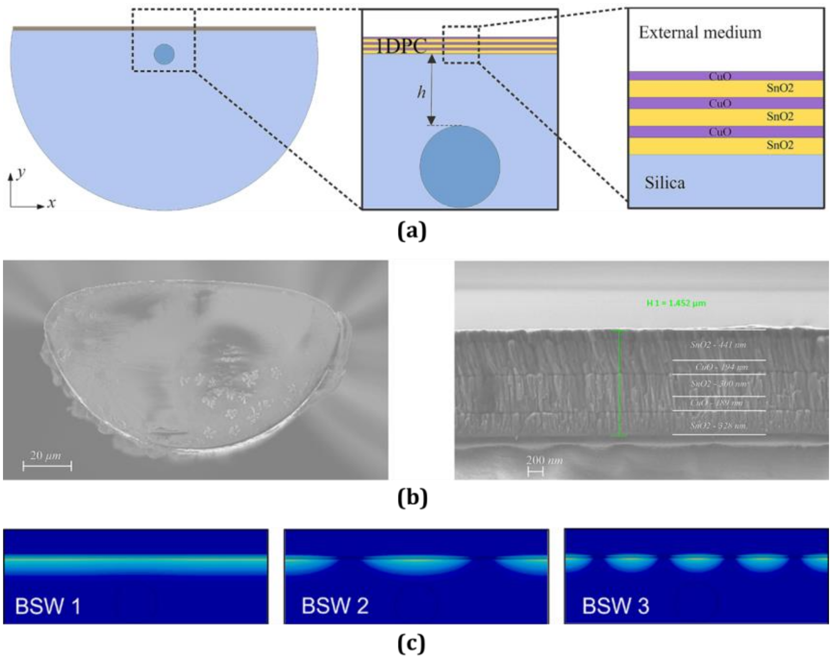

Fig.2. BSW excitation platform based on D-shaped optical fibers. (a) Schematic of the designed structure. (b) SEM images of the fiber cross-section with 5-layer 1DPC. (c) Electric field distribution of the BSW modes supported by the multilayer structure. Adapted from [8].

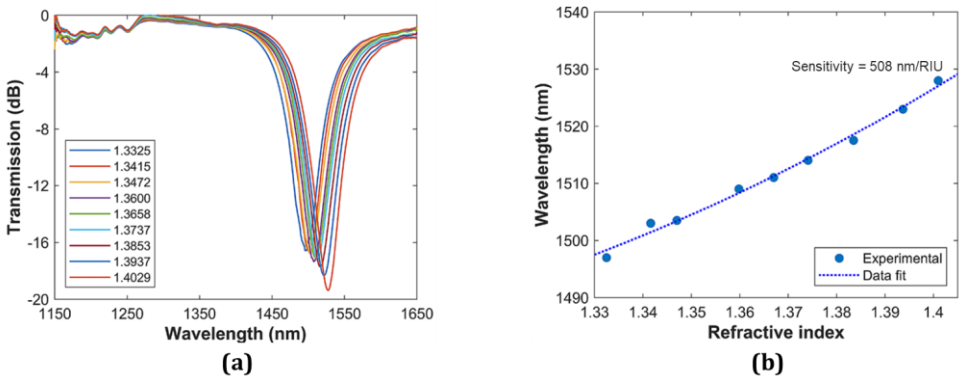

Fig.3. BSW excitation as a function of the surrounding RI: (a) Transmission spectra, (b) resonance wavelength shift. Adapted from [8].

Fiber-coupled BSW can be optimized with the use of a suitable optical platform, such as photonic crystal fibers (PCFs), which offers several advantages over conventional fibers [23,31]. Due to the design flexibility of the PCF, such as the diameter and distribution of the air holes and the air hole spacing, it enables the realization of various applications that are not possible to achieve using conventional fiber. Recently, we proposed the use of a Ge-doped suspended-core three-hole silica PCF, with a 4-period TiO_2/SiO_2 1DPC (250/600 nm) deposited on one PCF hole, as shown in Fig. 4. Due to its configuration, the PCF can have exposed regions of the fiber core to accelerate the fluid filling and access the fiber core for real-time sensing [28]. The evanescent field of the cored-guided light can excite TE- and TM-polarized BSW modes, while the top layer thickness determines which surface mode polarization is generated at the designed resonance wavelength.

As shown in Fig. 4b, this kind of structure supports multiple BSW modes leading to obtaining transmission spectra with multiple resonance peaks, as shown in Fig. 4c. Here, because the resonance peaks are narrow, they can be individually identified and tracked. As an example, the BSW1 resonance peak exhibits a sensitivity of 1693 nm/RIU at a surrounding RI of 1.33, which, in combination with its narrow spectral width, achieves an extremely high FoM of 669 RIU^{-1}. When the surrounding RI is 1.4, the sensor sensitivity reaches 2575 nm/RIU, which is comparable to the vast majority of PCF-based SPP sensor [7]. This is the first near-infrared BSW resonance-based PCF sensor that can operate over an ultra-wide range of RI, from

1.0 to 1.4. The structure is simple, easy to fabricate and has potential applications in the sensing of gases, bio-analytes, and liquids of high-RI. Results are promising for high-resolution refractometry [23].

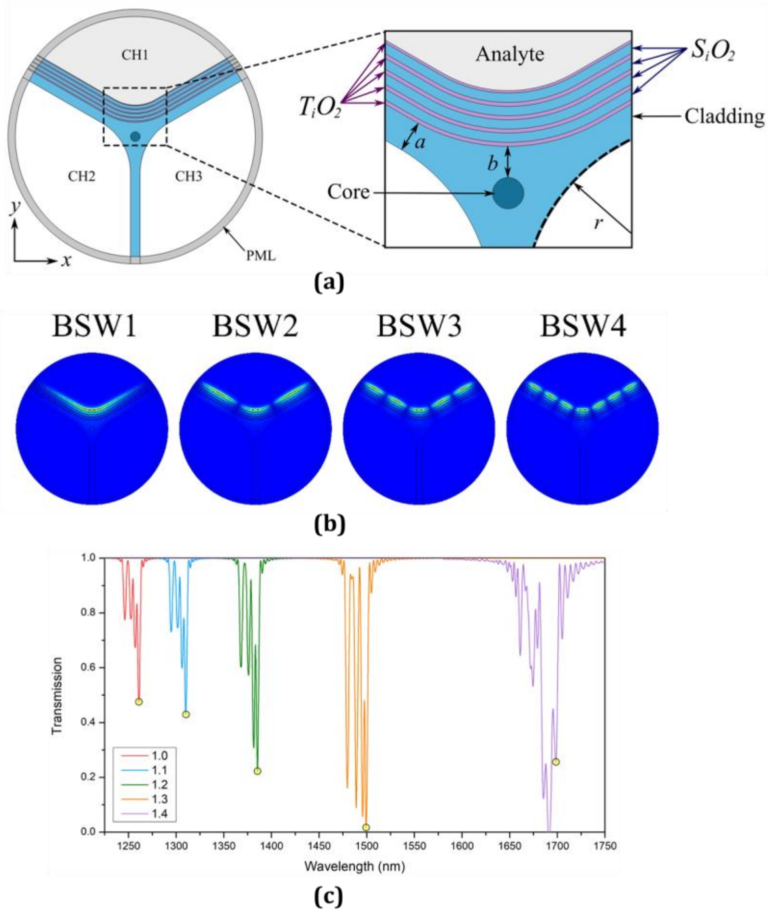

Fig.4. BSW excitation in Ge-doped suspended-core silica PCF with a TiO_2/SiO_2 multilayer structure. (a) Schematic of the Ge-doped suspended-core silica PCF with a 1DPC, designed to sustain BSWs. (b) Electric field distribution of the BSW modes. (c) Transmission spectra as a function of the surrounding RI. Adapted with permission from [23] © The Optical Society.

The BSW excitation in fiber optics has hitherto been limited to a periodic multilayer structure, a much more complicated configuration than in the case of SPPs. As an important step to overcome this drawback, we recently proposed a simpler and more efficient solution to excite BSW modes using PCFs [32]. The designed structure consists of a side-polished commercial triangular PCF, leaving two air hole rows between the flat surface and the PCF core to ensure coupling conditions between these two regions, as shown in Fig. 5a.

Because the PCF cladding constitutes a two-dimensional triangular PC (2DPC), the existence of surface modes depends strongly on the location of the PC termination. In this case, the BSW excitation can be realized with only a single high RI dielectric layer on its flat surface (termination layer in Fig. 5a). As shown in Fig. 5b, BSWs can be efficiently excited by the evanescent field of the core-guided mode and this structure supports multiple BSW modes.

The coupling conditions between the flat surface and the PCF core result in periodic transfer of optical power between these two regions along the fiber and a loss peak at the resonant wavelength appears at the transmission spectrum of the core-guided fundamental mode. As shown in Fig.5(c), loss peaks caused by the BSW excitation can be observed, which are consistent with the resonance wavelengths of the BSW modes in Fig. 5(b). The principal advantage of this structure is that each BSW resonance peak is very narrow and sufficiently separated from neighboring peaks that they can be differentiated and thus paves the way for developing sensors with improved characteristics. This structure can achieve much higher sensitivities than other fiber-based BSW platforms. We demonstrated that a sensitivity of 8800 nm/RIU, with an ultra-high FoM of 2042 RIU^{-1}, could be achieved for the TE-BSW1 mode, and a sensitivity of 7750 nm/RIU, with an ultra-high FoM of 2451 RIU^{-1}, for the TM-BSW1 mode. The resulting values are among the highest FoMs achieved by an optical sensor based on surface waves [32].

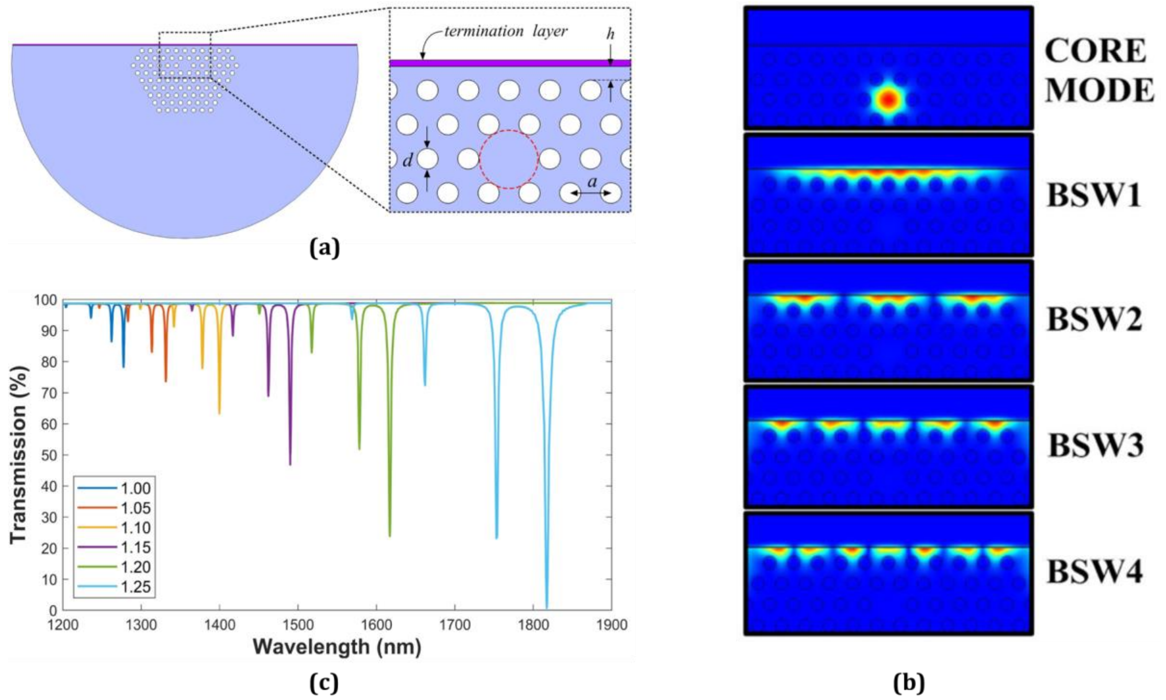

Fig.5. Side-polished solid-core triangular PCF with a termination dielectric layer. (a) Schematic of the designed structure. (b) Core-guided and surface modes supported by the structure. (c) Spectral response of the BSW sensing structure based on single-layer coating D-shaped PCF. Adapted with permission from [32] © The Optical Society.

Table 1 presents a comparison of recently reported fiber optic RI sensors based on ESW excitation. Although there are many other sensing configurations based on ESW, only those designed to detect bioanalytes were included in this table, in consideration of their potential applications in biosensing, and that also reported information on sensor sensitivity, FWHM and FoM. It is possible to highlight that the results obtained with the proposed optical fibers sensors based on BSW excitation are competitive and outperform many other sensor alternatives based on SPP and lossy mode resonances (LMR). Although ESW-based sensors can achieve comparable sensitivities, recent advances on BSW excitation make them an alternative with great potential to optimize the FoM of fiber optic refractometers. As a reference, it has been shown that sensors with an optical fiber-like structure (capillaries) with moderate sensitivity (850 nm/RIU) can show a FoM much higher than that reported for any ESW sensor (close to $4{\times}10^5$ RIU^{-1} assuming the resonance has a linewidth of 2 pm) [33]. Improving processes like this are seen as the next goal to be achieved with ESW-based sensors.

Table 1. Comparison of recently reported ESW-based fiber optic RI sensors.

ESW	FIBER TYPE	SENSITIVITY (nm/RIU)	FWHM (nm)	FoM (RIU^{-1})	REFERENCE	YEAR
SPP	PCF	7540	27	280	[4]	2020
SPP	PCF	595	6.6	60.7	[34]	2014
SPP	Unclad POF[1]	6570	186	35.4	[35]	2017
SPP	LPFG[2]	~4900	~2	~2500	[36]	2017
SPP	TGBG[3]	450	0.26*	1730	[37]	2016
LMR	D-shaped	3770	3.3	1021	[38]	2017
LMR	D-shaped	5855	7	836	[39,40]	2017
LMR	D-shaped	14501	7	2071	[40,41]	2015
BSW	PCF	535	1.7	315	[29]	2016
BSW	PCF	1693	2.5	669	[23]	2019
BSW	D-shaped PCF	8800	4.3	2042	[32]	2020
		7750	3.1	2451		

[1] Plastic optical fiber, [2] Long period fiber grating, [3] Tilted period fiber grating, * Average FWHM.

4. Conclusions

We have presented our more recent results on the design and realization of BSW fiber optic sensing structures. Sensors with Kretschmann-Raether configuration are usually bulky and difficult for integration due to the use of prism. Optical fiber coupling is a good alternative, as the BSWs can be efficiently excited through the evanescent field of the core-guided fundamental mode, which is miniatured, robust, and easily integrated with other optical, electronic, and fluidic components. The coupling conditions between the core-guided fundamental mode and the BSW mode result in a sharp loss peak in the transmission spectrum, creating the necessary conditions for the development of highly sensitive refractometers.

The simplicity of our configuration based on the D-shaped standard optical fiber with few-layer 1DPC deposited on its fat surface makes it a structure with broad development potential for new types of all-fiber photonic devices and sensing applications. On the other hand, the proposed PCF structures achieve sensitivities comparable to other reported ESW fiber optic sensors, but our BSW platform has the advantage of an ultra-high FoM, which makes it attractive for the development of chemical and biological sensors where this parameter is especially important. In particular, the single-layer coating commercial PCF-based structure is simple and easy to manufacture. We are continuing our efforts toward the development of surface wave sensors with ultra-wide RI sensing range and ultra-high figure of merit.

Acknowledgements

This work is partially funded by the Universidad Nacional de Colombia–Sede Medellín through the Postdoctoral Internship Program (Hermes code 53395) and the Instituto Tecnológico Metropolitano, project P20212. E.G.V. acknowledges the support of Minciencias (formerly known as Colciencias) through the Doctoral Scholarship program.

