Plasmonic Photonic Crystal Fibers

Dora Juan Juan Hu and Aaron Ho-Pui Ho

Abstract Surface plasmon waves are coupled electron–photon modes at the metal–dielectric interface. They can significantly enhance light–matter interactions that are favorable in many applications including nanophotonics, data storage, microscopy, solar cells, and sensing. Compared with the prism-based coupling configuration, optical fiber-based plasmonic devices offer more compact and robust configuration for exciting the plasmon modes. Photonic crystal fibers (PCFs) are a special class of optical fibers in which the presence of holey structures or periodic microstructures of refractive index modulations can provide a wide scope of flexibility in the control and engineering of the optical properties, thus opening up the potential for many new applications and scientific explorations. Notably, PCFs are a desirable platform to incorporate plasmonic structures for the excitation of surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR). Three main types of plasmonic PCF structures have been developed and reported in the literature, including metal nano-/microwire-filled plasmonic PCF, metal-coated plasmonic PCF, and nanoparticle-deposited/filled plasmonic PCF. This chapter provides a comprehensive review on the recent progress of these reported plasmonic PCF structures in terms of design and applications. Firstly, the operating principles based on surface plasmon polaritons and localized surface plasmon polaritons are presented. Secondly, the experimental studies of plasmonic PCF structures for various application areas are reviewed, including refractive index sensing, biosensing, temperature sensing, polarization, and birefringent devices. Lastly, design considerations and challenges are discussed.

D. J. J. Hu (✉)
Institute for Infocomm Research, Singapore, Singapore
e-mail: jjhu@i2r.a-star.edu.g

A. H.-P. Ho
Department of Biomedical Engineering,
The Chinese University of Hong Kong, Hong Kong SAR, China
e-mail: aaron.ho@cuhk.edu.hk

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1 Introduction

Plasmonics is an exciting bridging technology for electronics and photonics. The development of plasmonic technologies has led to remarkable capabilities in a wide range of areas such as nanophotonics, magneto-optic data storage, microscopy, solar cells, and sensing applications such as biological and chemical detection (Homola 2008; Barnes et al. 2003). Surface plasmon (SP) waves are coupled electron–photon modes at the boundaries between a metal and a dielectric. Generally, plasmonic sensing devices are categorized into two types: propagating surface plasmon resonance (SPR) sensors and localized surface plasmon resonance (LSPR) sensors. Because of the momentum mismatch between SPs and photons propagating in vacuum, special configurations are needed to excite the plasmon modes.

Plasmonics in optical fibers uses optical field to excite the SP waves, offering better compactness and robustness in comparison with traditional plasmonic devices based on prism coupling configurations. Optical fiber-based plasmonic devices have received wide interest for development and deployment for remote and in situ monitoring applications. The invention of PCF was an important milestone in the history of the optical fiber technology. Compared with conventional fibers, PCFs have the great flexibility to control in the waveguiding properties by modifying the microstructured geometry. For example, the air filling fraction can be engineered to control the refractive index contrast between the core and the cladding to obtain endless single-mode operation. Hollow core guidance can be realized by new light-guiding mechanisms of photonic bandgap effect in the microstructured cladding. PCFs can be characterized by various guiding mechanisms, including index-guiding mechanism, photonic bandgap (PBG)-guiding mechanism, inhibited coupling-guiding mechanism, antiresonance-guiding mechanism, and twist-induced guiding mechanism (Markos et al. 2017). PCFs with hybrid guiding mechanisms of index guiding and PBG guiding and their unique features as well as applications have been reviewed (Hu et al. 2019). The peculiar properties of PCFs have attracted enormous research interest to unlock their great potential in various applications. PCFs have undergone tremendous development in the past two decades for sensing, communication, and medical applications (Knight 2003; Russell 2003). In particular, PCF-based sensor devices have demonstrated superior performance in terms of sensitivity, versatility, sensing range, etc (Pinto and Lopez-Amo 2012; Villatoro and Zubia 2016; Hu et al. 2018). For example, the photonic bandgap effect in PCFs has enabled hollow core light guidance for gas sensing application (Debord et al. 2019). Moreover, the air hole channels in PCFs allow efficient integration of other functional materials to greatly enhance the tunability of optical properties and significantly expand the functionality of the fibers, such as sensing applications using PCFs as an optofluidic platform (Ertman et al. 2017). PCFs have brought new developments to fiber lasers and nonlinear optics (Knight 2007; Knight and Skryabin 2007; Travers et al. 2011).

Integrating plasmonic structures in PCF platforms has created many opportunities by leveraging on the flexibilities of the PCF platform to achieve better performance or to develop new devices for sensing applications. The works on plasmonic PCFs and their applications were reviewed in Yang et al. (2011), Zhao et al. (2014), Hu and Ho (2017). The reported plasmonic PCF structures can be broadly categorized in three types, i.e., metal nano-/microwire-filled plasmonic PCF structures, metal-coated plasmonic PCF structures, and nanoparticle-deposited/filled plasmonic PCF structures. In this chapter, we start with a discussion of the operating principles of the plasmonic PCF structures, mainly based on surface plasmon polaritons (SPPs) and localized surface plasmon polaritons (LSPPs). The excitation of the SPPs/LSPPs in the three types of plasmonic PCF structures is discussed. Subsequently, a review of applications based on plasmonic PCF structures is presented. The review in this chapter is focused on the experimental investigations. The fabrication techniques of plasmonic PCF structures and simulation studies of plasmonic PCF structures for various applications are referred to an earlier review article (Hu and Ho 2017).

2 Overview of PCFs

PCF technology is a revolutionary breakthrough in optical fiber technology. It has opened up new possibilities of light guidance mechanism and brought tremendous potential in a broad range of applications with performance enhancements. Based on different light-guiding mechanisms, the PCFs can be broadly categorized into two main groups. The first group of PCFs guide light by modified total internal reflection (TIR) or index-guiding mechanism. The effective refractive index of the core region is higher than that of the cladding region. The index contrast can be flexibly controlled by altering the air filling fraction of the holey cladding, resulting in enhanced tunabilities in optical properties or enhanced optical performance. Index-guiding PCFs are finding applications in highly nonlinear optical devices, high power delivery, polarization-maintaining fibers, dispersion-tailored fibers, etc. The second group of PCFs guide light by photonic bandgap (PBG) effect. The effective refractive index of the core region is lower than that of the cladding region; thus, TIR or index guiding is impossible for light confinement in such fiber structures. The light confinement in lower refractive index core region is realized by photonic crystal effect in the microstructured cladding, prohibiting light transmission in the cladding. PBG-guided PCFs such as hollow core PCFs and Bragg fibers are finding applications in high power delivery, gas-based nonlinear devices, guidance in broadened spectral regions, etc. PCFs operating with other guiding mechanisms such as inhibited coupling and antiresonance and twist-induced guidance (Markos et al. 2017) and hybrid PCFs with coexistence of both index-guiding and PBG-guiding mechanisms (Hu et al.

2019) have been reported previously. Notably, the presence of holey structure in PCF offers a desirable platform for incorporating functional materials to achieve new or enhanced functionalities. Examples include liquid crystals, liquids, magnetic fluids, gases, chalcogenide glasses, and metals. Metal-filled or metal-deposited PCF structures are two main types of plasmonic PCF structures that use PCFs as substrates for incorporating plasmonic structures and manipulating plasmonic properties.

3 Operating Principles of Plasmonic PCF Structures

The electromagnetic waves that propagate along the interface between a metal and a dielectric are surface plasmon polaritons (SPPs). They can be optically excited by photons when the parallel optical wave vector matches the propagation constant of the corresponding SPP modes. This wave vector matching requirement is very sensitive to the ambient parameters, which is the fundamental principle of the surface plasmon resonance (SPR) sensors. Figure 1 shows the Kretschmann configuration and the optical fiber-based configuration of the SPR sensors. The Kretschmann configuration has been widely adopted for SPR sensor. The matching of wave vectors takes place at the metal–glass interface in an inverted metal-coated prism. Optical fiber-based SPR sensors enable efficient coupling between the evanescent optical field and the

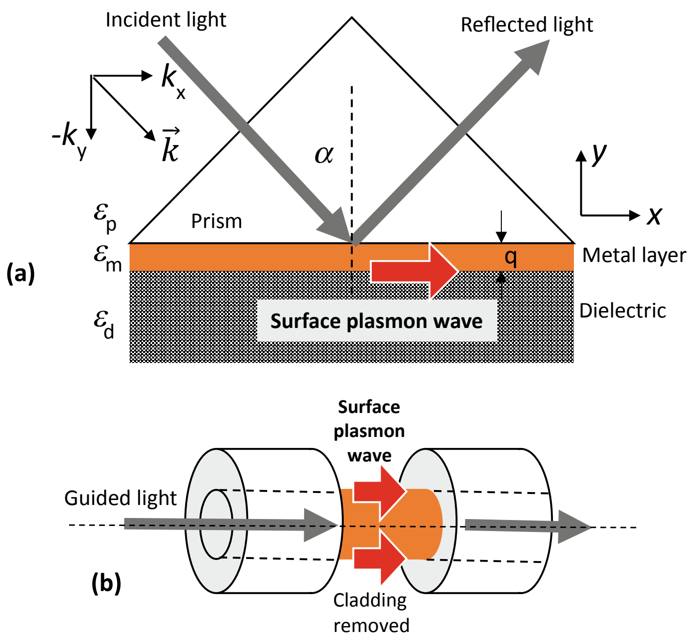

Fig. 1 Plasmonic PCF based on the SPP

SPP modes by exposing the core using side-polishing (Chiu et al. 2007) or selective etching in hydrofluoric acid (Coelho et al. 2015). The optical excitation of SPP modes in metal thin-film-coated PCF and metal nanowire-filled PCF structures can be understood from Fig. 1, relying on the coupling between the fiber modes and the SPP modes.

Localized surface plasmon polaritons (LSPPs) is another operating principle of plasmonic PCF structures that have plasmonic nanoparticles (NPs) or plasmonic nanostructures. Plasmonic nanoparticles (NPs) such as gold or silver nanoparticles have spectral properties in the UV-to-near-IR range. The LSPR is a highly localized electromagnetic field around NPs or the nanostructures, and it can be directly excited as the illumination frequency matches the eigenfrequency of the LSPR (Sauvan et al. 2013). The LSPR-based plasmonic PCF structures can be realized by depositing plasmonic NPs on the inner wall throughout the PCF length (Csaki et al. 2010; Schröder et al. 2012).

4 Review of Applications

- Refractive index sensing and biosensing

Refractive index sensing and biosensing is one of the most exploited applications by plasmonic PCFs. The SPR and LSPR configuration in the PCF structures can be realized at the external/outer surface of fiber, or at the inner walls of the fiber.

Deposition of high-quality metal thin films outside the PCFs could be achieved by the electroless plating method or sputtering technique, using exposed core PCF (Klantsataya et al. 2015), side-hole PCF (Wang et al. 2009), side-polished PCF (Wu et al. 2017), or PCF with collapsed cladding (Wong et al. 2013). These PCF structures provide greater evanescent field compared unperturbed PCF structures, thus enabling more efficient excitation of SPR which occurs at the boundary of the silica–metal thin film. For example, Wu et al. reported a gold-coated side-polished PCF SPR sensor for refractive index sensing (Wu et al. 2017). The sensor was immersed in liquid with varying refractive index. The transmission spectra and the resonance wavelengths were monitored as shown in Fig. 2. The experimental data of the resonance wavelength shift as a function of the refractive index agreed reasonably well with the simulation results, despite the nonlinearity observed in the measurement toward higher refractive index values.

In fact, the process of depositing a metal thin layer in the internal surfaces of PCFs itself is a challenging task. High-pressure microfluidic chemical deposition of semiconductor and metal within the internal surfaces of PCFs was reported by Sazio et al. The work has provided a significant step further toward the development of optoelectronic fiber devices (Sazio et al. 2006). Boehm et al. reported a silver-deposited PCF using an optimized chemical coating method. The method was based on the Tollens reaction, which was optimized to coat 60-nm-thick silver layer over a 1-m-long suspended core fiber with three large holes around the solid core. Slides with

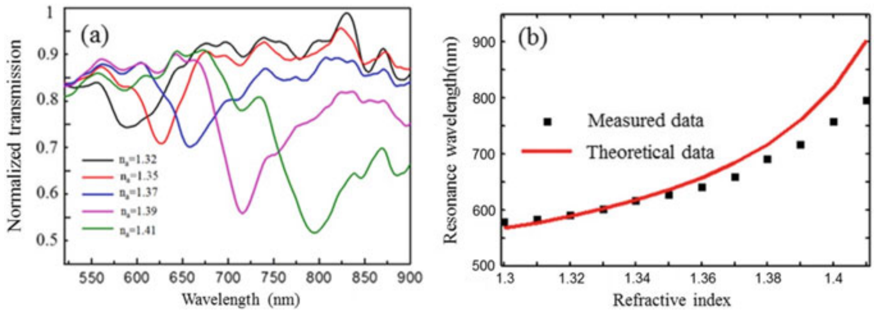

Fig. 2 **a** Experimental normalized transmission spectra of the D-shaped PCF-SPR sensor testing in different RI. **b** Experimental and theoretical values for the wavelength sensitivity. Reprinted with permission from (Wu et al. 2017) © The Optical Society

chemically deposited silver using the optimum recipe as well as sputtering technique were tested for SPR signal measurements. The sensitivity was 160°/RIU. Although the silver-coated PCF was not tested for SPR measurement, the reported technique provided a viable approach to produce plasmonic PCF based on SPR signals (Boehm et al. 2011).

The combination of plasmonic NPs in the PCF platform provides promising potential for LSPR-based sensing applications. Using the self-assembly monolayer technique, the inner walls of the PCF structures could be chemically modified for the deposition of metal NPs. Csaki et al. and Schröder et al. reported the gold/silver NP-deposited PCFs for refractive index sensing with sensitivities up to 78 and 80 nm/RIU, respectively (Csaki et al. 2010; Schröder et al. 2012).

Through the excitation of LSPR for local enhancement of electric field in various PCF structures, the Raman scattering response has been significantly enhanced to sufficient levels for revealing molecular features (Yang et al. 2010). A side-channel PCF structure with strong evanescent field was used as the platform for highly sensitive surface-enhanced Raman scattering (SERS) sensing (Zhang et al. 2016). The fiber design was optimized to ensure light propagation with fundamental mode at 632.8 nm. When the side channel and the air holes in the cladding were filled with liquids, the power of the evanescent field in the side channel increased linearly with the increasing refractive index of the liquid. To test the SERS sensing capability, the gold NPs were mixed in the rhodamine (R6G) solutions, which were filled into the side channel via capillary effect. The SERS spectra of different concentrations of R6G solution were measured, and the results are shown in Fig. 3. A low detection limit of 50 fM R6G solution was achieved.

Hollow core PCFs with the inner wall coated with NPs were used as a SERS sensing platform for biosensing applications, which include detection of EGFR extracted from human epithelial carcinoma cells (Dinish et al. 2012), serological liver cancer biomarkers (Dinish et al. 2014), and leukemia cells (Khetani et al. 2015).

Another technique for depositing metal NPs into the inner walls of PCF was reported by Amezcua-Correa et al., using an organic solvent under high pressure to

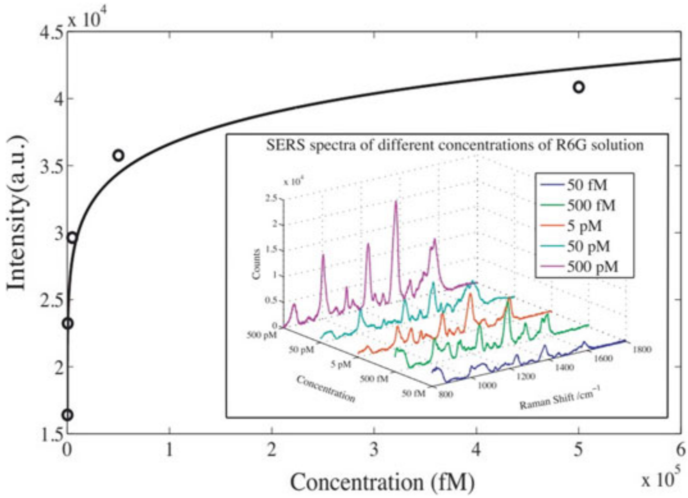

Fig. 3 SERS intensity as a function of concentration of R6G solution. The black solid curve is fitted with the Langmuir isotherm. (Inset) SERS spectra of various concentrations of R6G solutions (Zhang et al. 2016). Reproduced with permission. All Rights Reserved

deliver a silver precursor complex into the fiber holes, followed by a simple thermal reduction of the precursor to form an annular deposition of silver nanoparticles inside the holes (Amezcua-Correa et al. 2007; Peacock et al. 2008). The NP-deposited PCFs demonstrated enhanced SERS sensing performance due to several factors including high numerical aperture for efficient collection and detection of Raman response, and low-loss core-guided modes with large optical component propagating in the voids for large excitation area and long interaction length.

- Temperature sensing

The plasmonic resonance is highly tunable with temperature, which enables developments of functional plasmonic PCF devices for temperature sensing (Yang et al. 2016). In this work, silver nanowire solutions in ethanol and chloroform were filled into the air holes of PCF structure for several centimeters by capillary effect. As shown in the experiment, the silver nanowire colloid was a stable translucent colloidal suspension of silver nanowires in ethanol carrier. The liquid was regarded as a physical mixture of ethanol and chloroform. The diameter of the nanowires was about 90 nm, and the average length was about 30 μm. The mixing volume ratio of the silver nanowire solution and the chloroform was changed to tune the plasmonic resonance and the transmission loss. As shown in Fig. 4, the sensor with a mixing ratio of 1:2 yielded narrower and deeper loss curves at all temperatures compared to that with a mixing ratio of 1:1. The loss curves shifted to shorter wavelengths with increasing temperature from 25 to 60 °C. The temperature sensitivities were −1.8 and −2.08 nm/°C for mixing ratios 1:1 and 1:2, respectively. The temperature sensitivities were lower compared with the results of PCF sensor (−5.5 nm/°C) selectively

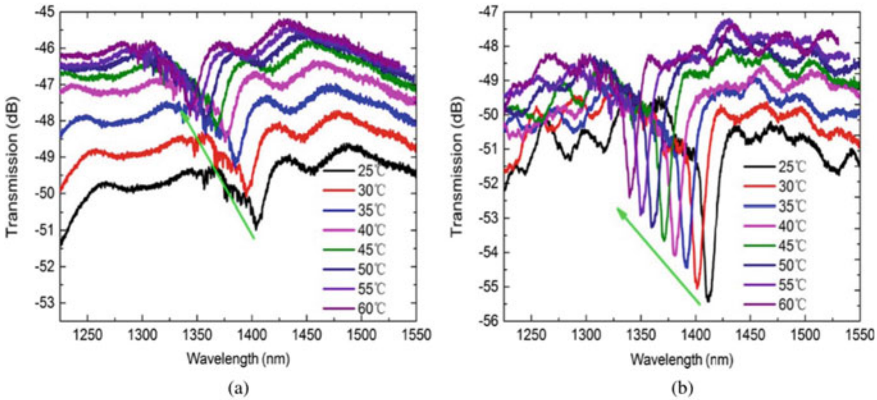

Fig. 4 Transmission spectra of the designed sensor when temperature varies from 25 to 60 °C with a step of 5 °C, filled with different volume ratios of ethanol and chloroform. **a** 1:1. **b** 1:2 (Yang et al. 2016). Reproduced with permission. All Rights Reserved

filled with gold nanoparticles (Peng et al. 2013), and PCF sensor selectively filled with liquid crystal based on coupler configuration (−3.9 nm/°C) (Hu et al. 2012) or hybrid guiding mechanism (4.91 nm/°C) (Xu et al. 2018).

- Polarization and birefringent devices

Plasmonic nanowires or microwires can be embedded in fiber structure in periodic arrangement to form metamaterial. The fabrication is challenging in volume. A feasible drawing technique to fabricate the metallic microwires in a PCF was introduced by Tuniz et al., demonstrating codrawing of polymethyl methacrylate and indium and producing several meters of metamaterial. The wire diameter was down to ~10 μm, and the lattice constant was ~100 μm. The metamaterial fiber transmittance was measured via THz time domain spectroscopy. Experimental results demonstrated that the metamaterial fiber acted as THz high-pass filter and polarizer. Notably, the technique can be used to further reduce the wire diameters down to nanoscales, which means much better prospect for practical plasmonic devices (Tuniz et al. 2010).

Lee et al. reported strong polarization-dependent spectral splitting in the double-nanowire PCF. The attenuation spectra of the fiber were measured and are shown in Fig. 5. The double-peak feature of the attenuation was due to optical mode coupling to SPP modes at phase-matching wavelengths. The polarization dependence in the fiber can be used for polarization-dependent polarizers (Lee et al. 2012). Polarization-dependent attenuation was also observed in selectively metal-coated PCF structure, showing promise for in-fiber absorptive polarizers (Zhang et al. 2007).

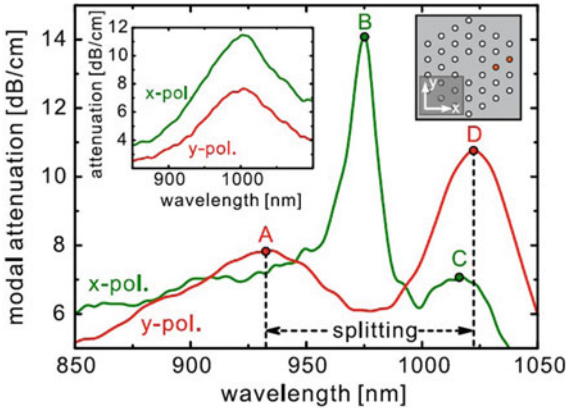

Fig. 5 Measured attenuation spectrum of the x- and y-polarized glass core mode in the double-nanowire fiber. The polarization directions are defined in the right-hand inset. Top left-hand inset: measured attenuation spectrum for the single-wire fiber. **a** 932.2 nm; **b** 974.8 nm; **c** 1015.9 nm; **d** 1022.4 nm. Reprinted with permission from (Lee et al. 2012) © The Optical Society

- New developments and opportunities

The combination of graphene and plasmonic structures has led to new opportunities as significant enhancement of the evanescent field is observed associated with the presence of the graphene. Graphene-based plasmonic sensors have been explored for sensing applications. Zeng et al. reported significant sensitivity enhancements of graphene–gold metasurface architectures (Zeng et al. 2015). The graphene–gold architecture was fabricated in a PCF-based SPR sensor, showing sensitivity improvement by 390 nm/RIU after the introduction of graphene (Li et al. 2019). The fiber sensor structure is shown in Fig. 6. The exposed core fiber was coated by gold film and graphene at the notch, and the measured liquid was covering the graphene.

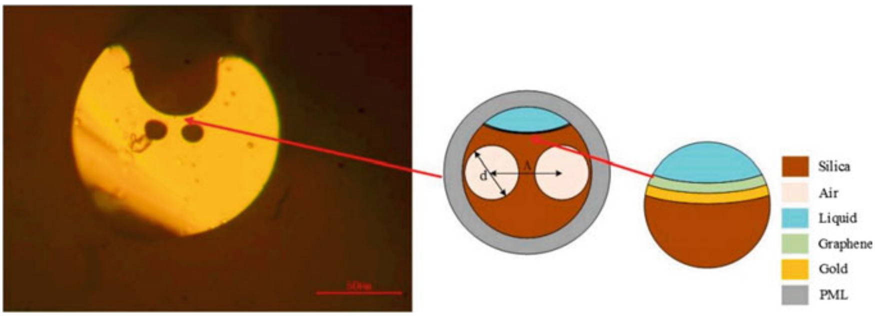

Fig. 6 Structure of the sensor (Li et al. 2019). Reproduced with permission. All Rights Reserved

The average sensitivity performance by the gold film-coated PCF SPR sensor was measured to be 1900 nm/RIU. Subsequently, the graphene was coated on the gold film and the average sensitivity performance of the PCF SPR sensor was measured to be 2290 nm/RIU.

The fabrication challenge of depositing graphene in the inner wall of the PCF structure was addressed by Chen et al. in a recent report. Up to half-meter-long PCF deposited with graphene was demonstrated using the chemical vapor deposition method (Chen et al. 2019). Such capability could enable realization of the graphene–gold architecture in the inner wall of the PCF for developments of new sensors with performance enhancements.

5 Conclusion

The integration of plasmonics in the PCF platform is a promising field of research. By leveraging on the flexibilities offered by PCF, SPP modes and LSPR can be efficiently excited for enhanced sensor performance. The operating principles are based on coupling between fiber modes and SPP modes in metal thin-film-coated PCF and metal nanowire-filled PCF structures, and direct excitation of the LSPR in nanoparticle-deposited/filled plasmonic PCF structures. The plasmonic PCF devices are particularly useful for sensing applications through the detection of refractive index, temperature, and biological events, and as conventional photonic components such as filters and polarizers. New developments in terms of fabrication techniques, which will expand the scope of coupling between the plasmonic effects and the unique photon confinement characteristics of PCFs, should further open up more exciting more opportunities, which were previously not possible, for plasmonic PCF devices.

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References

A. Amezcua-Correa, J. Yang, C.E. Finlayson, A.C. Peacor, J. Hayes, P.J. Sazio, S.M. Howdle, Surface-enhanced Raman scattering using microstructured optical fiber substrates. Adv. Func. Mater. **17**, 2024–2030 (2007)

W.L. Barnes, A. Dereux, T.W. Ebbesen, Surface plasmon subwavelength optics. Nature **424**, 824–830 (2003). https://doi.org/10.1038/nature01937

J. Boehm, A. Francois, H. Ebendorff-Heidepriem, T.M. Monro, Chemical deposition of silver for the fabrication of surface plasmon microstructured optical fibre sensors. Plasmonics **6**, 133–136 (2011)

K. Chen, X. Zhou, X. Cheng, R. Qiao, Y. Cheng, C. Liu et al., Graphene photonic crystal fibre with strong and tunable light–matter interaction. Nat. Photonics **13**(11), 754–759 (2019)

M.-H. Chiu, C.-H. Shih, M.-H. Chi, Optimum sensitivity of single-mode D-type optical fiber sensor in the intensity measurement. Sens. Actuators B **123**(2), 1120 (2007)
L. Coelho, J.M. de Almeida, J.L. Santos, R.A. Ferreira, P.S. André, D. Viegas, Sensing structure based on surface plasmon resonance in chemically etched single mode optical fibres. Plasmonics **10**(2), 319 (2015)
A. Csaki, F. Jahn, I. Latka, T. Henkel, D. Malsch, T. Schneider, W. Fritzsche, Nanoparticle layer deposition for plasmonic tuning of microstructured optical fibers. Small **6**(22), 2584–2589 (2010)
B. Debord, F. Amrani, L. Vincetti, F. Gérôme, F. Benabid, Hollow-core fiber technology: the rising of "gas photonics". Fibers **7**(2), 16 (2019)
U.S. Dinish, C.Y. Fu, K.S. Soh, R. Bhuvaneswari, A. Kumar, M. Olivo, Highly sensitive SERS detection of cancer proteins in low sample volume using hollow core photonic crystal fiber. Biosens. Bioelectron. **33**, 293–298 (2012)
U.S. Dinish, G. Balasundara, Y.T. Chang, M. Olivo, Sensitive multiplex detection of serological liver cancer biomarkers using SERS-active photonic crystal fiber probe. J. Biophotonics **7**(11–12), 956–965 (2014)
S. Ertman, P. Lesiak, T.R. Woliński, Optofluidic photonic crystal fiber-based sensors. J. Lightwave Technol. **35**(16), 3399–3405 (2017)
J. Homola, Surface plasmon resonance sensors for detection of chemical and biological species. Chem. Rev. **108**, 462–493 (2008)
D.J. Hu, H.P. Ho, Recent advances in plasmonic photonic crystal fibers: design, fabrication and applications. Adv. Opt. Photonics **9**(2), 257–314 (2017)
D.J. Hu, J.L. Lim, Y. Cui, K. Milenko, Y. Wang, P.P. Shum, T. Wolinski, Fabrication and characterization of a highly temperature sensitive device based on nematic liquid crystal-filled photonic crystal fiber. IEEE Photonics J. **4**(5), 1248–1255 (2012)
D.J. Hu, R.Y.-N. Wong, P.P. Shum, Photonic crystal fiber–based interferometric sensors, in *Selected Topics on Optical Fiber Technologies and Applications* (Intech, London, 2018), pp. 21–41
D.J. Hu, Z. Xu, P.P. Shum, Review on photonic crystal fibers with hybrid guiding mechanisms. IEEE Access **7**, 67469–67482 (2019)
A. Khetani, A. Momenpour, E.I. Alarcon, H. Anis, Hollow core photonic crystal fiber for monitoring leukemia cells using surface enhanced Raman scattering (SERS). Opt. Express **23**(22), 4599–4609 (2015)
E. Klantsataya, A. Francois, H. Ebendorff-Heidepriem, P. Hoffmann, T.M. Monro, Surface plasmon scattering in exposed core optical fiber for enhanced resolution refractive index sensing. Sensors **15**, 25090–25102 (2015)
J.C. Knight, Photonic crystal fibres. Nature 847–851 (2003)
J.C. Knight, Photonic crystal fibers and fiber lasers. J. Opt. Soc. Am. B **24**(8), 1661–1668 (2007)
J.C. Knight, D.V. Skryabin, Nonlinear waveguide optics and photonic crystal fibers. Opt. Express **15**(23), 15365–15376 (2007)
H.W. Lee, M.A. Schmidt, P.S. Russell, Excitation of a nanowire "molecule" in gold-filled photonic crystal fiber. Opt. Lett. **37**(14), 2946–2948 (2012)
B. Li, T. Cheng, J. Chen, X. Yan, Graphene-enhanced surface plasmon resonance liquid refractive index sensor based on photonic crystal fiber. Sensors **19**, 3666 (2019)
C. Markos, J.C. Travers, A. Abdolvand, B.J. Eggleton, O. Bang, Hybrid photonic crystal-fiber. Rev. Mod. Phys. **89**, 045003 (2017)
A.C. Peacock, A. Amezcua-Correa, J. Yang, P.J. Sazio, S.M. Howdle, Highly efficient surface enhanced Raman scattering using microstructured optical fibers with enhanced plasmonic interactions. Appl. Phys. Lett. **92**, 114113 (2008)
Y. Peng, J. Hou, Y. Zhang, Z. Huang, R. Xiao, Q. Lu, Temperature sensing using the bandgap-like effect in a selectively liquid-filled photonic crystal fiber. Opt. Lett. **38**(3), 263–265 (2013)
A.M. Pinto, M. Lopez-Amo, Photonic crystal fibers for sensing applications. J. Sens. **2012**, 598178 (2012)
P. Russell, Photonic crystal fibers. Science 358–362 (2003)

C. Sauvan, J.P. Hugonin, I.S. Maksymov, P. Lalanne, Theory of the spontaneous optical emission of nanosize photonic and plasmonic resonators. Phys. Rev. Lett. **110**, 237401 (2013)
P.J. Sazio, A. Amezcua-Correa, C.E. Finlayson, J.R. Hayes, T.J. Scheidemantel, N.F. Baril, J.V. Badding, Microstructured optical fibers as high-pressure microfluidic reactors. Science **311**, 1583–1586 (2006)
K. Schröder, A. Csáki, A. Schwuchow, F. Jahn, K. Strelau, I. Latka, W. Fritzsche, Functionalization of microstructured optical fibers by internal nanoparticle mono-layers for plasmonic biosensor applications. IEEE Sens. J. **12**(1), 218–224 (2012)
J.C. Travers, W. Chang, J. Nold, N.Y. Joly, P.S. Russell, Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers. J. Opt. Soc. Am. B **28**(12), A21–A26 (2011)
A. Tuniz, B.T. Kuhlmey, R. Lwin, A. Wang, J. Anthony, R. Leonhardt, S.C. Fleming, Drawn metamaterials with plasmonic response at terahertz frequencies. Appl. Phys. Lett. **96**, 191101 (2010)
J. Villatoro, J. Zubia, New perspectives in photonic crystal fibre sensors. Opt. Laser Technol. 67–75 (2016)
A. Wang, A. Docherty, B.T. Kuhlmey, F.M. Cox, M.C. Large, Side-hole fiber sensor based on surface plasmon resonance. Opt. Lett. **34**(24), 3890–3892 (2009)
W.C. Wong, C.C. Chan, J.L. Boo, Z.Y. Teo, Z.Q. Tou, H.B. Yang, K.C. Leong, Photonic crystal fiber surface plasmon resonance biosensor based on protein G immobilization. IEEE J. Sel. Top. Quantum Electron. **19**(3), 460217 (2013)
T. Wu, Y. Shao, S.C. Ying Wang, W. Cao, F. Zhang, C. Liao, Y. Wang, Surface plasmon resonance biosensor based on gold-coated side-polished hexagonal structure photonic crystal fiber. Opt. Express **25**(17), 20313–20322 (2017)
Z. Xu, B. Li, D.J. Hu, Z. Wu, S. Ertman, T. Wolinski, P.P. Shum, Hybrid photonic crystal fiber for highly sensitive temperature measurement. J. Opt. **20**(7), 075801 (2018)
X. Yang, C. Shi, R. Newhouse, J.Z. Zhang, C. Gu, Hollow-core photonic crystal fibers for surface-enhanced raman scattering probes. Int. J. Opt. **2011**, 751610 (2010)
X. Yang, C. Shi, R. Newhouse, J.Z. Zhang, C. Gu, Hollow-core photonic crystal fibers for surface-enhanced raman scattering probes. Int. J. Opt. **2011**, 754610 (2011)
X.C. Yang, Y. Lu, B.L. Liu, J.Q. Yao, Temperature sensor based on photonic crystal fiber filled with liquid and silver nanowires. IEEE Photonics J. **8**(3), 6803309 (2016)
S. Zeng, K.V. Sreekanth, J. Shang, T. Yu, C.-K. Chen, F. Yin, K.-T. Yong, Graphene-gold metasurface architectures for ultrasensitive plasmonic biosensing. Adv. Mater. **27**(40), 6163–6169 (2015)
X. Zhang, R. Wang, F.M. Cox, B.T. Kuhlmey, M.C. Large, Selective coating of holes in microstructured optical fiber and its application to in-fiber absorptive polarizers. Opt. Express **15**(24), 16270–16278 (2007)
N. Zhang, G. Humbert, T. Gong, P.P. Shum, K. Li, J.-L. Auguste, L. Wei, Side-channel photonic crystal fiber for surface enhanced Raman scattering sensing. Sens. Actuators B Chem. **223**, 195–201 (2016)
Y. Zhao, Z.-Q. Deng, J. Li, Photonic crystal fiber based surface plasmon resonance chemical sensors. Sens. Actuators B Chem. **202**, 557–567 (2014)