Early Cancer Detection by Plasmonic PCF Sensor

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Abstract— **Great research work has been studied for cancer detection due to its high death rate. In this paper, a novel design of photonic crystal fiber (PCF) biosensor based on surface plasmon resonance (SPR) is introduced and numerically analyzed for cancer cell detection. Full vectorial finite element method (FVFEM) is used throughout the numerical analysis of the reported structure. The reported PCF has a V-shaped surface that is coated by ZrN as a plasmonic material. A coupling occurs between the core guided mode and surface plasmon mode which depends on the studied analyte. The geometrical parameters are optimized to achieve high sensor sensitivity. The proposed biosensor achieves high optical sensitivity of 5600 nm/RIU, 5700 nm/RIU for the x- and y-polarized modes, respectively. The reported optical sensor can pave the road for efficient and simple technique for cancer detection instead of surgical and chemical techniques.**

***Index Terms*— Photonic crystal fibers, Refractive index sensor, surface plasmon, cancer detection.**

Plasmonic effect occurs when maximum loss transfers from the core mode to the lossy material at a resonance wavelength which depends on the analyte refractive index. The shift in the resonance wavelength can be used to detect the analyte refractive index (RI) variation. Plasmonics are used in many applications, such as cancer therapy[1], optical sensors[2,3,4], light manipulation[5], coupler[6], imaging[7], and polarization handling devices[8,9].

Externally coated SPR-PCF based sensors can facilitate the fabrication process where no selective infiltration into the air hole is needed. Therefore, the D- shape configuration is a good choice for SPR-PCF sensor which achieved sensitivity of 2900 nm/RIU[10]. Peng *et al.*[11] proposed a D-shaped PCF-SPR sensor with rectangular pattern of air hole with sensitivity of 7481nm/RIU. Ming *et al.* [12] reported a silica core D-shaped PCF-SPR sensor based on silver coating with optical sensitivity of 7300 nm/RIU. However silver has a lot of oxidation problems [13]. Further, Jha *et al.* [14] reported a D-shaped graphene coated biosensor where sensitivity of 3700 nm/RIU was achieved in the RI range of 1.330 to 1.370. Further, a D-shaped PCF-SPR with ITO and graphene coating layers have been designed with sensitivity of 5700 nm/RIU [15]. Luan *et al.* [10] also proposed a hollow core D shaped sensor based on gold metal coating with sensitivity of 2900 nm/RIU. Additionally, Wang *et al.*[16] reported D-shaped PCF-SPR based on gold coating inside the core region with sensitivity of 6430 nm/RIU. Such a design has an ITO coating with graphene layer where the sensitivity was enhanced to 10693 nm/RIU[17]. Kaur *et al.*[18] suggested a D-shaped PCF biosensor based on indium tin oxide (ITO) and zinc oxide (ZnO) coating layers with high sensitivity of 10000 nm/RIU.

The V-shaped configuration can be used to implement PCF for different applications. Qu *et al.*[19] proposed V-shaped PCF polarization filter where the air holes are arranged in the core region in V- shaped configuration. Later, they also proposed a V-dual core -PCF coated with gold film through dual-core PCF polarization beam splitter [20]. Wojcik *et.al.* [21] reported a V-type highly birefringent PCF fiber for sensing the hydrostatic pressure.

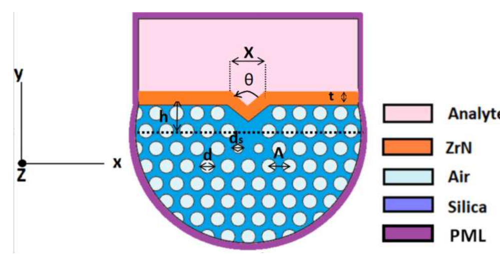


Fig. 1 Transverse cross-section of the suggested SPR PCF sensor

As shown in Fig. 1, the background of the PCF is silica, and the air holes with a radius d are arranged in a hexagonal lattice with a hole pitch Λ. Further, smaller air holes are used with diameter d_s to control the field confinement through the core region. The upper surface is etched at a distance h from the PCF center. Further, V-grove is then made with an angle θ corresponding to a distance x between the two vertices of the V-shape. The etched surface is coated with a layer of ZrN with a thickness t. Then, the studied analyte will be put over the plasmonic layer as shown in Fig.1. The frequency-dependent ZrN permittivity is taken from the model of Johnson and Christy[22]. Additionally, silica RI is determined by the wavelength dependent Sellmeier equation[23]. In this study, COMSOL Multiphysics software package [24] based on the well-known full vectorial finite element method (FVFEM) [25] is utilized to study and analyze the proposed PCF structure. The v-shaped structure is discretized into small triangular elements with a minimum element size and degree of freedom of 1×10^{-4} μm and 1086496, respectively. Further, perfect matched layer (PML)[26] absorbing boundary conditions is employed to shrink the simulation domain from all transverse directions and calculate the confinement loss of the studied modes.

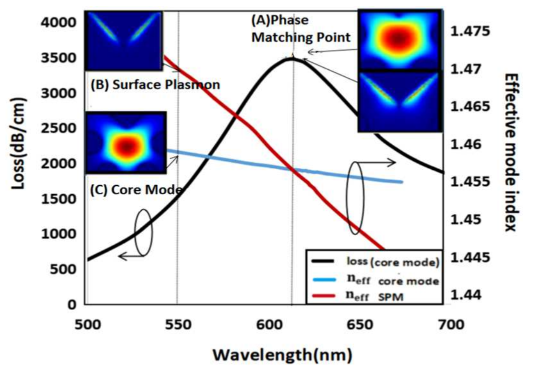
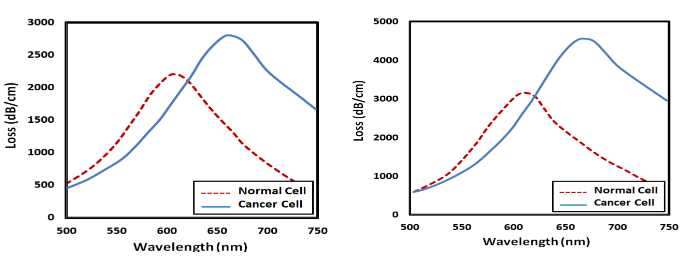


Fig. 2. Dispersion of n_{eff} of the core mode and SP mode, and confinement losses of the core mode for normal cell analyte.

The dispersion of the core mode and SP mode are plotted in Fig. 2. Further, the loss spectrum of the core mode is represented in black color, while the real parts of y-polarized core mode and SPM effective indices are shown in blue and red colors, respectively. It may be seen that maximum loss occurs at resonance wavelength where maximum power transfer occurs from the core mode to the SP mode. At the maximum loss point, a strong coupling between core mode and SPM is achieved as the real effective indices of the core mode and SPM are equal. The insets (a), (b) and (c) depict the electric field profiles of the phase matching point (at λ=612 nm), SPM (at λ=550 nm) and the y-polarized core mode (at λ=550 nm), respectively.



(a) (b)

Fig. 3 Wavelength dependent confinement losses of the core guided modes for normal and cancer cells of the (a) x-polarized and (b) y-polarized core modes

The confinement loss variation for *x*- and *y*- polarized core modes for two different samples of normal cells (n_n= 1.385) and cancer cells (n_d=1.399), respectively, is depicted in Fig. 3. It may be seen from Figs. 3 that when the RI increases, the resonance loss peaks are shifted to longer wavelengths where RI sensitivity of 5600 nm/RIU and 5700 nm/RIU are obtained for *x*- and *y*-polarized modes, respectively. Moreover, good corresponding resolution of 2.5×10^{-5} RIU and 2.45×10^{-5} RIU are obtained. Thus the proposed biosensor is a promising candidate device for early detection of cancer cells.

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REFERENCES

1. Gobin, A. M. *et al.* Near-infrared resonant nanoshells for combined optical imaging and photothermal cancer therapy. *Nano Lett.* **7**, 1929–1934 (2007).
2. Gamal, Y. *et al.* Highly Sensitive Multi-Functional Plasmonic Biosensor Based on Dual Core Photonic Crystal Fiber. *IEEE Sens. J.* (2022).
3. Gamal, Y. *et al.* Highly Sensitive Plasmonic PCF Biosensor. in *2021 International Applied Computational Electromagnetics Society Symposium (ACES)* 1–2 (IEEE, 2021).
4. Azzam, S. I., Hameed, M. F. O., Shehata, R. E. A., Heikal, A. M. & Obayya, S. S. A. Multichannel photonic crystal fiber surface plasmon resonance based sensor. *Opt. Quantum Electron.* **48**, 142 (2016).
5. Younis, B. M., Heikal, A. M., Hameed, M. F. O. & Obayya, S. S. A. Highly wavelength-selective asymmetric dual-core liquid photonic crystal fiber polarization splitter. *JOSA B* **35**, 1020–1029 (2018).
6. Lee, B. H. *et al.* Photonic crystal fiber coupler. *Opt. Lett.* **27**, 812–814 (2002).
7. Sokolov, K. *et al.* Real-time vital optical imaging of precancer using anti-epidermal growth factor receptor antibodies conjugated to gold nanoparticles. *Cancer Res.* **63**, 1999–2004 (2003).
8. Hameed, M. F. O., Abdelrazzak, M. & Obayya, S. S. A. Novel design of ultra-compact triangular lattice silica photonic crystal polarization converter. *J. Light. Technol.* **31**, 81–86 (2012).
9. Gamal, Y. *et al.* Highly efficient modified dual D-shaped PCF polarization filter. *Opt. Fiber Technol.* **62**, 102459 (2021).
10. Luan, N., Wang, R., Lv, W. & Yao, J. Surface plasmon resonance sensor based on D-shaped microstructured optical fiber with hollow core. *Opt. Express* **23**, 8576–8582 (2015).
11. Peng, L. *et al.* A surface plasmon biosensor based on a D-shaped microstructured optical fiber with rectangular lattice. *IEEE Photonics J.* **7**, 1–9 (2015).
12. Tian, M., Lu, P., Chen, L., Lv, C. & Liu, D. All-solid D-shaped photonic fiber sensor based on surface plasmon resonance. *Opt. Commun.* **285**, 1550–1554 (2012).
13. Boltasseva, A. & Shalaev, V. M. All that glitters need not be gold. *Science (80-.).* **347**, 1308–1310 (2015).
14. Dash, J. N. & Jha, R. On the performance of graphene-based D-shaped photonic crystal fibre biosensor using surface plasmon resonance. *Plasmonics* **10**, 1123–1131 (2015).
15. Patnaik, A., Senthilnathan, K. & Jha, R. Graphene-based conducting metal oxide coated D-shaped optical fiber SPR sensor. *IEEE Photonics Technol. Lett.* **27**, 2437–2440 (2015).
16. Wang, G. *et al.* Highly sensitive D-shaped photonic crystal fiber biological sensors based on surface plasmon resonance. *Opt. Quantum Electron.* **48**, 46 (2016).
17. An, G., Li, S., Wang, H. & Zhang, X. Metal oxide-graphene-based quasi-D-shaped optical fiber plasmonic biosensor. *IEEE Photonics J.* **9**, 1–9 (2017).
18. Kaur, V. & Singh, S. Design of D-Shaped PCF-SPR sensor with dual coating of ITO and ZnO conducting metal oxide. *Optik (Stuttg).* **220**, 165135 (2020).
19. Qu, Y. *et al.* A V-shape photonic crystal fiber polarization filter based on surface plasmon resonance effect. *Opt. Commun.* **452**, 1–6 (2019).
20. Qu, Y. *et al.* A Novel Gold Film-Coated V-Shape Dual-Core Photonic Crystal Fiber Polarization Beam Splitter Covering the E+ S+ C+ L+ U Band. *Sensors* **21**, 496 (2021).
21. Wójcik, J. *et al.* V type high birefringent PCF fiber for hydrostatic pressure sensing. *Photonics Lett. Pol.* **2**, 10–12 (2010).
22. Naik, G. V, Shalaev, V. M. & Boltasseva, A. Alternative plasmonic materials: beyond gold and silver. *Adv. Mater.* **25**, 3264–3294 (2013).
23. Hameed, M. F. O. & Obayya, S. *Computational photonic sensors*. (Springer, 2019).
24. COMSOL 5.1. Multiphysics software. https://www.comsol.com (2020).
25. Obayya, S. S. A., Rahman, B. M. A., Grattan, K. T. V & El-Mikati, H. A. Full vectorial finite-element-based imaginary distance beam