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A Brief Review on Plasmonic Nanomaterials in No-Core Optical Fiber Sensor Applications

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Abstract

The use of plasmonic nanomaterials in no-core fiber (NCF)-based optical sensor technology has grown rapidly due to their ability to increase the sensitivity and selectivity for various environmental sensing. The Localized Surface Plasmon Resonance (LSPR) phenomenon produced by metal nanoparticles, especially gold and silver nanoparticles, allows the resonance of the electric field around the nanoparticles. Therefore, the LSPR effect is highly responsive to changes in the surrounding media. The SMF–NCF–SMF is a commonly used optical fiber structure because it is simple, easy to fabricate, and capable of producing multimode interference that is sensitive to external changes. This review discusses the working principle of nanoplasmonic-based NCF sensors, the development of their applications, for example in detecting temperature, pH, glucose, and other parameters. The challenges and prospects for future research in the development of nanoplasmonic-based optical sensors are also articulated in this present review. By utilizing nanoplasmonics to improve the performance of optical sensors, this paper is expected as a reference for the development of more innovative and applicable optical fiber sensor technology in the future.

Keywords: No-Core Fiber, Plasmonic Effect, Optical Sensing, Nanomaterials

1. Introduction

In recent years, plasmonic nanomaterials have attracted the attention of researchers due to their distinct optical properties as compared to other nanomaterials [1]. Plasmonic nanomaterials have the ability to produce electron oscillations on their surfaces when exposed to electric fields from light [2]. LSPR is an outstanding optical phenomenon and occurs when light hits plasmonic nanoparticles. In this interaction, the electric field of the light causes the electrons to oscillate in conjunction with the frequency of the light source. The strengthening of the electric field around the nanoparticle is produced by this resonance, which can be applied for many purposes, such as sensors, medical applications, and optical devices [3].

Plasmonic nanomaterials play an important role in the development of fiber optic sensors, especially no-core fiber (NCF) structures. NCF-based sensors offer some advantages over conventional sensors as they can monitor long-distance distribution in real-time without being affected by electromagnetic interference. They are often used to measure temperature [4], liquid refractive index [5], [6], [7], pressure [8], strain [9], humidity [10], and magnetic field [11]. In NCF, the fiber itself functions as the core while the external medium functions as the cladding [13]. The most basic NCF-based sensors combine NCF sections between communication optical fibers. They work by stably transmitting light modes with different propagation constants through an optical waveguide, where each mode accumulates a different phase over a given distance. The interference condition will be met, and interference will occur and form interference fringes [14]. Based on this feature, NCF can be applied for sensors because it shows a sensitive response to the environment [15].

Using surface plasmon resonance to measure glucose concentration and ambient temperature, Li et al. discussed the development of NCF [16]. In their study, the construction of a sensor consisting of two layers was discussed: one to detect temperature and another to detect glucose concentration. Gold and polydimethylsiloxane (PDMS) layers were used to detect temperature, and another layer was coated with silver to detect glucose concentration [16]. Zhao et al. developed a sensitive seawater temperature sensor using NCF type optical fiber [4]. The sensor is made by connecting a piece of NCF layer between Single Mode Fiber. The layer consisting of acrylic resin has a high optical thermal coefficient, which makes the sensor more sensitive to temperature [4]. Both papers have limitations in terms of complex temperature calibration, and when installed in an unusual environment, the sensor is unstable and selective. Research by Li et al. showed that the sensor is sensitive to interference from non-glucose factors [16]. On the other hand, Zhao et al. found that the refractive index of the layer and the position of the interference wavelength can be affected by changes in external temperature [4]. Although the use of fiber optic sensors with NCF structures is widely used for various sensor applications, currently there is still not much literature that specifically discusses the increase in sensitivity in NCF sensors with plasmonic nanomaterials. Therefore, a review is needed on the application of plasmonic nanomaterials in NCF sensors to overcome this limitation.

The main objective of this review is to provide a better understanding of the working principles of plasmonic nanomaterials and NCF sensors, as well as their applications, mechanisms, and future research prospects for the development of more advanced sensor technologies. Therefore, it is expected that this review will help researchers in the sensor field to conduct further research involving new innovations in this technology.

2. No- Core Fiber Based Plasmonic Sensor Applications

The term plasmonic is used to describe the light-nanomaterial interaction [1]. In this sense, plasmons are generated from the interaction between a light beam and free electrons of metal nanostructure. The collective free electrons of metal nanoparticles interact with the light in such a way that some part of the light is absorbed, known as LSPR [18]. LSPR occurs when light waves are trapped in conductive nanoparticles [19]. It occurs especially when the size of nanoparticles is smaller than that of the wavelength of the incoming light, causing stronger electromagnetic fields around the nanoparticles. LSPR effect is widely used to enhance the fiber optic sensing performance as it promotes more light-matter interaction when fiber optic is subjected to test analytes [20].

In the context of its application, NCF-based plasmonic sensors have been widely used for refractive index detection of various solutions [6], [16], [21]. For example, in a sensor system with SMF–NCF–SMF structure. The NCF part can be modified with plasmonic nanoparticles to increase sensitivity through the LSPR effect seen from the shift in the absorbance peak that can show small changes that allow detection of solute concentration with high precision [22]. Several studies have shown that the use of plasmonic nanoparticles on the NCF surface has been widely carried out as shown in Table 1.

Table 1. Research Related to the Use of Plasmonic Nanomaterials in NCF-Based Sensors.

Materials	Applications	Optical Fiber Structure	Optical Phenomena	Ref
Au/Ag	Refractive index (RI) and temperature sensors	NCF	SPR	[23]
ZnO	RI sensor	MMF-NCF-MMF	-	[24]
Ag-PDMS	RI sensor	MMF-NCF-MMF	SPR	[25]
Ag-ZnO	Ultraviolet sensor	MMF-NCF-MMF	SPR	[26]
Ag-Cu Film	RI sensor	MMF-NCF-MMF	SPR	[27]
Ag Film	RI sensor	MMF-NCF-MMF	SPR	[28]
TiO_2–ZnO	Hydrogen sulfide (H_2S) gas sensors	TCF-NCF-TCF	-	[29]

3. No-Core Fiber Sensing Mechanism

The Optical fiber has become one of the leading technologies in refractive index sensing, which is a basic mechanism for detecting the type and concentration of analytes in various applications [30]. Fiber optic sensors have advantages in terms of small size, light weight, resistance to corrosion [21], immunity to electromagnetic intrusion, and excellent sensitivity [31]. The advancement of optical fiber technology as a refractive index sensor is inseparable from the development of plasmonic nanomaterials. Plasmonic nanoparticles such as AuNPs and AgNPs have been widely used to improve sensor sensitivity through plasmonic effects. LSPR-based fiber optic sensors are the development of fiber optic-based sensors by utilizing nanomaterials with superior optical properties such as AuNPs and AgNPs. Coating optical fibers with plasmonic nanomaterials can increase the interaction between light and the external medium, thereby increasing sensitivity to changes in the refractive index [32]. The progress of fiber optic technology as a refractive index sensor is increasingly rapid, as evidenced by the many previous studies that have utilized fiber optics as refractive index sensors. Fiber optic-based refractive index sensors have been applied in various fields, one of which is in the environmental field [33], this sensor is used to detect water quality [34] and pollutant concentrations [35]. In the medical field, this sensor is used for biomolecule analysis, such as glucose detection [36] and protein. With various existing applications, the development of fiber optic-based refractive index sensor technology has great potential for various other applications.

Optical fibers generally have a structure consisting of a core and cladding. The core is the main part that functions as a medium for light propagation, while the cladding functions to protect light waves and reflect light so that it can propagate to the other end [30]. NCF can be directly applied to the external environment because of its structural characteristics that only have a cladding. So just by connecting the NCF part between the single- mode-fiber (SMF) shown in Figure 1, or the multi-mode-fiber (MMF) shown in Figure 2 can form a sensor with high sensitivity.

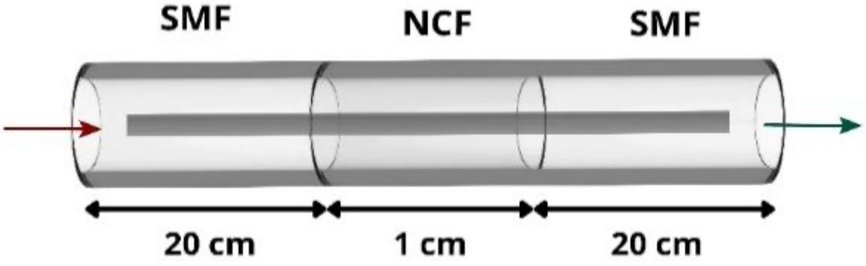


Figure 1. SMF-NCF-SMF Optical Fiber Structure (Not to Scale).

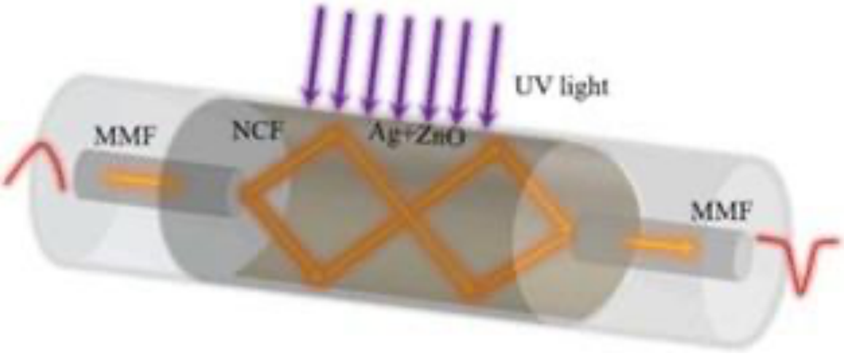


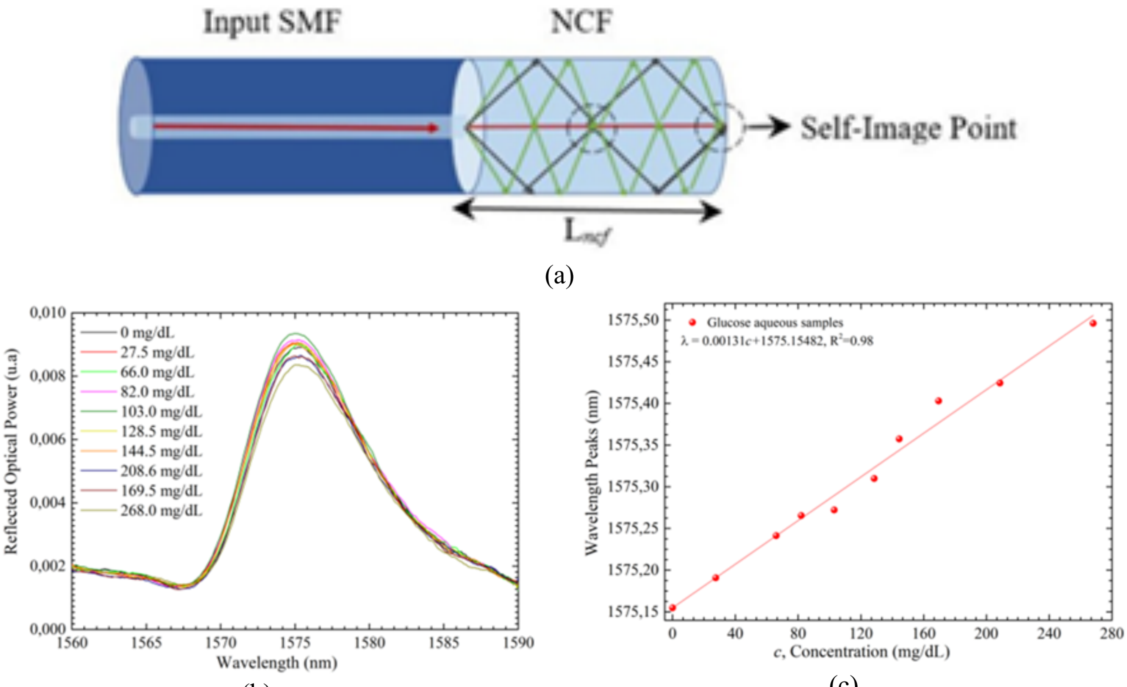
Figure 2. MMF-NCF-MMF Optical Fiber Structure [26].

The SNS sensor consists of two Single Mode Fibers (SMFs) connected by a NCF to form a sandwich structure [31]. The change in mode field causes multimode interference when incoming light is transmitted from SMF to NCF [14]. Specifically, the NCF guides the wave of a quartz fiber made of homogeneous material; it is also known as a coreless fiber because it acts as the core while the external medium acts as the cladding [13]. NCF-based sensors are one of the simplest types made by combining NCF sections between communication optical fibers. When different transmission constants of light modes propagate in NCF, each mode experiences different optical paths and phase accumulation after traveling a certain distance. This difference causes interference, so that an interference fringe pattern is formed when the interference conditions are met. [14]. Based on this feature, NCF can be applied for sensors because it shows a sensitive response to the environment [15]. NCF connected with (SMF) facilitates light to pass through the NCF and the sensitivity of sensing will increase [37]. Therefore, many studies have been carried out related to fiber optic sensors with NCF structures, as shown in Table 2.

Previous studies using fiber optic sensors with SMF-NCF-SMF structures include research by Cunha et al., who found a non-invasive fiber optic sensor for glucose detection in this study [38]. This sensor uses self-imaging techniques and is based on multimode interference (MMI). The joint structure between single-mode fiber (SMF) and no-core fiber (NCF) measures 29.1 mm, as shown in Figure 3(a). In this sensor, the parameters that can be measured are the shift in the resonance wavelength due to increasing glucose concentrations shown in Figure 3(b). The glucose sensor has a sensitivity of 1.31 pm /(mg/dL) in the glucose concentration range of 0–268 mg/dL and has high linearity with $R^2 = 0.98$ shown in Figure 3(c).

Table 2. Example of Previous Research on NCF Sensor Applications.

Sensor type	Optical Fiber Structure	Main parameters	Sensitivity	Ref
Glucose sensor	Reflective, multimode interference (MMI), SMF–NCF junction (29.1 mm)	Wavelength shift due to glucose concentration	1,31 pm/(mg/dL), $R^2 = 0{,}98$	[38]
Strain sensor	Simple multimode Mach-Zehnder interferometer, NCF length 3.1–3.7 cm	Spectral shift due to strain	−16.37 pm/με (3.1 cm) s.d. −12.26 pm/με (3.7 cm), $R^2 > 0.997$	[39]
pH sensor	NCF + SMF with sol-gel indicator layer (bromophenol blue, cresol red, chlorophenol red), Michelson interference type	Wavelength shift due to pH changes	1.02 nm/pH (acidic), −0.93 nm/pH (basic), pH range 2–13	[40]



(a)

(b)

(c)

Figure 3. (a) SMF-NCF-SMF Optical Fiber Structure of Glucose Sensor, (b) Test Results of Glucose Sensor at Various Glucose Concentrations, (c) Sensor response to Variations in Glucose Concentration [38].

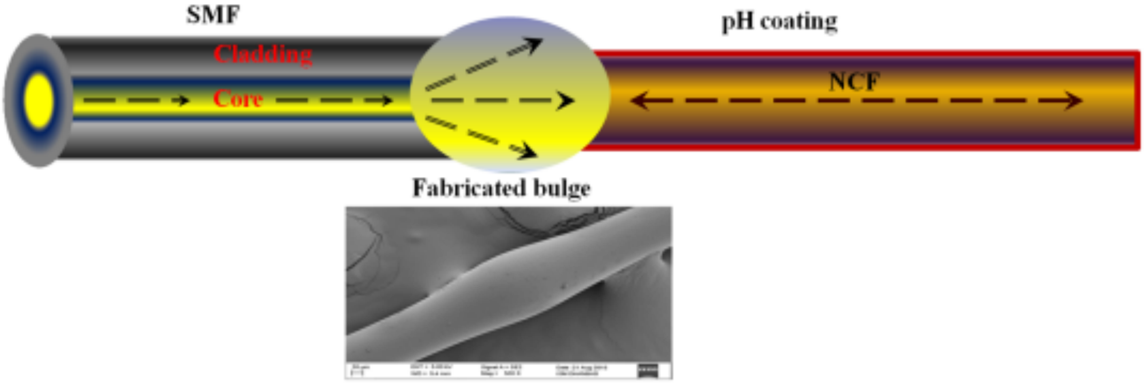


Figure 4. Structure of SMF-NCF-SMF sensor coated with sol-gel based pH sensitive layer [40].

A strain sensor in the form of a simple multimode Mach-Zehnder interferometer was also discussed in a study conducted by Taher et al. [39]. All sensors were tested using the infrared light spectrum and at room temperature (25 °C). The detected parameter was the NCF length (3.1–3.7 cm). This sensor showed the highest sensitivity at 3.1 cm (−16.37 pm/me) and the lowest sensitivity at 3.7 cm (−12.26 pm/me), all with good linear performance ($R^2 > 0.997$). Sensitivity decreases with fiber length [39].

Bhardwaj et al. [40] discussed their research on pH sensors. The sensor has an optical fiber structure in the form of a no-core fiber (NCF) connected to a single-mode fiber (SMF). As shown in figure 4, this structure produces Michelson type interference. The sol-gel based pH sensitive layer consists of a mixture of three indicators (bromophenol blue, cresol blue, and chlorophenol blue). This sensor has a sensitivity of 1.02 nm/pH for acidic solutions and −0.93 nm/pH for basic solutions, and covers a wide pH range from 2 to 13 [40].

4. Conclusion and Future Research

Plasmonic nanomaterials in NCF sensor technology have shown strong potential for enhancing sensitivity and selectivity in detecting environmental parameters such as temperature, pH, humidity, pressure, and chemical concentrations. The LSPR phenomenon that occurs in plasmonic nanoparticles such as gold and silver produce local electric field amplification that is very sensitive to changes in the refractive index around it, making it suitable for use in optical sensors. Various approaches have been done to improve sensor performance, including the use of plasmonic nanoparticle coatings, NCF surface modification, and incorporation with certain selective agents. With the advancement of plasmonic nanomaterial technology and the design of optical fiber structures such as NCF, research in the field of optical sensors has entered a new era promising high sensitivity and specific selectivity. However, to reach the stage of widespread implementation in the real world, further research in the aspects of materials, fabrication techniques, system design, and standardization is still urgently needed.

References

[1] D. Wang, S. C. Pillai, S.-H. Ho, J. Zeng, Y. Li, and D. D. Dionysiou, "Plasmonic-based nanomaterials for environmental remediation," *Appl. Catal. B Environ.*, vol. 237, pp. 721–741, Dec. 2018, doi: 10.1016/j.apcatb.2018.05.094.

[2] S. Eustis and M. A. El-Sayed, "Why gold nanoparticles are more precious than pretty gold: Noble metal surface plasmon resonance and its enhancement of the radiative and nonradiative properties of nanocrystals of different shapes," *Chem Soc Rev*, vol. 35, no. 3, pp. 209–217, 2006, doi: 10.1039/B514191E.

[3] B.-H. Jun, Ed., *Nanotechnology for Bioapplications*, vol. 1309. in Advances in Experimental Medicine and Biology, vol. 1309. Singapore: Springer Singapore, 2021. doi: 10.1007/978-981-33-6158-4.

[4] Y. Zhao, J. Zhao, and Q. Zhao, "High sensitivity seawater temperature sensor based on no-core

optical fiber," *Opt. Fiber Technol.*, vol. 54, p. 102115, Jan. 2020, doi: 10.1016/j.yofte.2019.102115.

[5] T. Khanikar, A. K. Pathak, and V. K. Singh, "Reflectance-based no core fiber sensor with enhanced Sensitivity for salinity detection," *Optik*, vol. 159, pp. 1–8, Apr. 2018, doi: 10.1016/j.ijleo.2018.01.053.

[6] N. Mohd Razali *et al.*, "No-core fiber by self-image length optimization for optical based refractive index sensor," *Opt. Fiber Technol.*, vol. 74, p. 103133, Dec. 2022, doi: 10.1016/j.yofte.2022.103133.

[7] S. Novais, C. I. A. Ferreira, M. S. Ferreira, and J. L. Pinto, "Optical Fiber Tip Sensor for the Measurement of Glucose Aqueous Solutions," *IEEE Photonics J.*, vol. 10, no. 5, pp. 1–9, Oct. 2018, doi: 10.1109/JPHOT.2018.2869944.

[8] B. Sun *et al.*, "Simultaneous measurement of pressure and temperature by employing Fabry-Perot interferometer based on pendant polymer droplet," *Opt. Express*, vol. 23, no. 3, p. 1906, Feb. 2015, doi: 10.1364/OE.23.001906.

[9] Y. Wu *et al.*, "Highly sensitive force sensor based on balloon-like interferometer," *Opt. Laser Technol.*, vol. 103, pp. 17–21, Jul. 2018, doi: 10.1016/j.optlastec.2018.01.008.

[10] H. Y. Zebian and H. J. Taher, "Relative humidity sensor based on no-core multimode interferometer coated with Al2O3-PVA composite films," *Opt. Fiber Technol.*, vol. 54, p. 102110, Jan. 2020, doi: 10.1016/j.yofte.2019.102110.

[11] X. Zhou, X. Li, S. Li, G.-W. An, and T. Cheng, "Magnetic Field Sensing Based on SPR Optical Fiber Sensor Interacting With Magnetic Fluid," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 1, pp. 234–239, Jan. 2019, doi: 10.1109/TIM.2018.2834222.

[12] Y. Zhao, J. Zhao, and Q. Zhao, "Review of no-core optical fiber sensor and applications," *Sens. Actuators Phys.*, vol. 313, p. 112160, Oct. 2020, doi: 10.1016/j.sna.2020.112160.

[13] Y. Zhang, L. Zhang, B. Han, P. Gao, Q. Wu, and A. Zhang, "Reflective mercury ion and temperature sensor based on a functionalized no-core fiber combined with a fiber Bragg grating," *Sens. Actuators B Chem.*, vol. 272, pp. 331–339, Nov. 2018, doi: 10.1016/j.snb.2018.05.168.

[14] Y. Zhao, J. Zhao, and Q. Zhao, "Review of no-core optical fiber sensor and applications," *Sens. Actuators Phys.*, vol. 313, p. 112160, Oct. 2020, doi: 10.1016/j.sna.2020.112160.

[15] W. Xu *et al.*, "Improved Numerical Calculation of the Single-Mode-No-Core-Single-Mode Fiber Structure Using the Fields Far from Cutoff Approximation," *Sensors*, vol. 17, no. 10, p. 2240, Sep. 2017, doi: 10.3390/s17102240.

[16] B. Li *et al.*, "No-core optical fiber sensor based on surface plasmon resonance for glucose solution concentration and temperature measurement," *Opt. Express*, vol. 29, no. 9, p. 12930, Apr. 2021, doi: 10.1364/OE.423307.

[17] A. R. Sadrolhosseini, S. Shafie, and Y. W. Fen, "Nanoplasmonic Sensor Based on Surface Plasmon-Coupled Emission: Review," *Appl. Sci.*, vol. 9, no. 7, p. 1497, Apr. 2019, doi: 10.3390/app9071497.

[18] M. A. Fakhri *et al.*, "A gold nanoparticles coated unclad single mode fiber-optic sensor based on localized surface plasmon resonance," *Sci. Rep.*, vol. 13, no. 1, p. 5680, Apr. 2023, doi: 10.1038/s41598-023-32852-6.

[19] S. Lee, H. Song, H. Ahn, S. Kim, J. Choi, and K. Kim, "Fiber-Optic Localized Surface Plasmon Resonance Sensors Based on Nanomaterials," *Sensors*, vol. 21, no. 3, p. 819, Jan. 2021, doi: 10.3390/s21030819.

[20] T. Xu and Z. Geng, "Strategies to improve performances of LSPR biosensing: Structure, materials, and interface modification," *Biosens. Bioelectron.*, vol. 174, p. 112850, Feb. 2021, doi: 10.1016/j.bios.2020.112850.

[21] Y. Zhao, J. Zhao, and Q. Zhao, "High sensitivity seawater temperature sensor based on no-core optical fiber," *Opt. Fiber Technol.*, vol. 54, p. 102115, Jan. 2020, doi: 10.1016/j.yofte.2019.102115.

[22] E. I. Fazrin, A. I. Naviardianti, S. Wyantuti, S. Gaffar, and Y. W. Hartati, "Review: Sintesis Dan Karakterisasi Nanopartikel Emas (AuNP) Serta Konjugasi AuNP Dengan DNA Dalam Aplikasi Biosensor Elektrokimia," *PENDIPA J. Sci. Educ.*, vol. 4, no. 2, pp. 21–39, Jun. 2020, doi: 10.33369/pendipa.4.2.21-39.

[23] Z. Yin, K. Li, X. Jing, S. Ullah, and Z. Zhang, "A broadband SPR sensor based on a no-core fiber

coated with gold-silver for refractive index and temperature measurement," *Infrared Phys. Technol.*, vol. 132, p. 104756, Aug. 2023, doi: 10.1016/j.infrared.2023.104756.

[24] M. Chauhan and V. K. Singh, "ZnO nanostructures coated no-core fiber refractive index sensor," *Mater. Sci. Semicond. Process.*, vol. 147, p. 106757, Aug. 2022, doi: 10.1016/j.mssp.2022.106757.

[25] Z. Yin, K. Li, and X. Jing, "No-core fiber surface plasmon resonance dual-channel sensor for refractive index and temperature sensing with compact structure," *Infrared Phys. Technol.*, vol. 131, p. 104687, Jun. 2023, doi: 10.1016/j.infrared.2023.104687.

[26] B. Li *et al.*, "An ultraviolet sensor based on surface plasmon resonance in no-core optical fiber deposited by Ag and ZnO film," *Surf. Interfaces*, vol. 31, p. 102074, Jul. 2022, doi: 10.1016/j.surfin.2022.102074.

[27] Y. Feng, H. Li, S. Li, Y. Liu, and X. Meng, "A High-Sensitivity SPR Refractive Index Sensor Based on No-Core Fiber with Ag-Cu Composite Films," *Sensors*, vol. 21, no. 21, p. 7000, Oct. 2021, doi: 10.3390/s21217000.

[28] Y. Liu *et al.*, "High-performance surface plasmon resonance refractometer based on a no-core fiber coated with a silver film," *J. Opt. Soc. Am. B*, vol. 38, no. 9, p. 2536, Sep. 2021, doi: 10.1364/JOSAB.433055.

[29] W. Feng, X. Yang, Z. He, and M. Liu, "Hydrogen sulfide gas sensor based on TiO_2 –ZnO composite sensing membrane-coated no-core fiber," *J. Phys. Appl. Phys.*, vol. 54, no. 13, p. 135105, Apr. 2021, doi: 10.1088/1361-6463/abd503.

[30] N. Hidayat *et al.*, "Sensitivity enhancement of gold nanospheres assisted CO2 laser tapered optical fiber for refractive index sensor," *Opt. Fiber Technol.*, vol. 77, p. 103275, May 2023, doi: 10.1016/j.yofte.2023.103275.

[31] C. Ling, J. Li, Y. Wang, H. Chen, L. Gu, and Y. Ding, "Structure optimization of a liquid-sealed SNS fiber optic temperature sensor," *Opt. Laser Technol.*, vol. 162, p. 109290, Jul. 2023, doi: 10.1016/j.optlastec.2023.109290.

[32] Y.-S. Borghei, S. Hosseinkhani, and M. R. Ganjali, "Plasmonic Nanomaterials': An emerging avenue in biomedical and biomedical engineering opportunities," *J. Adv. Res.*, vol. 39, pp. 61–71, Jul. 2022, doi: 10.1016/j.jare.2021.11.006.

[33] S. D. Masitoh, Y. H. P. Isnomo, and L. D. Mustafa, "Desain Sensor Tingkat Kekeruhan Air Menggunakan Bahan Fiber Optik," *J. Jartel J. Jar. Telekomun.*, vol. 11, no. 3, pp. 130–135, Sep. 2021, doi: 10.33795/jartel.v11i3.113.

[34] B. D. Waluyo and J. S. Rambey, "Serat Optik Plastik sebagai Sensor Level Air," *J. Electr. Electron. Eng.*, vol. 7, no. 2, 2023.

[35] P. Halkare, N. Punjabi, J. Wangchuk, A. Nair, K. Kondabagil, and S. Mukherji, "Bacteria functionalized gold nanoparticle matrix based fiber-optic sensor for monitoring heavy metal pollution in water," *Sens. Actuators B Chem.*, vol. 281, pp. 643–651, Feb. 2019, doi: 10.1016/j.snb.2018.10.119.

[36] B. Li *et al.*, "No-core optical fiber sensor based on surface plasmon resonance for glucose solution concentration and temperature measurement," *Opt. Express*, vol. 29, no. 9, p. 12930, Apr. 2021, doi: 10.1364/OE.423307.

[37] S. Daud and J. Ali, "Operational Principles of Fibre Bragg Grating and No-Core Fibre," in *Fibre Bragg Grating and No-Core Fibre Sensors*, in SpringerBriefs in Physics., Cham: Springer International Publishing, 2018, pp. 5–13. doi: 10.1007/978-3-319-90463-4_2.

[38] C. Cunha, S. Silva, O. Frazão, and S. Novais, "Non-Invasive Glucose Fiber Sensor Based on Self-Imaging Technique: Proof of Concept," *EPJ Web Conf.*, vol. 287, p. 09009, 2023, doi: 10.1051/epjconf/202328709009.

[39] M. M. Hasan and H. J. Taher, "The Influence of No-Core Fiber Length on the Sensitivity in Fiber Optic Strain Sensor," 2021.

[40] V. Bhardwaj, A. K. Pathak, and V. K. Singh, "No-core fiber-based highly sensitive optical fiber pH sensor," *J. Biomed. Opt.*, vol. 22, no. 5, p. 057001, May 2017, doi: 10.1117/1.JBO.22.5.057001.