Hindawi
Journal of Nanomaterials
Volume 2023, Article ID 9645272, 7 pages
https://doi.org/10.1155/2023/9645272

Research Article

Intensity Loss of ZnO Coated on Fiber Optic

Noor Azie Azura Mohd Arif[1] **Sahbudin Shaari,**[2] **and Abang Annuar Ehsan**[2]

[1]*Centre for Pre-Universiti Studies, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia*
[2]*Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43000 Bangi, Selangor, Malaysia*

Correspondence should be addressed to Noor Azie Azura Mohd Arif; manaazura@unimas.my and Abang Annuar Ehsan; aaehsan@ukm.my

Received 4 April 2022; Revised 24 November 2022; Accepted 10 December 2022; Published 13 February 2023

Academic Editor: Osman Ahmed Zelekew

Macrobends are optical fiber structures suitable for detecting motion changes. This structure has been developed using single-mode fibers and a combination of single-mode and multimode fibers called hetero-core. In this study, a new macrobending structure was designed and developed by adding a nano-ZnO element to the fiber optic core based on Revolution 4.0. The addition of nanomaterial elements involves an etching process that uses harmful chemicals or high-cost laser technology. Therefore, hetero-core was applied in this study to replace the etching process. The ZnO-coated fiber optics with 10 (ZnO1), 20 (ZnO2), and 30 (ZnO3) times of dip coating were developed using the dip-coating method and characterized using scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) spectroscopy. Sensitivity measurement was conducted with glued optical fiber in the form of bending using a tape with a bending dimension of 2.5 cm × 1.5 cm and a wavelength of 1,550 nm. Morphological characterization using SEM proves that nanoparticles are attached to the optical fiber, and the EDX characterization confirms that the nanoparticles are ZnO elements. Optical fiber sensor sensitivity using core sizes 9, 50–9–50, 50–9–50 (ZnO1), 50–9–50 (ZnO2), and 50–9–50 (ZnO3) achieved sensitivity values of 0.91, 1.61, 2.98, 3.34, and 3.51, respectively. This study successfully produced ZnO-coated optical fiber sensors with a hetero-core structure without performing the etching process and successfully increased the sensitivity of the sensors.

1. Introduction

The studies on respiratory detection using smart watches known as Fitbit have evolved since 2013 [1]. In 2006, researchers in Japan started producing respiratory detection systems using optical fibers affixed to elastic textiles [2]. This study has attracted significant attention because of its importance for human health. Several studies have been conducted on smart textiles. Researchers have studied smart textiles using Bragg grating structures, microbending, and macrobending. The production of smart textiles using Bragg grating-structured optical fibers [3–7] has been developed; however, the operation process is complex and involves high-cost usage [8]. Simpler and more effective smart textiles are designed based on macro- and microbending structures. Krebber et al. [9] conducted studies using a single-mode and bending numbers of more than seven. Alemdar et al. [10] and Koyama et al. [11] developed macrobending and hetero-core-structured sensors to improve the performance of sensor sensitivity [10–12]. The operation of hetero-core optical fiber sensors (62.5–50–62.5 μm) typically involves evanescent field mechanisms to improve sensor sensitivity. This study proves that the sensitivity increases by using only a bending number of seven with the influence of the bending radius [13]. Dhia et al. [13] and Purnamaningsih et al. [14] developed sensors using a single fiber optic mode with a wavelength of 1,550 nm. They successfully produced a bending number of seven without a hetero-core structure. Based on a recent study, macrostructured optical fiber sensors have been successfully used by researchers to detect respiratory system movements. However, the large number of bends makes it difficult for users to wear freely, and most likely, the optical fiber is easily broken when multiple bending is adopted.

The sensitivity generated from an optical fiber sensor can be improved by changing the design of the optical fiber structure.

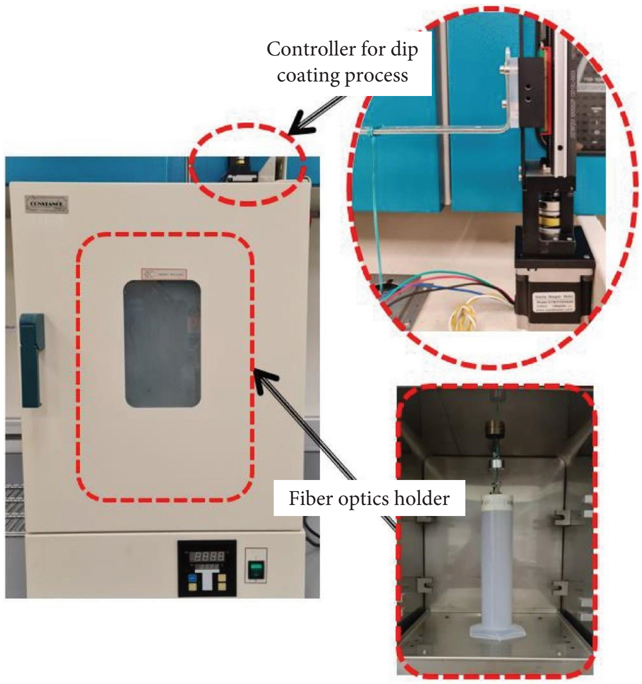


FIGURE 1: Dip-coating process of ZnO nanoparticles.

The sensitivity of the optical fiber sensor increases if the fiber coating refractive index is higher than the fiber core refractive index. The addition of nanomaterial elements to the optical fiber in line with Industry Revolution 4.0 has attracted significant attention because these elements can improve the performance of the optical fiber sensor in terms of the sensor's sensitivity. Macrobending sensors with a small number of macrobending can be developed. However, the addition of nanomaterial elements to the optical fiber involves the removal of the optical fiber coating layer. Nano-coated optical fiber sensors have been developed; however, this process is difficult because it involves an etching process [15–21]. Wet etching can be performed using a cheap method for removing optical fiber silica coated with harmful chemicals, such as hydrofluoric acid [22–25]. Dry etching and inexpensive processes can be conducted mechanically using sandpaper; however, this method is only suitable for polymer fiber optics [26]. Dry etching can be applied to silica fibers using plasma or laser, but it involves high costs [27]. The fragility of equipment and technology for the production process, cost savings, and risk reduction in this research has sparked the idea of developing optical fiber sensors without involving the exposure process. Moreover, the use of hetero-core structures can replace the etching process. This structure helps create the evanescent field phenomenon and helps the light move easily to the fiber coating. This study aimed to develop sensors through the optical fiber inhibition process and the ZnO coating process of nanomaterial on the core optical fiber based on a design optimized using the Taguchi method with a bending dimension of 2.5 cm × 1.5 cm and analyzing the light intensity output on the sensor designed.

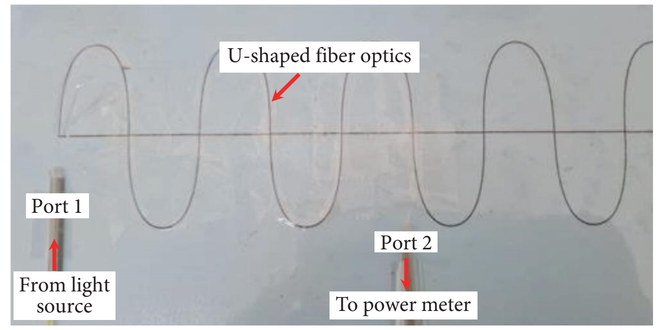


FIGURE 2: Optical fibers are formed in accordance with the U-shaped printed on thick paper.

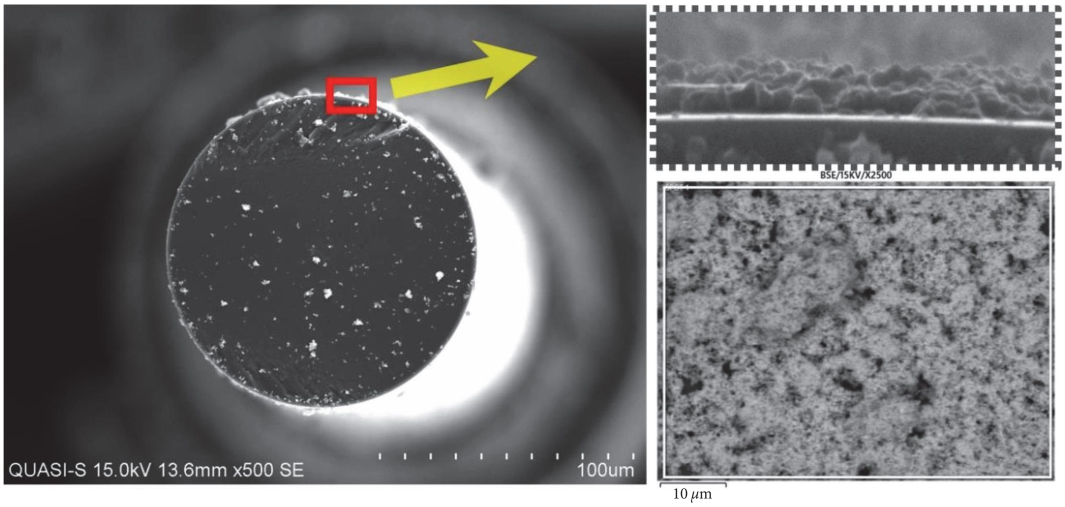
2. Methodology

2.1. Preparation of ZnO-Coated Optical Fiber. ZnO solution was produced by dissolving ZnO powder nanomaterial (544906-50G Sigma Aldrich) into 99.5% ethanol, acting as a solvent. Stirring was conducted for 1 hr with a magnetic stirrer (SH-2). During the stirring process, the solution temperature was set to 78°C, and the process was performed for 30 min. The coating method was used to produce ZnO-coated fiber optic sensors. This method was selected to obtain a uniform coating thickness of ZnO nanoparticles. Optical fiber modification is unnecessary because optical fiber connectivity involves the use of different core sizes but retains the same size of cladding fiber optic. ZnO nanoparticles were coated using a dip coating technique with a dipping movement of 0.0195 cm s^{-1}. The motion controller was placed on the top of the oven (Constance GCH series) to facilitate the coating, evaporation, and annealing processes without involving any movement on the optical fiber (Figure 1). After the coating process, the optical fiber was dried in an oven for 1 min at 78°C to ensure full evaporation. The coating and heating processes were repeated to form several layers of ZnO nanoparticles on the fiber optic surface. ZnO samples of nanomaterials were characterized using SEM and EDX. Furthermore, characterization was performed to confirm that the resulting sample is a ZnO nanomaterial, and morphological structure was observed to determine the thickness and size of the nanomaterial coated on optical fiber.

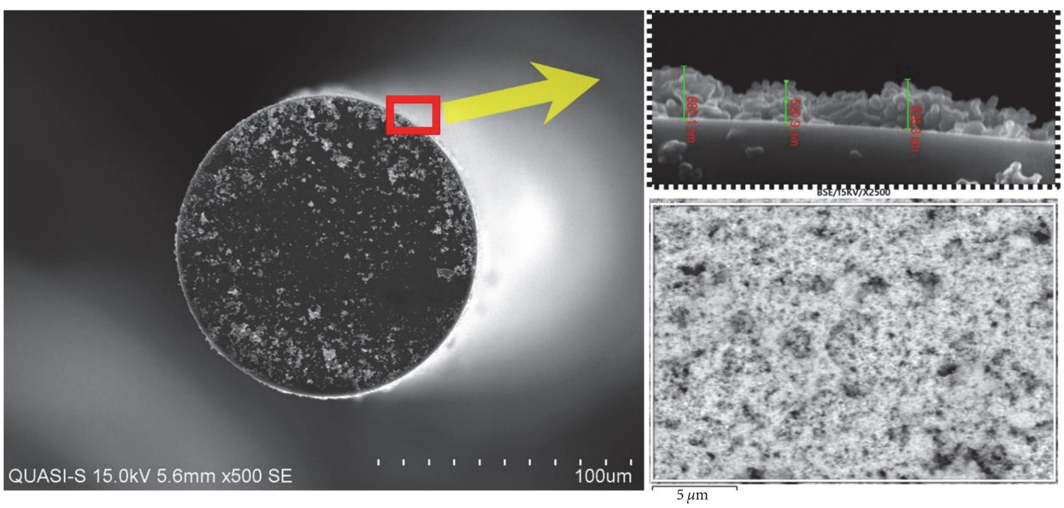
2.2. Output Intensity Measurement. Figure 2 shows a simple and easy method for measuring the intensity output produced by optical fiber sensors. Optical fibers are glued to the paper in the form of bending using a tape. Optimal parameters with bending dimensions of 2.5 cm × 1.5 cm and wavelength of 1,550 nm are used [28].

3. Results and Discussion

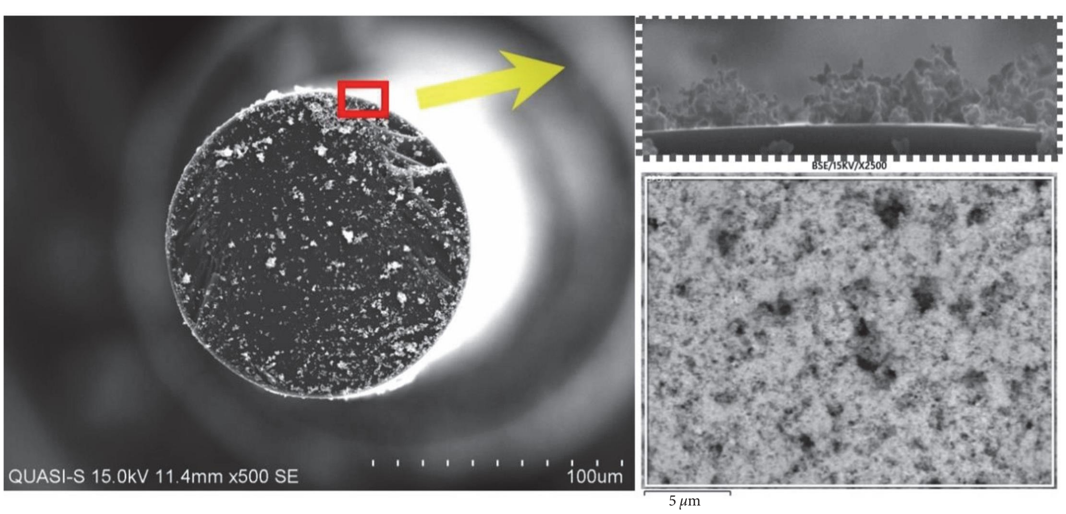
3.1. Characterization of ZnO Nanoparticles. ZnO1, ZnO2, and ZnO3 samples were produced with a total of 10, 20, and 30 times, respectively. The characteristics discussed are morphological structure, film thickness, and film composition. Figure 3 shows the SEM images of ZnO film-coated



(a)

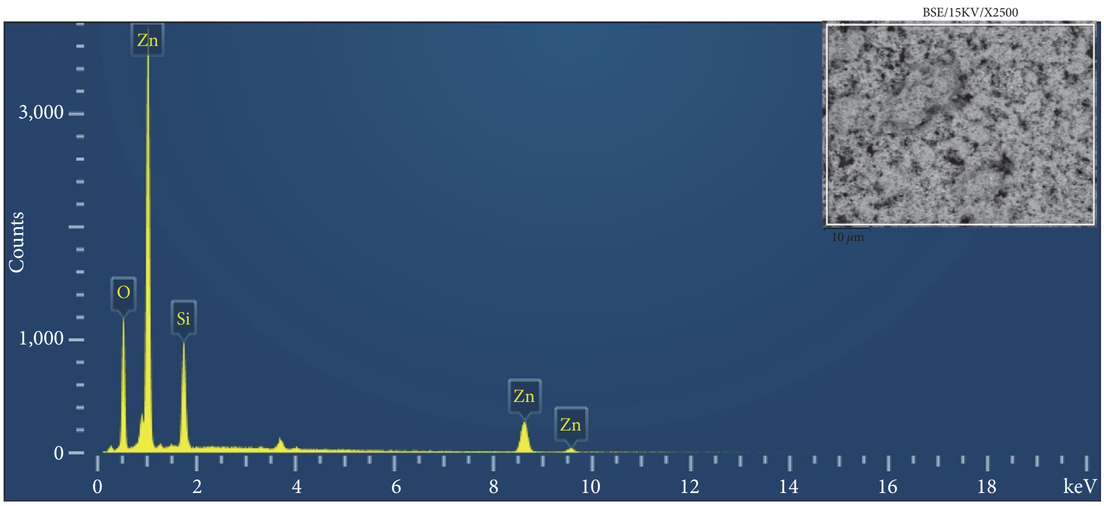


(b)

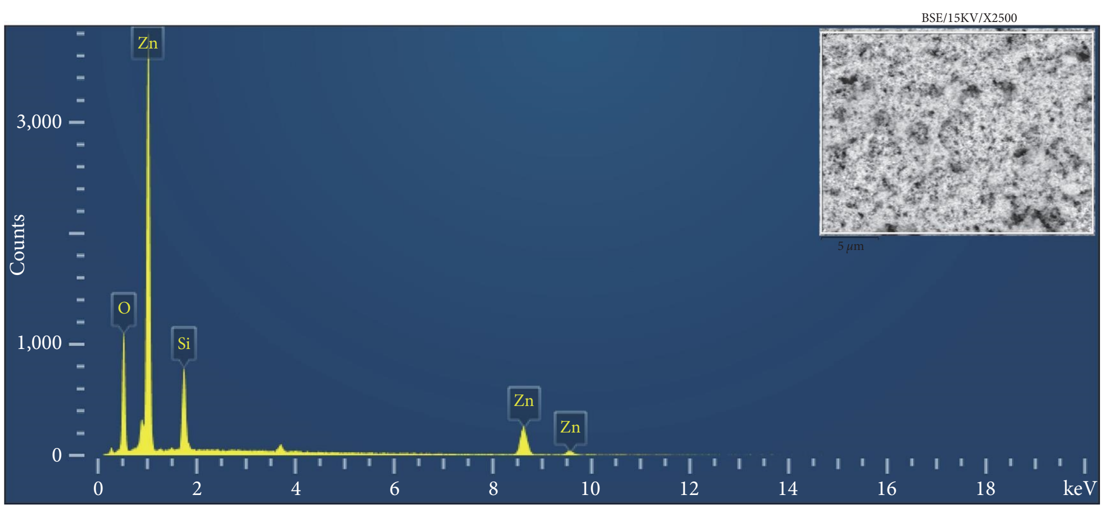


(c)

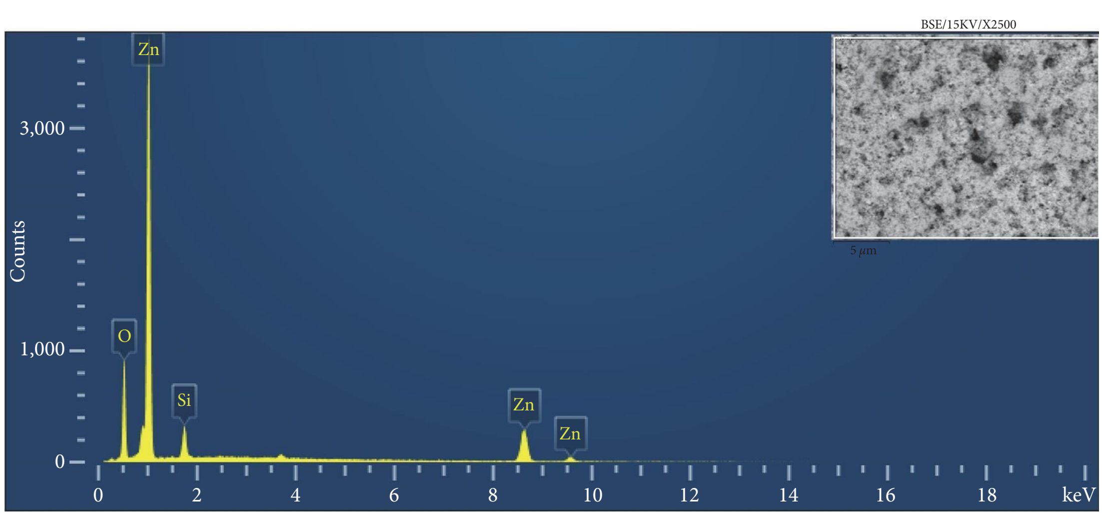
Figure 3: SEM image cross-section sample. (a) ZnO1, (b) ZnO2, and (C) ZnO3 on the fiber optic sphere with a size of 500x magnification, image thickness of ZnO nanoparticles coating scanned on spherical section, and image layer of ZnO nanoparticles on optical fiber surface scanned from the optical fiber surface.



(a)



(b)



(c)

FIGURE 4: Zn and O composition detected by EDX characterization on samples: (a) ZnO1; (b) ZnO2; (c) ZnO3 optical fibers.

TABLE 1: Percentage of atoms measured in ZnO1, ZnO2, and ZnO3 samples through EDX analysis.

Element	Line	Percentage of atoms (%)		
		ZnO1	ZnO2	ZnO3
O	K series	47.93	47.23	46.57
Si	K series	17.00	14.72	7.06
Zn	L series	35.06	38.05	46.36
Total		100.00	100.00	100.00

optical fibers with different thicknesses. It is worth noting that ZnO is successfully coated on the fiber optic surface, and the thickness of ZnO nanoparticles is higher after the fibers had a dip coating of 30 times. The layer of ZnO nanoparticles has thicknesses of 300, 600, and 800 nm with dip coating of 10, 20, and 30 times, respectively. The SEM image clearly shows that the spherical part of the ZnO layer is more attached to the part when the optical fiber is dipped 30 times. High surface balance is visually visible. Additionally, the layer of ZnO nanoparticles approaches a good level of uniformity where mostly the entire surface of the optical fiber is coated with ZnO nanoparticles.

Figure 4 shows that Zn and O are elements detected in silica (Si) compounds. The presence of Si compounds is due to the platform, which is a Si optical fiber. The data reinforce the presence of ZnO nanoparticles formed on the fiber optic layer. Table 1 shows the percentage of composition in three different samples. The Zn values are higher in the ZnO3 sample. This finding is consistent with SEM imaging, indicating that ZnO3 sample has more ZnO nanoparticles on optical fibers dip coated 30 times.

3.2. Analysis of the Design of Optical Fiber Sensor. The resulting output intensity by comparing 9, 50–9–50, and 50–9–50 μm with ZnO nanoparticles was discussed. Bending numbers 1–3 were used to view the intensity output with bending dimensions of 2.5 cm × 1.5 cm operating at a wavelength of 1,550 nm. This study used optimized parameters with the Taguchi method. Figure 5 shows the resulting variation. This figure shows that the combination of heterocore fiber structures with the addition of ZnO layers can increase the sensitivity in terms of bending loss produced by the optical fiber sensor. This sensitivity is observed through the output value generated at the optical fiber output terminal with increasing bending numbers. ZnO1, ZnO2, and ZnO3 labels indicate that optical fibers are coated with a frequency of 10, 20, and 30 times.

The gradient on the graph is determined by Origin software, and the resulting data are summarized in Table 2 to determine the specific sensitivity of each combination. All five combinations showed an increase in loss with an increase in the number of bends. Table 2 clearly shows that the presence of ZnO elements can enhance the sensitivity of the designed fiber optic sensors. Optical fiber sensor sensitivity using core sizes 9, 50–9–50, 50–9–50 (ZnO1), 50–9–50 (ZnO2), and 50–9–50 (ZnO3) provided a sensitivity value of 0.91, 1.61, 2.98, 3.34, and 3.51, respectively.

The sensitivity of these sensors can be attributed to the index differences in the optical fiber structure. The index of the fiber optic coating ranges from 1.45 to 1.55 [29]. Optical fiber coating uses polymer material to protect the optical fiber from fracture. In this study, optical fiber coating was removed using a cleaver and replaced with a ZnO nanoparticle coated with a refractive index of 1.7–2.5 [30–35]. In addition to the nanoparticles produced on optical fibers, the ZnO refractive index plays an essential role in the light propagation throughout the designed optical fiber. This condition is linked to a study by Michel et al. [36]. They stated that greater loss occurs when the coating refractive index is high from the optical fiber cladding refractive index. This study reinforces the findings of Michel et al. [36], where the refractive index is the dominant parameter that determines the output yield at the optical fiber output terminal. The concept highlighted in this study is to perform custom

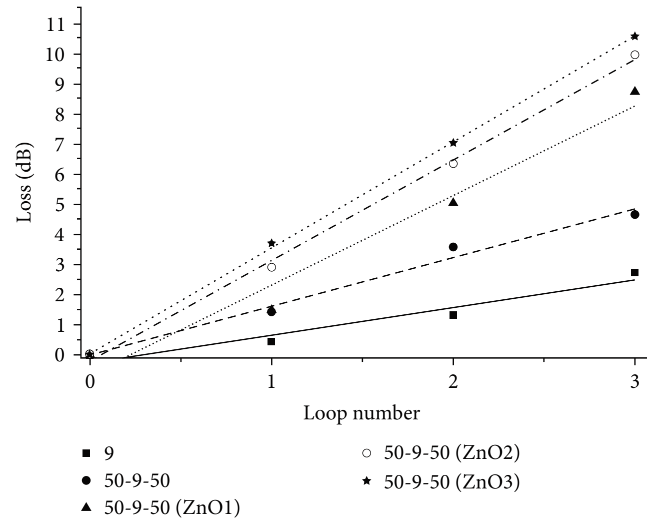


FIGURE 5: Variation in output intensity against bending numbers with the use of 9, 50–9–50, and 50–9–50 μm ZnO nanocoating with different times of dip coating.

TABLE 2: Analytical data for optical fiber combinations with core sizes 9, 50–9–50, 50–9–50 (ZnO1), 50–9–50 (ZnO2), and 50–9–50 (ZnO3) μm using Origin.

Fiber optic combination (μm)	Slope (dB)	Intercept (dB)	Pearson value, R
9	0.91	−0.24	0.97
50–9–50	1.61	−0.01	0.99
50–9–50 (ZnO1)	2.98	−0.65	0.98
50–9–50 (ZnO2)	3.34	−0.20	1.00
50–9–50 (ZnO3)	3.51	0.07	1.00

fiber optic sensor coating. Light will be provided at one end of the optical fiber input, and light transmission will be received at the end of the optical fiber output. When the modification is performed on the optical fiber, some of the light that propagated along the optical fiber is lost through the coating modification area. Changes in output intensity are associated with interactions between optical fiber modification surfaces with light leaks [37].

The light propagation situation is described as where light moves from the dense medium to the less dense and causes the rays to bend away from the normal line. With the addition of ZnO to the hetero-core, light is more likely to go out and cause loss. This condition causes the output of the optical fiber output terminal to decrease compared with that without the ZnO. This change is associated with the light scattering ($n_{\mathrm{ZnO}} > n_{\mathrm{coating}}$) condition. In terms of the light scattering mechanism, the light propagates in the fibers because the ZnO refractive index is higher than the cladding refractive index.

This situation has also been investigated by Apriyanto et al. [38]. Here, when the coating has a low refractive index of the cladding, the mode propagates in the fiber core called full reflection, where the evanescent wave is generated throughout the core–cladding interface. However, when the coating has a refractive index between the core and cladding of the fiber optic core, two phenomena affect the loss of optical power, which reduces the number of propagation modes due to the critical angle influenced by the coating refractive index and the absorption of evanescent waves that occur on the coating–coating interface. Meanwhile, when the coating refractive index is larger than the cladding and core refractive index, the propagation leading to full reflection is no longer met. The transmission beam is not reflected back into the core fiber optic. However, some parts of the power are reflected back into the fiber core with an external reflection mechanism [38]. Figure 5 shows that higher loss is experienced by propagating light inside the optical fiber with an increase in the number of dips. This condition is consistent with the Beer–Lambert law, where the higher the sample thickness, the higher the loss experienced by the input light [39].

4. Conclusion

This study successfully demonstrated the influence of the addition of ZnO nanoparticle elements on optical fibers on the performance of hetero-core macrostructured optical sensor efficiency. The morphological characterization using SEM proves that nanoparticles are attached to the optical fiber, and the EDX characterization confirms that the nanocrystal is ZnO. Comparison is conducted based on the sensitivity of the optical fiber sensor coated with the ZnO nanocrystal with different coating numbers and without the ZnO nanoparticles through the plotted graph on Origin software. Optical fiber sensor sensitivity using core sizes 9, 50–9–50, 50–9–50 (ZnO1), 50–9–50 (ZnO2), and 50–9–50 (ZnO3) provided a sensitivity value of 0.91, 1.61, 2.98, 3.34, and 3.51, respectively. The addition of nanomaterial elements according to Industry Revolution 4.0 can increase the sensitivity of the designed sensors and benefit from research on manufacturing motion detection sensors.

Data Availability

All images and data of samples used to support the findings of this study are included within the article. Further data or information are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are thankful to the Nanophotonics Lab, Institute of Microengineering and Nanoelectronics (IMEN), UKM, and UKM-MTDC Smart Technology Center for providing facilities. Financial support from the Ministry of Higher Education (MOHE), Universiti Malaysia Sarawak (UNIMAS), and Research Innovation and Enterprise Centre (RIEC, UNIMAS) are gratefully acknowledged.

References

[1] Y. Siradj, "Potensi smartwatch untuk kesehatan," *Telekontran*, vol. 4, no. 1, pp. 35–41, 2016.

[2] M. Nishiyama, H. Sasaki, and K. Watanabe, "Wearable sensing clothes embedding a hetero-core optic fiber for recognizing arm segment posture and motion," in *SENSORS, 2006 IEEE*, pp. 1519–1522, IEEE, 2006.

[3] M. Fajkus, J. Nedoma, R. Martinek, M. Novak, J. Jargus, and V. Vasinek, "Fiber optic sensor encapsulated in polydimethylsiloxane for heart rate monitoring," *Fiber Optic Sensors and Applications XIV*, vol. 10208, Article ID 102080W, 2017.

[4] S. Poeggel, D. Tosi, D. B. Duraibabu, G. Leen, D. McGrath, and E. Lewis, "Optical fibre pressure sensors in medical applications," *Sensors*, vol. 15, no. 7, pp. 17115–17148, 2015.

[5] D. Lo Presti, C. Massaroni, P. Saccomandi, M. A. Caponero, D. Formica, and E. Schena, "A wearable textile for respiratory monitoring: feasibility assessment and analysis of sensors position on system response," in *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 4423–4426, IEEE, 2017.

[6] D. Lo Presti, C. Massaroni, D. Formica et al., "Smart textile based on 12 fiber Bragg gratings array for vital signs monitoringe," *IEEE Sensors Journal*, vol. 17, no. 18, pp. 6037–6043, 2017.

[7] D. Lo Presti, C. Massaroni, P. S. E. Schena, D. Formica, M. A. Caponero, and G. Di Tomaso, "Smart textile based on FBG sensors for breath-by-breath respiratory monitoring: tests on women," in *2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, pp. 1–6, IEEE, 2018.

[8] X. Yang, Z. Chen, C. S. M. Elvin et al., "Textile fiber optic microbend sensor used for heartbeat and respiration monitoring," *IEEE Sensors Journal*, vol. 15, no. 2, pp. 757–761, 2015.

[9] K. Krebber, S. Liehr, and J. Witt, "Smart technical textiles based on fibre optic sensors," *OFS2012 22nd International Conference on Optical Fiber Sensors*, vol. 8421, Article ID 84212A, 2012.

[10] K. Alemdar, S. Likoglu, K. Fidanboylu, and O. Toker, "A novel periodic macrobending hetero-core fiber optic sensor embedded in textile for respiratory movements' analysis," *Smart Sensor Phenomena, Technology, Networks, and Systems Integration 2014*, vol. 9062, Article ID 90620D, 2014.

[11] Y. Koyama, M. Nishiyama, and K. Watanabe, "Smart textile using hetero-core optical fiber for heartbeat and respiration monitoring," *IEEE Sensors Journal*, vol. 18, no. 15, pp. 6175–6180, 2018.

[12] C. Massaroni, P. Saccomandi, and E. Schena, "Medical smart textiles based on fiber optic technology: an overview," *Journal of Functional Biomaterials*, vol. 6, no. 2, pp. 204–221, 2015.

[13] A. Dhia, K. Devara, T. Abuzairi, N. R. Poespawati, and R. W. Purnamaningsih, "Design of fiber optic based respiratory sensor for newborn incubator application," *AIP Conference Proceedings*, vol. 1933, no. 1, Article ID 040018, 2018.

[14] R. W. Purnamaningsih, A. Widyakinanti, A. Dhia et al., "Respiratory monitoring system based on fiber optic macro bending," *AIP Conference Proceedings*, vol. 1933, no. 1, Article ID 040012, 2018.

[15] A. Hosoki, M. Nisiyama, and K. Watanabe, "Localized surface plasmon sensor using a hetero-core structured fiber optic with gold island films," *Journal of Physics: Conference Series*, vol. 922, Article ID 012018, 2017.

[16] V. Kapoor and N. K. Sharma, "Fiber optic SPR sensing using zinc oxide," *Materials Today: Proceedings*, vol. 28, Part 1, pp. 14-15, 2020.

[17] M. Nishiyama, M. Sonobe, and K. Watanabe, "Unconstrained pulse pressure monitoring for health management using hetero-core fiber optic sensor," *Biomedical Optics Express*, vol. 7, no. 9, pp. 3675–3685, 2016.

[18] R. Okimuro, M. Nishiyama, A. Hosoki, and K. Watanabe, "Hetero-core fiber optic humidity sensor with layer-by-layer polymer film including TiO_2 nanoparticles using UV light," in *2015 9th International Conference on Sensing Technology (ICST)*, pp. 320–324, IEEE, 2015.

[19] A. Seki, K. Narita, and K. Watanabe, "Refractive index measurement in sucrose solution and beverage using surface plasmon resonance sensor based on hetero-core structured fiber optic," *Procedia Chemistry*, vol. 20, pp. 115–117, 2016.

[20] A. Urrutia, J. Goicoechea, and F. J. Arregui, "Optical fiber sensors based on nanoparticle-embedded coatings," *Journal of Sensors*, vol. 2015, Article ID 805053, 18 pages, 2015.

[21] W.-T. Wu, C.-H. Chen, C.-Y. Chiang, and L.-K. Chau, "Effect of surface coverage of gold nanoparticles on the refractive index sensitivity in fiber-optic nanoplasmonic sensing," *Sensors*, vol. 18, no. 6, Article ID 1759, 2018.

[22] N. H. Sulaiman, H. A. Razak, H. Haroon, A. S. M. Zain, and S. H. S. M. Fadzullah, "Sensitivity enhancement of singlemode–multimode–singlemode fiber optic sensor based on macrobending effect for food composition monitoring," *Journal of Physics: Conference Series*, vol. 1151, Article ID 012026, 2019.

[23] A. R. A. Rashid, A. N. A. Latiff, W. M. Mukhtar, N. A. M. Taib, S. Suhaimi, and K. A. Dasuki, "ZnO coated optical fiber for alcohol sensing applications," *Solid State Phenomena*, vol. 307, pp. 70–77, 2020.

[24] N. Saidin, N. F. Idris, M. H. Yaacob, S. W. Harun, A. A. M. Ralib, and N. F. Hasbullah, "Single-mode fiber coated with zinc oxide (ZnO) nanorods for H_2 gas sensor applications," in *2019 IEEE International Conference on Sensors and Nanotechnology*, pp. 1–4, IEEE, 2019.

[25] P. Zaca-Morán, J. P. Padilla-Martínez, J. M. Pérez-Corte, J. A. Dávila-Pintle, J. G. Ortega-Mendoza, and N. Morales, "Etched optical fiber for measuring concentration and refractive index of sucrose solutions by evanescent waves," *Laser Physics*, vol. 28, no. 11, Article ID 116002, 2018.

[26] F. Abdurrahman, N. Arsad, A. Ashrif, A. Bakar, G. K. Beng, and S. Shaari, "Modified multimode polimer optical nanofiber for volatile organic compound sensing in room temperature," *Journal of Optoelectronics and Advanced Materials*, vol. 21, no. 5-6, pp. 313–319, 2019.

[27] S. R. H. Largani, H.-Y. Wen, J.-L. Chen, and C.-C. Chiang, "Photoresist-free, laser-assisted chemical etching process for long-period fiber grating," *Optics Express*, vol. 27, no. 20, pp. 28606–28617, 2019.

[28] N. A. A. M. Arif and A. A. Ehsan, "Sensitivity optimization of U-shaped fiber optics based on the Taguchi method," *OSA Continuum*, vol. 4, no. 7, pp. 2024–2035, 2021.

[29] S. K. Singh, D. Dutta, S. Das, A. Dhar, and M. C. Paul, "Synthetic and structural investigation of ZnO nano-rods, hydrothermally grown over Au coated optical fiber for evanescent field-based detection of aqueous ammonia," *Materials Science in Semiconductor Processing*, vol. 107, Article ID 104819, 2020.

[30] Z. N. Kayani, M. Iqbal, S. Riaz, R. Zia, and S. Naseem, "Fabrication and properties of zinc oxide thin film prepared by sol–gel dip coating method," *Materials Science-Poland*, vol. 33, no. 3, pp. 515–520, 2015.

[31] S. Sharma, C. Periasamy, and P. Chakrabarti, "Thickness dependent study of RF sputtered ZnO thin films for optoelectronic device applications," *Electronic Materials Letters*, vol. 11, pp. 1093–1101, 2015.

[32] S. R. Schmid and A. F. Toussaint, "Optical fiber coatings," in *Specialty Optical Fibers Handbook*, A. Méndez and T. F. Morse, Eds., pp. 95–122, Academic Press, Burlington, 2007.

[33] M. Hirsch, P. Listewnik, P. Struk, M. Weber, M. Bechelany, and M. Szczerska, "ZnO coated fiber optic microsphere sensor for the enhanced refractive index sensing," *Sensors and Actuators A: Physical*, vol. 298, Article ID 111594, 2019.

[34] N. F. Idris, N. A. M. Yahya, M. H. Yaacob, A. H. Idris, S. W. Harun, and N. Saidin, "Optical fiber coated Zinc Oxide (ZnO) nanorods decorated with Palladium (Pd) for hydrogen sensing," *Optical Materials*, vol. 96, Article ID 109291, 2019.

[35] H. Rafis and A. Rahim, "*Structured growth of zinc oxide nanorods on plastic optical fiber and light side coupling towards sensing applications*," Ph.D thesis, Universiti Malaya, Malaysia, 2017.

[36] Y. P. Michel, M. Lucci, M. Casalboni, P. Steglich, and S. Schrader, "Mechanical characterisation of the four most used coating materials for optical fibres," in *Proceedings of the 3rd International Conference on Photonics, Optics and Laser Technology - Volume 1: PHOTOPTICS*, pp. 96–102, SciTePress, 2015.

[37] S. Devendiran and D. Sastikumar, "Gas sensing based on detection of light radiation from a region of modified cladding (nanocrystalline ZnO) of an optical fiber," *Optics & Laser Technology*, vol. 89, pp. 186–191, 2017.

[38] H. Apriyanto, G. Ravet, O. D. Bernal et al., "Comprehensive modeling of multimode fiber sensors for refractive index measurement and experimental validation," *Scientific Reports*, vol. 8, Article ID 5912, 2018.

[39] A. R. A. Rashid, "*Interaksi medan evanesen dengan pelapisan bahan nano zink oksida untuk sensor gentian optik*," Ph.D thesis, Universiti Kebangsaan Malaysia, Malaysia, 2014.