Real Time in Situ Remote Monitoring for Cladding Modified SMF Integrating Nanocomposite Based Ammonia Sensors Deploying EDFA

HUSAM ABDULDAEM MOHAMMED1,2, MUHAMMAD HAFIZ ABU BAKAR2, (Member, IEEE), SITI BARIRAH AHMAD ANAS2, (Senior Member, IEEE), MOHD ADZIR MAHDI2, (Senior Member, IEEE), AND MOHD HANIF YAACOB2, (Senior Member, IEEE)

1Electronic and Communication Engineering Department, College of Engineering, University of Baghdad, Baghdad 00964, Iraq
2Wireless and Photonics Network Research Centre, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia

Correspondence author: Mohd Hanif Yaacob (hanif@upm.edu.my)

This work was supported in part by the Universiti Putra Malaysia; and in part by the Ministry of Education, Malaysia, under Research Grant FRGS/1/2014/TK03/UPM/03/1 and Grant FRGS/2/2014/TK03/UPM/01/1.

ABSTRACT The increased deployment of optical fiber sensors along with the development of internet of things has increased the demand for real-time in situ remote monitoring systems in the optical sensing industry. Etched-tapered single-mode optical fiber (ETSMF) sensors coated with polyaniline nanofiber/graphite nanofiber (PANI/GNF) nanocomposites have been developed for the real-time in situ remote monitoring of NH3. In this investigation, the sensors with a reel of SMF with 3 km length were integrated with Erbium-doped fiber amplifier (EDFA) with 15 dB gain. Modification performed on SMF significantly enhanced the interaction between the PANI/GNF sensing layer and the evanescent wave due to the light that propagates from the core layer. The response of the modified fiber sensor to NH3 with different concentrations over the C-band (1535–1565 nm) was investigated. The integration of EDFA into SMF sensors extended the remote monitoring distance. In the C band, the developed sensor showed the response, recovery time, and sensitivity of 59 s, 461 s, and 210, respectively. ETSMF sensors coated with nanocomposite of PANI/GNF exhibit successful remote-sensing performances.

INDEX TERMS Remote monitoring, modified SMF sensor, etched-tapered, EDFA, real time, graphite nanofiber.

I. INTRODUCTION Optical fibers have played vital roles in the development of optical communication systems and the telecommunication industry over the past few decades. Intensive studies [1], [2] have been conducted on the consolidation and development of optical fiber sensor networks for applications in communications and in other fields. The research, fabrication, and applications of optics, have drastically expanded. In particular, the gas sensors development led to a technological revolution similar to that facilitated by computers during the 1980s. Thus, the first decade of the present century has been termed as the sensor decade [3]. Sensor technology has witnessed a tremendous advance and more developments are yet to come.

The optical fiber sensors produce fast response in the order of seconds. They also can provide real-time monitoring, that is an important aspect of the industry [4]. The optical sensors have a substantial advantage, which is the ability to be used for in situ real-time remote sensing so that more extensive areas be covered [5]–[7]. Researchers showed intensive focus on modified optical fiber platforms as sensing tools because they have better sensitivity compared to the conventional fibers. Better sensitivity of the modified fiber is due to the evanescent wave which propagates beyond the core area [8].

The implication of optical fiber-based sensors in gas sensing applications has enabled new opportunities for the in-situ detection of various gases like ammonia (NH3) in remote or inaccessible areas. Several fields, such as process control, automotive industry, and medicine, have high demand for the continuous remote monitoring in real-time of
monitoring network to increase monitoring distance. Fiber laser schemes, such as erbium-doped fiber (EDF), are used to extend remote monitoring distance because of their good signal-to-noise ratio (SNR) practically. These schemes usually comprise Raman amplification or other types of amplification methods that combine Raman amplification with Brillouin [26], [27].

This work aims to design and demonstrate a real-time in situ remote monitoring system that is based on a modified SMF gas sensor coated with polyaniline/graphene nanofiber (PANI/GNF) composite. NH$_3$ gas is tested because of its adverse effects and extensive industrial application. Erbium-doped fiber amplifier (EDFA) is incorporated for loss compensation and extending monitoring distance.

II. MATERIALS AND METHODS

A real-time in situ remote monitoring system for etched-tapered single mode optical fiber (ETSMF) NH$_3$ sensors was designed and developed. The system is shown in Fig. 1. The system is comprised of a 3 km SMF link for ETSMF ammonia sensors (G1–G3) coated with PANI/GNF nanocomposite. The design parameters for sensors G1–G3 are listed in Table 1. A standard single-mode silica fiber (SMF-28) with core/cladding diameter of 9 and 125 µm, respectively, was used as the optical sensing platform for ammonia sensing. The fiber was modified using combination of etching and tapering processes. Three chemically etched SMF platforms with diameters of 50 µm were fabricated using hydrofluoric acid (HF). The etched platforms were tapered by using the Vytran Glass Processing System workstation (GPX-3000, USA) with waist diameters of 15, 20, and 25 µm and up tapering, down tapering, and waist lengths of 2, 2, and 10 mm, respectively. The ETSMF platforms were spray-coated with a thin film of PANI/GNF nanocomposite as a sensing layer. In order to prepare the PANI/GNF solution, a 10 mg of PANI powder, 5 mg of GNF, and 15 mg of camphor sulfonic acid are mixed [15]. This mixture is then dissolved in 8 ml chloroform. Next, the solution is stirred for 1 hour and sonicated for one hour (Hielscher, Ultrasound Technique, UPS2005 sonication) [15]. Using the spray method, the PANI/GNF solution is deposited on the modified area of the SMF and under a fume hood. The solution is heated on a hotplate for thirty minutes up to fifty centigrade before deposition. By this, a uniform coating is obtained since the binding of the nanomaterial is increased. The PANI/GNF nanocomposite morphology was investigated using scanning electron microscopy (SEM) as depicted in Fig. 2 (a and b) as published previously by authors in [15]. An ETSMF sensor G1–G3 were used in the investigation. The NH$_3$ sensing performance of the SMF sensors coated with PANI/GNF nanocomposite was remotely monitored and investigated at room temperature over the link of 3 km SMF with the use of EDFA. The measurements are based on the transmission characteristics in the C-band (1535–1565 nm) wavelength range (output optical power in dBm) under exposure to 0.125%–1% NH$_3$. The performance
parameters of the SMF sensors including response, recovery times, and sensitivity were calculated.

The modified SMF sensors were tested by using an ASE source (Amonics ALS 18-B-FA) as a broadband light source and an optical spectrum analyzer (OSA Yoqoqawa AQ-6317) as an optical detector over the C-band wavelength range. For real-time in situ remote monitoring, the 3 km SMF was included as a telecommunication route, and EDFA was included to increase optical response power and transmission distance. EDFA compensates for different sources of losses in the system. These losses include connector loss, splice loss, optical fiber attenuation, and nanostructured thin film absorption, which is the demonstrated loss source. The responses of ETSMF sensor upon exposure to a series of different NH\textsubscript{3} concentrations were investigated to obtain the dynamic response of the sensors. Each gas concentration cycle persisted for 8 min, and sensor air regeneration lasted for 15 min.

### III. REMOTE SENSING RESULTS

The plot of the responses of the sensors over 3 km in the absence of EDFA is shown in Fig. 3. The output optical power of the sensors decreased upon exposure to different NH\textsubscript{3} concentrations beginning from 0.125%. This response, however, weakened as the waist diameter of the platforms increased. The SMF Sensor G3 with the smallest waist diameter (15 µm) showed the maximum decrease in output optical power in response to increasing NH\textsubscript{3} concentrations. The decrease in output optical power is attributable to the increased absorbance of the PANI/GNF nanocomposite upon interaction with NH\textsubscript{3} molecules. Moreover, the response of G3 is more intense than that of G1 and G2. This difference in response resulted from the interaction between the evanescent wave and PANI/GNF nanocomposite. This interaction is stronger in SMF sensors with small waist diameters than in SMF sensors with large waist diameters. Thus, the light intensity decreased. G1 and G2 exhibit similar responses to different concentrations because the evanescent wave on the surfaces of these sensors is not as strong as those on the surfaces of other sensors (G3) and is thus resulted in a detect slight changes in the PANI/GNF sensing layer.

### IV. REMOTE SENSING RESULTS USING EDFA

Longer sensing distances are preferred in remote-sensing applications. The previous subsection showed that optical power declines over a transmission distance of 3 km because of optical fiber attenuation. EDFA (IPG Photonics model EAU-1LT 30 dBm) was used to extend remote monitoring distance. Optical amplification would enhance response magnitude before transmission and enable long-distance monitoring. The ETSMF sensors were remotely monitored over a distance of 3 km, and their NH\textsubscript{3} sensing performance at room temperature in the presence of EDFA was investigated by using the setup shown Fig. 1. Fig. 4 shows the spectrum of the received SMF sensor responses upon exposure.
to different concentrations of NH$_3$ at room temperature after amplification with 15 dB by using EDFA. The optical spectrum of the SMF sensors decreases when the NH$_3$ concentration increased over the range of 0.125% – 1%. Notably, power drastically increases in the presence of EDFA, which compensates for the losses inherent to the developed setup. Moreover, the output optical power decreases as the SMF sensor waist diameter decreases. The use of EDFA has enabled the successful real-time remote sensing of NH$_3$ by the PANI/GNF-coated SMF sensor. As shown in Fig. 2 and 4, the incorporation of EDFA leads to a change in the spectrum of the sensor’s response due to the change in EDFA gain with wavelengths shown in Fig. 5. The maximum gain occurs at 1,535.7 and 1,543 nm. Wavelengths below 1550 nm are intensely amplified by EDFA. By contrast, the power of wavelengths above 1550 nm negligibly increases. Fig. 6 represents the dynamic response of G1–G3 over distances of 3 km in the presence of EDFA. The response time, recovery time, and sensitivity parameters have remained clear and measurable. As shown in the figure, the optical power of the system with EDFA has improved compared with that of the system without EDFA. The increased response of the PANI/GNF nanocomposite-coated SMF sensors to increased NH$_3$ concentrations (0.125%–1%) could be attributed to the increase in the absorbance of the PANI/GNF sensing layer.

There is an inverse proportion between the increase in the NH$_3$ concentration and response time and an inverse relationship with the recovery time. Based on the definition of response time as the duration it takes to rise 90% of the total magnitude, and recovery time as the duration it takes...
to recover to 10% of its baseline [87]. The overall response time for all NH₃ concentrations three sensors are found to be 67.3 s (G1), 61.5 s (G2) and 59 s (G3). The recovery time is 419 s (G1), 438 s (G2) and 461 s (G3).

Remote-sensing performance parameters are dependent on the waist diameters of G1–G3. The output response of G1 is higher than that of G2 and G3, which have small waist diameters. Upon exposure to 0.125% and 1% NH₃, G1 exhibits a received optical power of 9.5 and 8.98 dBm, respectively, over a transmission distance of 3 km with 15 dB EDFA. These values are higher than those measured for the same sensor upon exposure to the same NH₃ concentrations in the absence of EDFA. These results indicates that EDFA successfully compensates for losses within the developed setup without affecting the responses of different SMF sensors to different NH₃ concentrations.

To prove the selectivity of the developed sensors towards ammonia, the sensor G3 was investigated toward methane (CH₄), hydrogen (H₂), and ammonia (NH₃) individually, as shown in Fig. 7. The concentrations of these gases range from 0.125% to 1% at room temperature. It can be seen from the figure that the change in the output optical power during NH₃ exposure is higher than that in the response toward CH₄ and H₂. Thus, the sensors are highly selective towards NH₃.

V. CONCLUSION

The real-time in situ remote monitoring of NH₃ at room temperature by PANI/GNF-coated ETSMF sensors in the presence of EDFA was successfully developed and investigated. Sensing performance was considered in the C-band (1,535–1,565 nm) and through absorbance measurements. The interaction between NH₃ molecules and the PANI/GNF nanocomposite sensing layer increased with NH₃ concentration resulted in light intensity modulation at the sensor output. The remote-sensing response of ETSMF sensors was dependent on the waist diameter of the ETSMF sensors. The ETSMF sensor with the smallest waist diameter showed stronger and faster response with higher sensitivity than SMF sensors with high waist diameters. The ETSMF could detect NH₃ remotely online. Results verified that ETSMF design may enable the elaboration of SMF-transducing platforms with nanostructured sensitive materials. To the best of the author’s knowledge, this work is the first to demonstrate the successful real-time remote monitoring of NH₃ by PANI/GNF-coated SMF sensors in the C-band and in the presence of EDFA.

REFERENCES

[1] N. Abe, N. Shinomiya, and Y. Teshigawara, “Optical fiber sensor network integrating communication and sensing functions using hetero-core spliced fiber optic sensors,” in Proc. Int. Conf. Adv. Inf. Netw. Appl., 2009, pp. 749–757.
[2] S. N. Abdullah, H. A. Jewad, and H. Mohammed, “Design considerations of laser source in a ring network based on fiber distributed data interface (FDDI),” Iraqi J. Laser, vol. 1, no. 1, pp. 39–46, 2002.
[3] S. Rahman, “An approach & evaluation of intelligent sensors & their applications, in electronics and communication engineering,” Ph.D. dissertation, Integral Univ., Lucknow, India, 2015.
[4] P. Castillero, J. Roales, T. Lopes-Costa, J. R. Sánchez-Valencia, A. Barranco, A. R. González-Elípe, and J. M. Pedrosa, “Optical gas sensing of ammonia and amines based on protonated porphyrin/TiO₂ composite thin films,” Sensors, vol. 17, no. 1, pp. 24–38, 2016, doi: 10.3390/s17010024.
[5] Y. S. Chiam, K. S. Lim, S. W. Harun, S. N. Gan, and S. W. Phang, “Conducting polymer coated optical microfiber sensor for alcohol detection,” Sens. Actuators A, Phys., vol. 205, pp. 58–62, Jan. 2014.
[6] N. Díaz-Herrera, O. Esteban, M. C. Navarrete, M. L. Hairet, and A. González-Canó, “In situ salinity measurements in seawater with fibre-optic probe,” Meas. Sci. Technol., vol. 17, pp. 2227–2232, Jul. 2006.
[7] Y. Zhao, X. Zhang, T. Zhao, B. Yuan, and S. Zhang, “Optical salinity sensor system based on fiber-optic array,” IEEE Sensors J., vol. 9, no. 9, pp. 1148–1153, Sep. 2009, doi: 10.1109/JSEN.2009.2026527.
M. Fernandez-Vallejo and M. Lopez-Amo, “Optical fiber networks for
R. A. Perez-Herrera and M. Lopez-Amo, “Fiber optic sensor networks,”
J. Hu, Z. Chen, X. Yang, J. Ng, and C. Yu, “100-km long distance
R. A. Perez-Herrera, M. Fernandez-Vallejo, and M. Lopez-Amo, “Robust
H. A. Mohammed and M. H. Yaacob, “A novel modified fiber Bragg
H. Qazi, A. Mohammad, and M. Akram, “Recent progress in optical
S. Guo and S. Albin, “Transmission property and evanescent wave
G. K. Mani and J. B. B. Rayappan, “A highly selective room temper-
S. Sekimoto, H. Nakagawa, S. Okazaki, K. Fukuda, S. Asakura,
T. Shimogori, and T. Takahashi, “A fiber-optic evanescent-wave hydrogen
gas sensor using palladium-supported tungsten oxide,” Sens. Actuators
H. A. Mohammed, N. A. Rahman, M. Z. Ahmad, M. H. A. Bakar,
S. Guo and S. Albin, “Transmission property and evanescent wave absorption of cladded multimode fiber tapers,” Opt. Exp., vol. 11, no. 3, pp. 215–223, 2003.
G. K. Mani and J. B. B. Rayappan, “A highly selective room temperature ammonia sensor using spray deposited zinc oxide thin film,” Sens. Actuators B, Chem., vol. 183, pp. 459–466, Jul. 2013, doi: 10.1016/j.snb.2013.03.132.
M. H. Yaacob, M. Breedon, K. Kalantar-Zadeh, and W. Wlodarski, “Absorption spectral response of nanotextured WO3 thin films with Pt catalyst towards H2,” Sens. Actuators B, Chem., vol. 137, no. 1, pp. 115–120, Mar. 2009, doi: 10.1016/j.snb.2008.12.035.
S. Sekimoto, H. Nakagawa, S. Okazaki, K. Fukuda, S. Asakura, T. Shimogori, and T. Takahashi, “A fiber-optic evanescent-wave hydrogen gas sensor using palladium-supported tungsten oxide,” Sens. Actuators B, Chem., vol. 66, nos. 1–3, pp. 142–145, Jul. 2000, doi: 10/1016/S0925-4005(00)00330-0.
H. A. Mohammed, Z. Duan, Z. He, X. Li, J. Xu, B. Liu, and Y. Jiang, “Enhanced ammonia response of TiO2 nanoparticles at room temperature,” Sens. Actuators B, Chem., vol. 298, Nov. 2019, Art. no. 126874.
S. Wang, B. Liu, Z. Duan, Q. Zhao, Y. Zhang, G. Xie, Y. Jiang, S. Li, and H. Tai, “PANI nanofibers-supported Nb2O5 nanosheets enabled selective NH3 detection driven by TENG at room temperature,” Sens. Actuators B, Chem., vol. 327, Jan 2021, Art. no. 128923.
Y. Zhang, J. Zhang, Y. Jiang, Z. Duan, B. Liu, Q. Zhao, S. Wang, Z. Yuan, and H. Tai, “Ultrasensitive flexible NH3 gas sensor based on polyaniline/SrGeO2 nanocomposite with ppt-level detection ability at room temperature,” Sens. Actuators B, Chem., vol. 319, Sep. 2020, Art. no. 128293.
H. A. Mohammed, S. A. Rashid, M. H. A. Bakar, S. B. A. Anas, M. A. Mahdi, and M. H. Yaacob, “Fabrication and characterizations of a novel etched-tapered single mode optical fiber ammonia sensors integrating PANI/GNF nanocomposite,” Sens. Actuators B, Chem., vol. 287, pp. 71–77, May 2019, doi: 10.1016/j.snb.2019.01.115.
W. Lei, W. Si, Y. Xu, Z. Gu, and Q. Hao, “Conducting polymer composites with graphene for use in chemical sensors and biosensors,” Microchim. Acta, vol. 181, nos. 7–8, pp. 707–722, 2014, doi: 10.1007/s00604-014-1160-6.
A. M. Lentz, G. Gheno, T. Maraschin, J. A. Malmonge, N. R. de Souza Basso, N. M. Balzaretti, and G. B. Galland, “Nanocomposites of polyethylene/polyaniline/graphite with special morphology,” Polym. Compos., vol. 39, no. 10, pp. 3645–3655, 2017, doi: 10.1002/pc.24392.
A. Nasir, A. Kausar, and A. Younus, “Polymer/graphite nanocomposites: Physical features, fabrication and current relevance,” Polym-Plastics Technol. Eng., vol. 54, no. 7, pp. 750–770, May 2015, doi: 10.1080/360255992014.979503.
Z. Wu, X. Chen, S. Zhu, Z. Zhou, Y. Yao, W. Quan, and B. Liu, “Enhanced sensitivity of ammonia sensor using graphene/polyaniline nanocomposites,” Sens. Actuators B, Chem., vol. 178, pp. 485–493, Mar. 2013, doi: 10.1016/j.snb.2013.01.014.
E. Udd, Fiber Optic Sensors an Introduction for Engineers and Scientists, 2nd ed. New York, USA: CRC Press, 2008.
H. A. Mohammed, N. A. Rahman, M. Z. Ahmad, M. H. A. Bakar, S. B. A. Anas, M. A. Mahdi, and M. H. Yaacob, “Sensing performance of modified single mode optical fiber coated with nanomaterials based ammonia sensors operated in the C-band,” IEEE Access, vol. 7, pp. 5467–5476, 2018, doi: 10.1109/ACCESS.2018.2885560.
H. Qazi, A. Mohammad, and M. Akram, “Recent progress in optical chemical sensors,” Sensors, vol. 12, no. 12, pp. 16522–16556, Nov. 2012.
H. A. Mohammed and M. H. Yaacob, “A novel modified fiber Bragg grating (FBG) based ammonia sensor coated with polyaniline/graphite nanofibers nanocomposites,” Opt. Fiber Technol., vol. 58, Sep. 2020, Art. no. 102282.
R. A. Perez-Herrera, M. Fernandez-Vallejo, and M. Lopez-Amo, “Robust fiber-optic sensor networks,” Photon. Sensors, vol. 2, no. 4, 2021, pp. 368–380.
R. A. Perez-Herrera and M. Lopez-Amo, “Fiber optic sensor networks,” Opt. Fiber Technol., vol. 19, no. 6, pp. 689–699, 2013.
M. Fernandez-Vallejo and M. Lopez-Amo, “Optical fiber networks for remote fiber optic sensors,” Sensors, vol. 12, no. 4, pp. 3929–3951, 2012.
J. Hu, Z. Chen, X. Yang, J. Ng, and C. Yu, “100-km long distance fiber Bragg grating sensor system based on erbium-doped fiber and Raman amplification,” IEEE Photon. Technol. Lett., vol. 22, no. 19, pp. 1422–1424, Oct. 1, 2010.

HUSAM ABDULDAEM MOHAMMED received the B.Sc. degree in electronic and communication engineering and the M.Sc. degree in laser applications in electronic and communication engineering from the University of Baghdad, in 1996 and 2001, respectively, and the Ph.D. degree in photonic engineering field from the Department of Computer and Communication Engineering, University Putra Malaysia, in 2018. Since 2020, he has been with the College of Engineering, University of Baghdad. His research interests include optical fiber communication systems, visible light communications (VLC), LIFI, OCDMA, the Internet of Things (IoT), embedded systems, sensor multiplexing techniques, nanomaterial-based sensors, and optical fiber gas networks.

MUHAMMAD HAFIZ ABU BAKAR (Member, IEEE) received the Ph.D. degree in photonics and fiber optic systems engineering, in 2012. He is currently a Senior Lecturer with Universiti Putra Malaysia (UPM). His current research interests include photonics devices and sensors. He is a member of IEEE Photonics Society and the Optical Society (OSA).

SITI BARIRAH AHMAD ANAS (Senior Member, IEEE) received the B.Eng. degree (Hons.) in computer and electronic systems from the University of Strathclyde, U.K., in 1999, the M.Sc. degree in communication and network engineering from Universiti Putra Malaysia, Malaysia, in 2003, and the Ph.D. degree in electronic systems engineering from the University of Essex, U.K., in 2009. She is currently an Associate Professor with the Faculty of Engineering, University Putra Malaysia. She also actively involved in the Institute of Electronics and Electrical Engineering (IEEE) by serving as the Executive Committee in IEEE Photonics Society Malaysia Chapter for many years. Her research interests include optical transmission systems, optical multiplexing techniques, and optical access network technologies.

MOHD ADZIR MAHDI (Senior Member, IEEE) received the B.Eng. degree from Universiti Kebangsaan Malaysia, in 1996, and the M.Sc. and Ph.D. degrees from Universiti Malaya, in 1999 and 2002, respectively. He is currently an Associate Professor in photonic engineering and joined the Faculty of Engineering, Universiti Putra Malaysia, in 2003. Since 1996, he has been involved in photonics research specializing in optical amplifiers, lasers, and sensors. He has authored and coauthored over 300 journal articles and 200 conference papers. His research interests include optical communications, optical sensors, and nonlinear optics.

MOHD HANIF YACOB (Senior Member, IEEE) received the Bachelor of Engineering degree in electronic computer systems from Salford University, U.K., in 1999, the Master of Science degree in communication and network engineering from Universiti Putra Malaysia, Malaysia, in 2002, and the Ph.D. degree from RMIT University, Melbourne, Australia, in 2012, in the area of optical sensor based on nanomaterials for chemical sensing applications. He is currently the Head of the Wireless and Photonic Networks Research Centre (WiPNET) and also a Lecturer with the Department of Computer and Communication Systems Engineering, Universiti Putra Malaysia. His research interests include nanomaterial-based optical sensors and optical communication systems.