HYBRID FIBER-OPTIC/NANOFIBER SENSOR FOR BRAKE FLUID CONDITION MONITORING

[1]Mayza IBRAHIM, [1]Stanislav PETRÍK

[1]Department of Advanced Materials, Institute for Nanomaterials, Advanced Technology and Innovation, Technical University of Liberec, Liberec, Czech Republic, EU, mayza.ibrahim@tul.cz, stanislav.petrik@tul.cz

https://doi.org/10.37904/nanocon.2022.4584

Abstract

Focus of this paper is to build and investigate an optical fiber sensor based on silica nanofibers prepared by a reliable and low cost electrospinning technique to detect water content in DOT-4 brake fluid. For the best of our knowledge, this is a novelty study of optical fiber sensor to detect water content in an aqueous substance using electrospinning nanofibers. The proposed sensor has a sensitivity of 5.9 nW/1% of water change.

Keywords: Optic fiber sensor, electrospinning, nanofibers, intensity modulation

1. INTRODUCTION

Brake fluid is very important to the brake system and safety of automobiles. Brake fluid is composed of polyethylene glycol which is hydroscopic. Hence it absorbs water from air. Since the brake fluid is not designed in a vacuum system within cars, the moisture easily finds its way to brake fluid. Moisture deteriorates the main function of any brake fluid. Moisture corrodes the main parts of the brake system. Moreover, it decreases the boiling point of brake fluid. Hence the brake fluid will vaporize faster before even reaching its original boiling point. Eventually, it leads to decrease or even failure of the brake capacity.

In automobile industry, oil engine sensors have attracted many researchers and engineers to develop many sensors. Concerning brake fluid condition monitoring, many researchers have focused on developing brake fluid testers. Nowadays at least three commercial brake fluid testers are available in which they mainly depend on physical methods. One of these methods depends on measuring directly the boiling point of the brake fluid, another depends on electrical methods (conductance or capacitance), and the third depends on optical method. These methods mainly depend on electric methods. Hence the brake fluid is usually checked manually with a certain time interval e.g., one or two years [1–3], whereas this checkup could be missed or not even a priority of a driver's vehicle maintenance routine. Hence it is utmost importance for on-line and safe method to monitor brake fluid condition [4–6].

A few studies have been reported for on-line monitoring [7–9]. However, they mainly depend on electric methods. It is not totally safe to depend on electricity when dealing with a flammable substance. Spark could be generated and cause fire which threaten people lives. Data from United states U.S. that more people die in car fires than in apartment fire each year where 1 out of 5 fires involve motor vehicles. U.S. fire department responded to an estimated 278,000 vehicles fire in U.S. during 2006. These fires caused an estimated 490 civilians death and 1,200 civilian injuries. 75 % of those fires were caused by bad maintenance, mechanical or electrical failures or malfunctions. Collision or over turns caused only 3 % of these fires [10]. Therefore, on-line safer method to monitoring brake fluid is utmost importance. Optic methods is safer, however many of optic sensors are still bulky, expensive, and complicated. Much research is going on to involve optic fibers in sensing applications.

Fiber optic sensor technology has been rapidly developed in the past 30 years due to the innovations in telecommunication, semiconductor and electronics sectors which have significantly reduced the prices of optical components and stimulated the development of optical fiber sensor [11]. Optical fiber sensors are capable of measuring a wide variety of physical properties, such as chemical changes, strain, electric and magnetic fields, pressure, temperature, displacement (position), radiation, flow, liquid level, vibrations, and light intensity. Optical fiber sensors exhibit a number of advantages over the conventional electrical and electronic sensors e.g., small sizes and weights, allow access to inaccessible places, permit remote sensing, and immune to radio frequency and electromagnetic interference. In order to improve the sensitivity of optical fiber sensors a layer of sensitive materials is coated on it.

Coating optical fiber surface with hygroscopic-sensitive material enhances the sensitivity. The refractive index of hygroscopic-sensitive material changes in accordance to the humidity or moisture level which change the power intensity of optical fiber. There are many methods for producing thin films for example vacuum evaporation, ion sputtering coating, sol-gel technology, layer-by-layer self-assembly (LBL), and the dip-coating method. Compared with these methods, electrospinning is a simple and effective method to form nanofibers layer.

Electrospinning manifests the capability of any material at the nanoscale especially concerning sensing materials. At nanoscale many features are easily accessible and even improved e.g., excellent mechanical properties, mainly flexibility, high porosity, and large surface area which increases the number of accessible sites for surface functionalization. Another important aspect from sensor point of view that electrospinning produces continuous nanofibers. This feature is important as the sensors are usually assembled in a certain measuring system which involves analog to digital conversion, therefore it should provide a continuous stable signal. Concerning about humidity sensor, the nanofibers layer processed by electrospinning has a larger specific surface area compared to conventional coating film, which can absorb a large number of water molecules [12,13]. Batool et al., 2013 [14] studied the effect of RH on dielectric response of SiO_2 nanofibers. However, it is rarely investigated the effect of RH on refractive index of SiO_2 nanofibers (NF).

In our study we developed a sensor based on hybrid nanofiber- optic fiber for detecting water content on brake fluid that could be later integrated into the vehicle's electronic system for on-line brake fluid monitoring

2. EXPERIMENTATION

Different concentration of DOT-4 (US Department of Transportation) [4–6] solutions were prepared by mixing pure DOT-4 with distilled water. Range of concentration is from 0 to 7 % V/V. The developed sensor

was used to determine the water content presented in brake fluid. The developed fiber optic sensor consists of fiber probe, PVP/SiO_2 composite NFs, Laser diode as a source of light, and Photodetector as a measuring device as pictorial on **Figure 1.**

The developed sensor based on reflective intensity-modulation [15–18]. PVP/SiO_2 composite NFs were produced according to the method descried in patent WO 2017/186201 [19]. The produced composite PVP/ SiO_2 composite NFs were thermal annealed at 300 °C for 6 h [20].

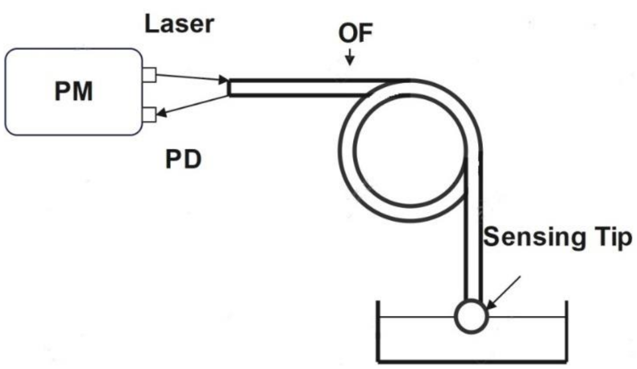

Figure 1 Experimental setup

3. CHARACTERIZATION OF THE COMPOSITE PVP/SIO_2 NFs

The obtained nanofibers composite were characterized by scanning electron microscopy (SEM). Fourier transform infrared microscopy (FTIR) was employed to study the composition of NFs before and after thermal treatment. Energy-dispersive X-ray spectroscopy (EDX) was also employed to investigate the percentage composition of fibers.

4. RESULTS AND DISSCUSSION

4.1. FTIR spectrum

Figure 2 shows the FTIR spectrum taken for the composite before and after thermal annealing. The peaks at 451 cm^{-1} and were assigned to Si-O vibration in TEOS [21]. A number of peaks between 3600 and 2400 long side with peaks at 1633 and 945 cm^{-1} were assigned to O-H vibrations. The peak at 945 cm^{-1} was assigned to Si-OH bond which is disappeared after thermal annealing along with OH bonds. The beaks at 1067 and 797 cm^{-1} were assigned to Si-O-Si bonds which became more intense after thermal annealing. The fibers after thermal annealing composed mainly of Si-O bonds which proved the formation of silica nanofibers.

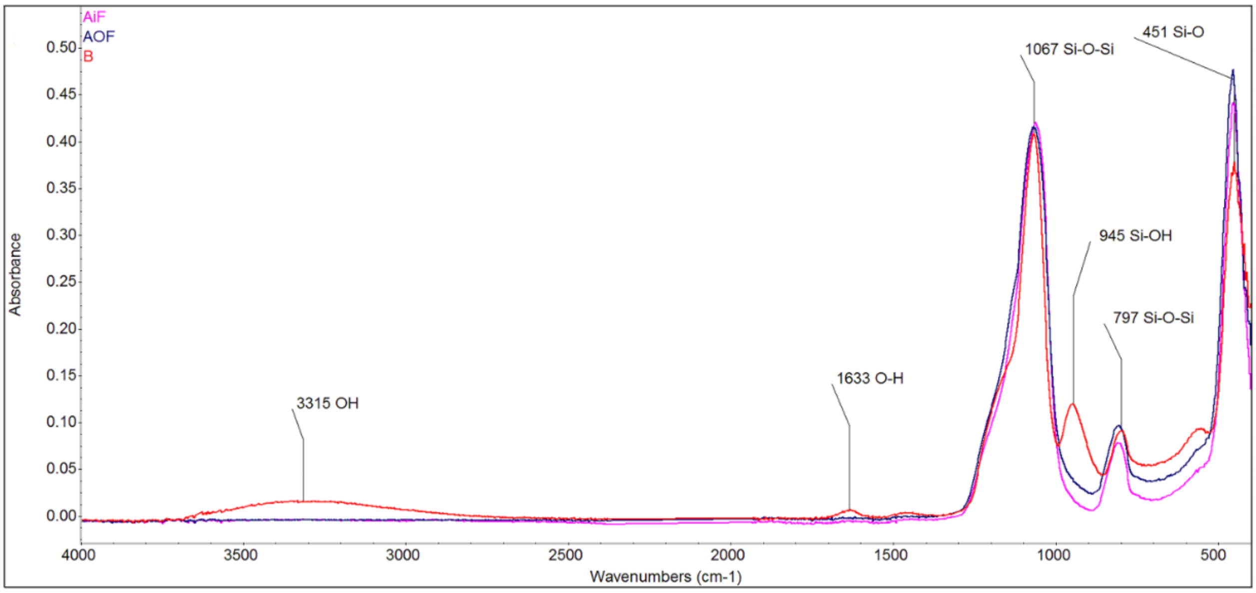

Figure 2 Fourier transform infrared microscopy spectrum taken for nanofibers before and after thermal annealing

4.2. Energy-dispersive X-ray spectroscopy characterization of fibers

Chemical composition of the composite before thermal annealing consisted of O with a percent of 63.7 %, Si of 33.1 % and C of 3.2 % as indicated in **Figure 3** and **Table 1**

Table 1 Chemical composition of the composite before thermal annealing

Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	1.96	0.16	3.25
O	K series	51.26	0.16	63.66
Si	K series	46.78	0.15	33.09
Total:		100.00		100.00

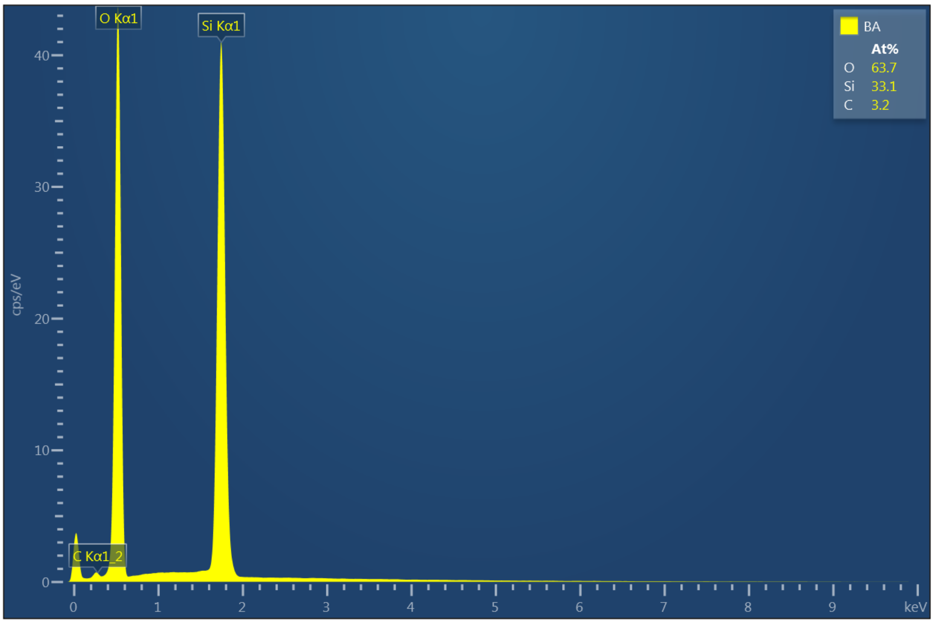

Figure 3 EDX spectrum of SiO_2/PVP Composite before thermal annealing

Chemical composition of the composite after thermal annealing consisted of O with a percent of 60.2%, Si of 36.3 % and C of 3.4 % as indicated in **Figure 4** and **Table 2**

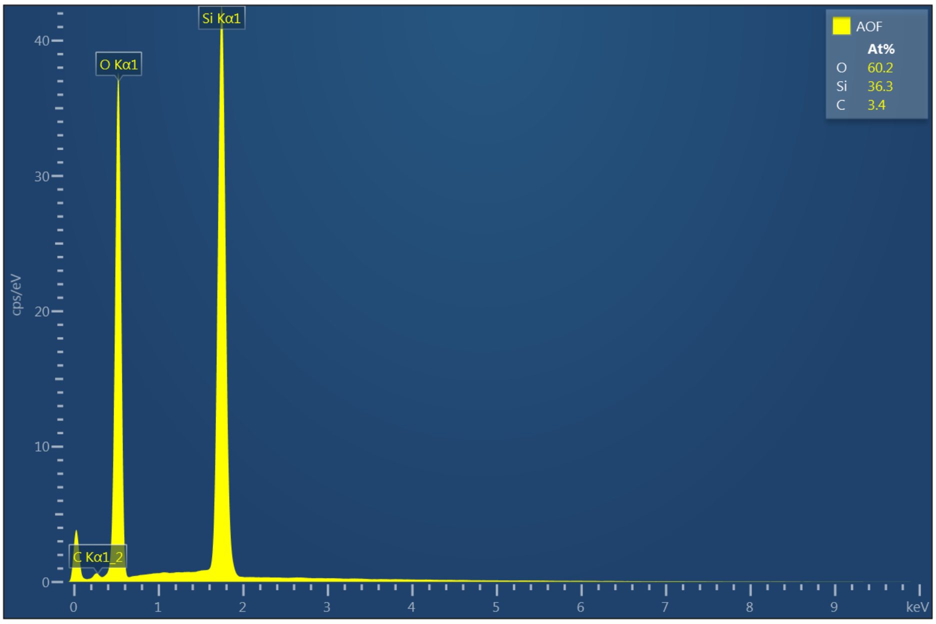

Figure 4 EDX spectrum of the composite NFs after thermal annealing

Table 2 Chemical composition of the composite NFs before thermal annealing

Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	2.02	0.16	2.41
O	K series	47.58	0.16	61.24
Si	K series	50.39	0.16	36.34
Total:		100.00		100.00

Since the thermal annealing was at 300 °C which didn't exceeded the thermal decomposition temperature of PVP, the percent of carbons didn't change. However, the percent of Si increased from 33 % to 36 % on the expense of O. This may be considered as a consequence of vaporization of moisture presented on NFs as FTIR confirms the disappear of hydroxyl group after thermal annealing. In general the chemical composition of SiO_2 NFs was optimally adjusted from the synthesizing process to keep the carbon percent as low as possible 3 % even before the thermal annealing. Hence silica structure was formed which mainly comprised of silicon and oxygen.

4.3. Results of proposed the hybrid-optic fiber sensor

As water content increased on DOT-4, the intensity of the reflected power decreased linearly with sensitivity of 5.9 nW/1% of water change as shown in **Figure 5**

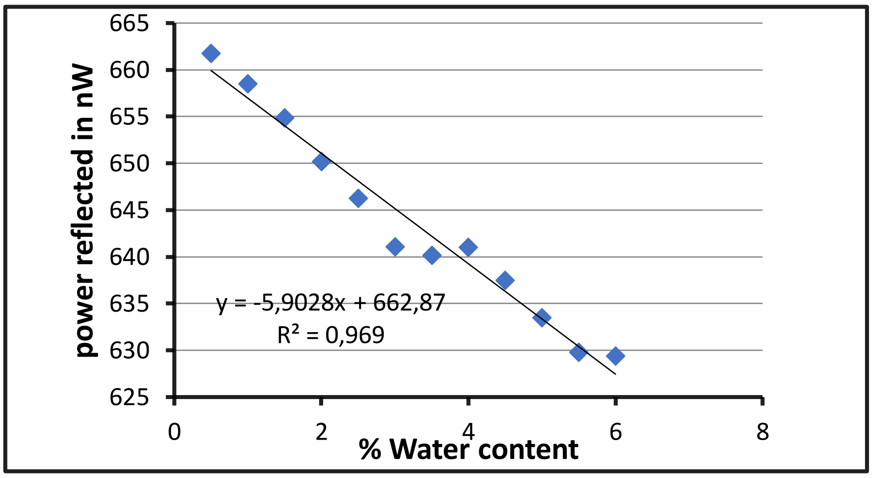

Figure 5 Intensity of reflected light as a function of water content of DOT-4

The power intensity of the reflected power changed linearly as a function of water content in DOT-4 as shown in **Figure 5**. The proposed sensor is based on reflected light intensity modulation. Based on Fresnel reflection, a proportion of lights are leaked out when the sensor is in the liquid rather than air. This amount of light depends on the refractive index of the liquid. For normal incidence, the reflectance simplifies to the following equation Eq. [1].

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2 \quad [1]$$

- n_1, n_2 are the RIs of optical fiber and exterior medium; n_1 are known by the fabrication of the optical fiber; n_2 is variable according to the exterior medium

Since the exterior medium is Dot-4 with different water contents, those water molecules may be absorbed and concentrated in the pores of the silica nanofibers. This effect will alter the refractive index (RI) of the composite NFs; hence change the reflectance. As a result, the accumulation of the water molecules changed the refractive index of composite NFs. Hence, leads to the leakage of the light through evanescent field [22,23]

5. CONCLUSION

The proposed sensor depends on hybrid nanofiber-optic fiber which is simple, straightforward, small size and cost effective has a good repeatability and reasonable sensitivity. Moreover, it is safer to incorporate into car's electronic system for on-line monitoring of DOT condition. The sensitivity could be further enhanced by a special designed electronic circuit in order to enlarge the output signals and at the same time compatible with car's system.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Industry and Trade under the "OP PIK programme" within the framework of project "Hybrid optical fiber sensor for sensing the level and quality of vehicle operating fluids" (registration number CZ.01.1.02/0.0/0.0/20_321/0024437

REFERENCES

[1] J., KUNTNER, R., CHABICOVSKY, and B., JAKOBY. "Oil condition monitoring using a thermal conductivity sensor." In *Proc. GMe Forum (Vienna, USA)*, 2005, pp. 203–209.

[2] S. S., WANG. "Road tests of oil condition sensor and sensing technique." *Sensors and Actuators B: Chemical*. 2001, vol. 73, no. 2–3, pp. 106–111.

[3] B. JAKOBY, M. BUSKIES, M. SCHERER, S. HENZLER, H. EISENSCHMID, and O. SCHATZ. "A novel multifunctional oil condition sensor." in *Advanced Microsystems for Automotive Applications 2001*. *Springer*. 2001, pp. 157–165.

[4] C. WANG and K. SHIDA. "A new method for on-line monitoring of brake fluid condition using an enclosed reference probe." *Measurement Science and Technology*. 2007, vol. 18, no. 11, p. 3625.

[5] R. W. RADLINSKI, R. J. FORTHOFER, and J. L. HARVEY. "Operating performance of motor vehicle braking systems as affected by fluid water content." *SAE Transactions*. 1971, pp. 1037–1045.

[6] K.-H. DIETSCHE and M. KLINGEBIEL. "Bosch Automotive Handbook." *7th Editio, Robert Bosch GmbH*. 2007.

[7] E. IRION, K. LAND, T. GÜRTLER, and M. KLEIN. "Oil-Quality Prediction and Oil-Level Detection with the TEMIC QLT-Sensor Leads to Variable Maintenance Intervals." *SAE International, Warrendale, PA*. SAE Technical Paper 970847, Feb. 1997. Available from: https://doi.org/10.4271/970847.

[8] M. J. KAO, D. C. TIEN, C. S. JWO, and T. T. TSUNG. "The study of hydrophilic characteristics of ethylene glycol," *J. Phys.: Conf. Ser.* 2005, vol. 13, pp. 442–445. Available from: https://doi.org/10.1088/1742-6596/13/1/102.

[9] T. E. RYAN and T. HINZ. "Analysis of Water Content in Brake Fluid. Part I. Method Comparison: Karl Fisher Titration Versus Refractive Index." *SAE Transactions.* 1997, vol. 106, pp. 3399–3404.

[10] "Escape and Safety from Vehicle Fire." *Arrive Alive*. https://www.arrivealive.mobi/Escape-and-Safety-from-Vehicle-Fire (accessed Sep. 06, 2022).

[11] M. YASIN, H. AROF, and S. W. HARUN. *Fiber optic sensors*. BoD–Books on Demand, 2012.

[12] M. D. MORALES-ACOSTA, M. A. QUEVEDO-LOPEZ, H. N. ALSHAREEF, B. E. GNADE, and R. RAMÍREZ-BON. "Dielectric properties of PMMA-SiO2 hybrid films." In *Materials Science Forum*, 2010, vol. 644, pp. 25–28.

[13] T. WAGNER *et al*. "A high temperature capacitive humidity sensor based on mesoporous silica." *Sensors*. 2011, vol. 11, no. 3, pp. 3135–3144.

[14] S. S. BATOOL *et al.* "Silica nanofibers based impedance type humidity detector prepared on glass substrate." *Vacuum*. 2013, vol. 87, pp. 1–6.

[15] J. ZHENG and S. ALBIN. "Self-referenced reflective intensity modulated fiber optic displacement sensor." *Optical engineering*. 1999, vol. 38, no. 2, pp. 227–232.

[16] W. YAO *et al.* "Intensity Modulated Fiber Optic Sensor: A Novel Grid Measurement Unit." *IEEE Transactions on Industrial Informatics*. 2022.

[17] P. RORIZ, A. RAMOS, J. L. SANTOS, and J. A. SIMÕES. "Fiber optic intensity-modulated sensors: A review in biomechanics." *Photonic Sensors*. 2012, vol. 2, no. 4, pp. 315–330.

[18] D. A. KROHN. "Intensity modulated fiber optic sensors overview." In *Fiber Optic and Laser Sensors IV.* 1987, vol. 718, pp. 2–11.

[19] J. RUZICKOVA, M. TEJKL, A. KUDROVA, Z. VOSATKA, and J. BUK, "Precursor Fibers Intended for Preparation of Silica Fibers, Method of Manufacture Thereof, Method of Modification Thereof, Use of Silica Fibers." 2017.

[20] S. S. BATOOL *et al.* "Silica nanofibers based impedance type humidity detector prepared on glass substrate." *Vacuum.* 2013, vol. 87, pp. 1–6.

[21] Y. ZHAO, H. WANG, X. LU, X. LI, Y. YANG, and C. WANG. "Fabrication of refining mesoporous silica nanofibers via electrospinning." *Materials Letters*. 2008, vol. 62, no. 1, pp. 143–146.

[22] T. YUAN *et al.* "Humidity sensor based on micro optical fiber array fabricated by electrospinning." *Optics Communications*. 2018, vol. 427, pp. 517–521.

[23] G. LIU *et al.* "Low-loss prism-waveguide optical coupling for ultrahigh-Q low-index monolithic resonators." *Optica*. 2018, vol. 5, no. 2, pp. 219–226.