Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Modelling a D-shaped Sensor for Transformer Oil Refractive Index Detection

Muhammad Zakir Md Yasin[1], Nor Hafizah Ngajikin[1,*], Siti Hajar Aminah Ali[1], Muhammad Sazlan Abdul Kadar[1], Nurfatihah Che Abd Rashid[1], Mohd Aizam Talib[2], Noran Azizan Cholan[1]

[1] Department of Electrical and Electronic Engineering Universiti Tun Hussein Onn, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[2] Advanced Diagnostic Services, TNB Labs Sdn Bhd, Kawasan Institusi Penyelidikan, 43000 Kajang, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 15 October 2023
Received in revised form 17 December 2024
Accepted 4 January 2024
Available online 23 February 2024

Keywords:
Plastic Optical Fiber; Refractive index sensor; Electric field distribution; Mode field diameter

ABSTRACT

A simulative-based investigation using COMSOL Multiphysics software has been carried out to study the sensing performance of a D-shaped refractive index (RI) sensor in the ageing detection of transformer oil. In this work, a D-shaped plastic optical fiber (POF) RI sensor has been modelled to have a curve surface for its D region. This surface that exposed some parts of the POF core and cladding, enables interaction between the transformer oil located in the D region with optical light propagate in the POF. The simulation has been conducted to study the effect of D region diameter towards the sensor electric field distribution, sensitivity and linearity performances. The transformer oil RI value is ranging from 1.4785 to 1.4807, which is based on the transformer oil samples provided by the TNB Labs Sdn Bhd. The RI variations affect the evanescent wave's penetration depth, thus varying the electric field distribution in the sensor. In this investigation, the 0.75cm diameter of the D-shaped POF RI sensor exhibits the highest sensitivity of -0.1426 RIU^{-1} with a linearity of 0.9998 at 660nm wavelength. The proposed D-shaped RI sensor offers a sensor with high linearity performance sensor to be applied in transformer oil ageing detection.

1. Introduction

In recent years, optical and fiber optic sensors have been widely discussed and gained increasing interest from researchers, primarily due to their numerous advantages over conventional sensors. These advantages have propelled the widespread adoption and exploration of fiber optic sensors in various fields and applications, including their high sensitivity, small size, safety, stability, capability for remote monitoring, and suitability for harsh environments [1-4]. Numerous researchers working on optical fiber sensors (OFS) have proposed various techniques and designs for optical fiber sensing elements, such as balloon-like bent [5], U-bent [6], D-shaped [7,8], and C-shaped [9] OFS. These sensors are suitable to be applied in various applications for monitoring physical parameters due to

* *Corresponding author.*
E-mail address: norhafizah@uthm.edu.my

https://doi.org/10.37934/aram.114.1.4350

their unique properties, such as strain, temperature, pressure, humidity, refractive index, and high voltage (HV) insulation ageing [1,3].

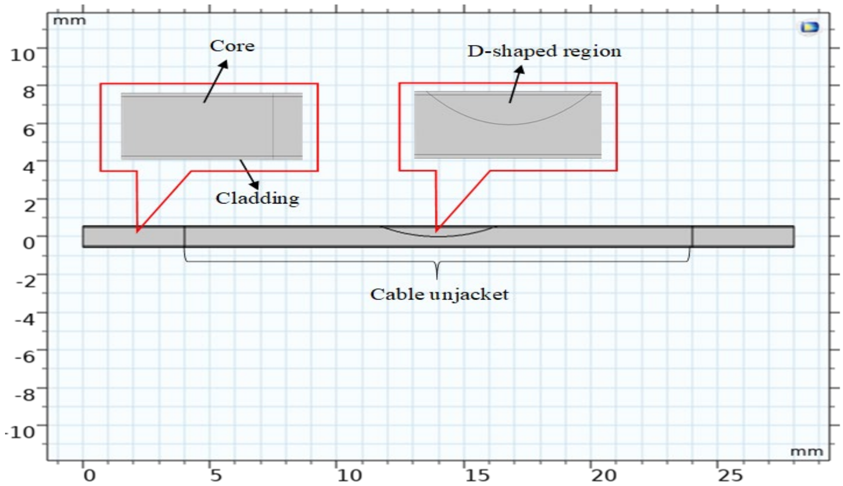
Refractive index (RI) measurement is significant across various fields, including chemical analysis, biological research, medical diagnostics, food and beverage Industry and environmental monitoring. In the literature, various types of refractive index (RI) sensors have been applied in electrical power engineering for transformer oil analysis including Mach–Zehnder Interferometer [10], Fabry–Perot interferometer [11] and multimode interference (MMI) [12,13]. These wavelength-modulated-based RI sensors have advantages in their immunity towards system attenuation. However, the sensors normally require more expensive detection equipment and complex fabrication procedures. In contrast, an intensity-based RI sensor can be implemented using a lower cost of detection equipment with a simple fabrication technique. In 2020, an intensity-based RI sensor has been deployed using a simple side polishing technique to form a D-shaped plastic optical fiber (POF) with a flat surface area for a transformer oil RI measurement [7]. This D-shaped POF sensor has a flat surface, which limits the reflection and refraction of light propagation on the POF and oil boundary.

Therefore, this work proposes a curved surface on the D-shaped POF to enhance the sensor sensitivity performance. This curvature introduces a multi-reflection and refraction of light propagation in the POF sensor, thus improving the RI sensing. The usage of POF in RI sensors offers ease of machinability in fabrication and handling [14,15]. The proposed sensor was developed using the wave optics module in COMSOL Multiphysics software to investigate the sensing performance. This software which works based on the finite element method (FEM) was utilized to identify the optimal design for detecting ageing in transformer oil. The simulation evaluates the electric field distribution throughout the sensor for 0.5, 0.75 and 1.0 cm diameters of the curve surface on the D-shaped structure.

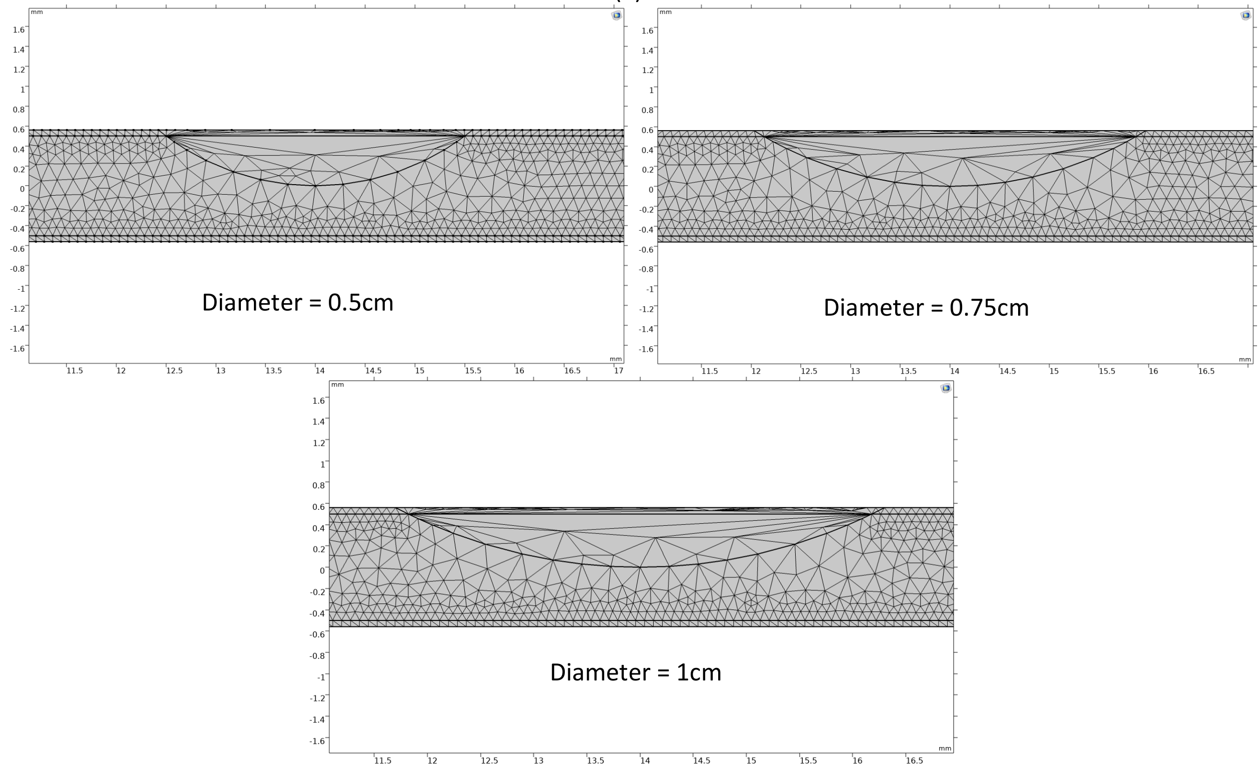
2. Modeling and Method

The development of the proposed D-shaped POF sensor in COMSOL Multiphysics software is described in this section. The sensor has a core and cladding diameter of 1000µm with a refractive index of the core and cladding of 1.492 and 1.417, respectively [16]. The sensor system was set to operate at 660nm wavelength [7]. In this paper, the proposed sensor features a new design that modifies the core and cladding configuration, forming a curved surface as opposed to the conventional D-shaped geometry structure with flat surfaces [17,20]. The D-shaped region refractive index value was set from 1.4785 to 1.4807. These values are the actual RI of the ageing transformer oils supplied by TNB Labs Sdn Bhd that was measured using a commercial refractometer. As aforementioned, the curved surfaces, enable the evanescent field of guided light to have better interaction with the external medium and measure changes in the refractive index due to multiple reflections and refractions in the sensor head [7].

To form a curved surface on the D-shape POF sensor shown in Figure 1(b), a part of the POF core and cladding was removed, forming a partly cylinder shape. In this work, 0.5cm, 0.75cm, and 1.0cm diameters were investigated. Theoretically, the D-shape diameters will influence the sensor performance by varying the reflected and refracted angle of light at the boundary [7]. This angle variation will influence the sensor performance. To simulate the light propagation, the developed sensor simulation domain is divided into smaller subdomains and meshed using a standard free triangular type and normal mesh size. For this setting, the software will automatically mesh the sensor structure into an optimal number of triangular shapes with various sizes. The normal setting is chosen to achieve the optimal computation process. In this type of mesh, the subdomains with varying mesh dimensions have smaller sizes near the boundaries between different media to accommodate steeper field variations [17]. Smaller mesh elements provide better accuracy of the sensor analysis on the interaction between the refracted light and the external medium with transformer oil refractive index value in the D-shape region. This mesh size, however, will influence the simulation processing time. As for the boundary condition, the 'Transition Boundary Condition' setting is selected in this software, which assumes that the wave travels in the normal direction at the thin layer.



(a)



(b)

Fig. 1. The D-shaped POF RI sensor developed in COMSOL Multiphysics (a) The 2D design of the D-shaped RI sensor (b) The meshed D-shaped RI sensor

To understand the sensing mechanism, understanding the evanescent field is discussed in this section. An evanescent field emerges from light propagating within an optical fiber, where a portion of the radiation extends a short distance from its original region into the surrounding medium with a lower refractive index [20]. Theoretically, an evanescent wave decays exponentially as the distance from the interface the refractive index of the fiber core and surrounding medium. The penetration depth (d_p) of an evanescent wave (EW) can be expressed as [18]:

$$d_p = \frac{\lambda}{2\pi\sqrt{N_{co}^2 sin^2\theta - N_{cl}^2}} \quad (1)$$

where λ is the wavelength of the light, N_{co} is the refractive index of the fiber core, N_{cl} is the refractive index of the analyte that covers the cladding, and θ is the angle of incidence of the wave concerning the normal to the interface between the core and cladding. The COMSOL Multiphysics uses the complex refractive index equation to model the behaviour of light in the D-shaped RI sensor. The complex refractive index equation is given by [19]:

$$n_{complex} = n_{real} + ik \quad (2)$$

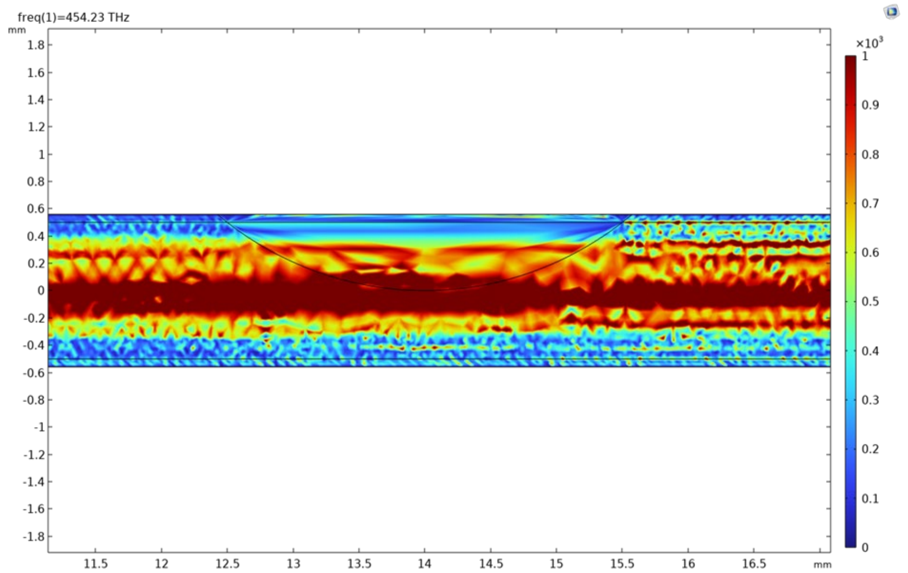
where $n_{complex}$ represents the complex refractive index, n_{real} corresponds to the real component of the refractive index, which determines the phase velocity of light. ik is the imaginary part of the refractive index, which determines the absorption or attenuation of light. Changes in the material's real refractive index or absorbance caused by an analyte's presence can alter the optical fibers' transmission properties. This alteration can be detected and analyzed to determine the presence or concentration of analytes in sensing applications. Table 1 lists the sensor parameters set in the simulation.

Table 1
Sensor parameter setting in COMSOL Multiphysics software

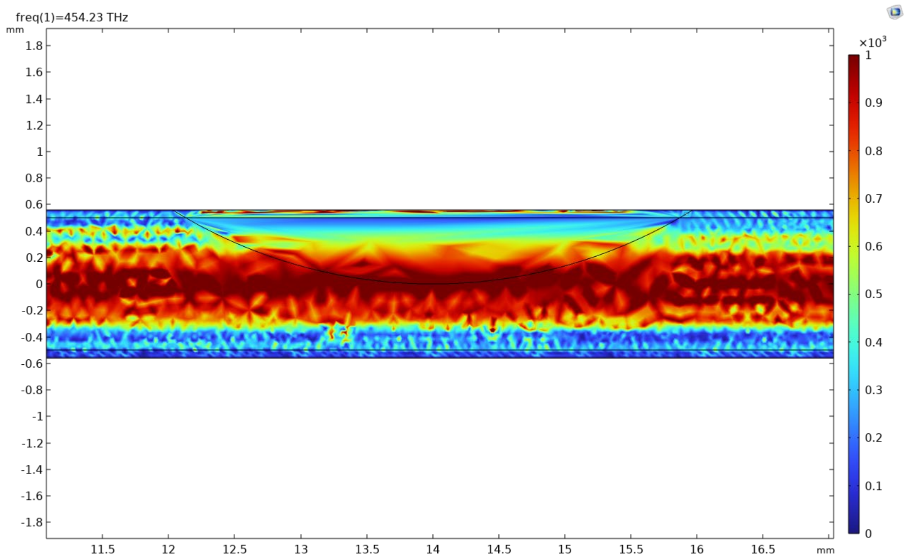
Symbol	Description	Value
n_cl	Refractive index cladding	1.417
n_co	Refractive index core	1.492
n_oil	Refractive index of oil	1.4785, 1.4790, 1.4798, 1.4803, 1.4807
lambda	Operating wavelength	660nm
Ida0	Vacuum condition	1µm
fo	Operating frequency	c_const/lambda[nm]

3. Results and discussion
3.1 Electric Field Distribution

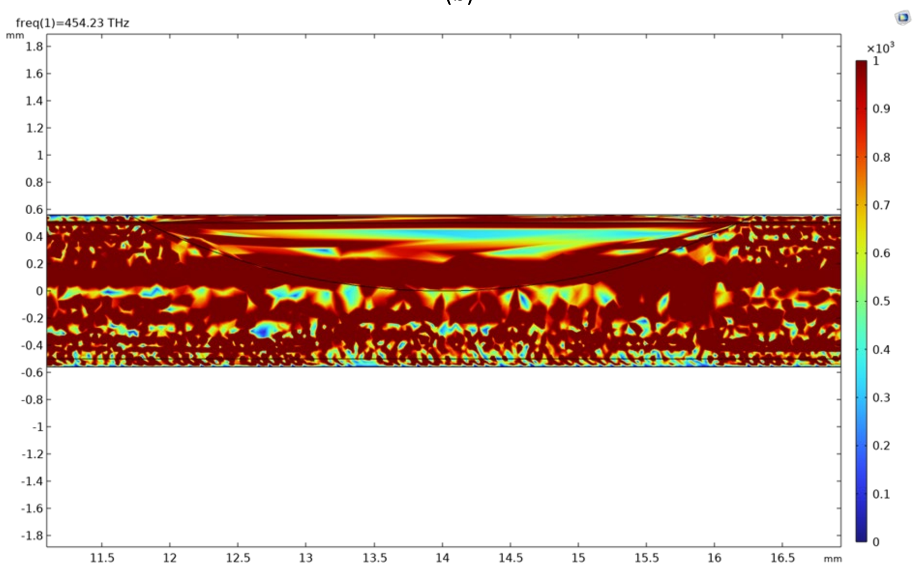
Analysis of the curve surface diameter effect in a D-shaped POF sensor was conducted using the Mode Analyses (MA) module in COMSOL Multiphysics software. The MA module produces an electric field intensity for 0.5, 1.0 and 1.5mm diameters. The results are plotted in Figure 2(a), (b) and (c) for an RI value of 1.4785. In this software, the magnitude of the field intensity is indicated by a colour indicator located next to these figures, where the red colour indicates the maximum field intensity while the blue colour indicates the minimum field intensity. It can be seen that electric field distribution in the sensor is concentrated along the fiber core except at the curve D region. In the D region, the electric field started to experience loss depending on the RI value.



(a)



(b)



(c)

Fig. 2. Electric field intensity of the D-shape POF sensor for RI=1.4785 (a) 0.5cm (b) 0.75cm and (c) 1cm

Next, the sensor intensity is analyzed for different values of transformer oil RI. In COMSOL Multiphysics software, this analysis was conducted using the Mode Field Diameter (MFD) module. Figure 3 shows the electric field for all sensor models analyzed using the MFD. It can be seen that the electric field experiences reduction for an increase of transformer oil RI, showing that the proposed sensor able to sense and differentiate the RI level [8]. For 1.4785 RI, the maximum electric field is 1004.45 V/m for the sensor with a 0.5cm diameter, while the minimum electric field is 973.61 V/m for the sensor with a 1.0cm diameter.

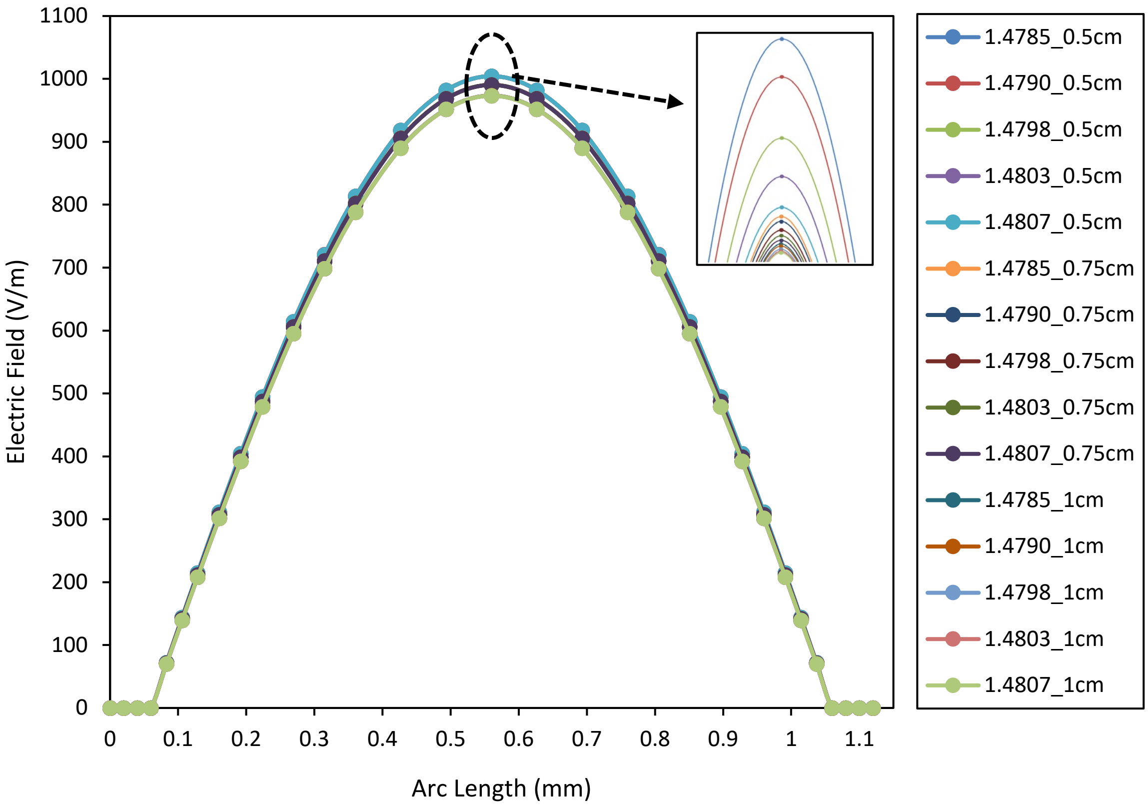


Fig. 3. The electric field intensity across the D-shape POF sensor

3.2 Sensor Sensitivity and Linearity Performances

The sensor sensitivity and linearity performances are analyzed from the normalized electric field curve shown in Figure 4. It was observed that an increase in the oil RI leads to a decrease in the normalized electric field. Theoretically, the increment of RI causes a corresponding change in the direction of light from the sensor into the D-shape region [8]. In this work, the sensor with a 0.75cm diameter has the highest sensitivity performance, which is 0.1426 RIU^{-1}. In contrast, the sensor with a 0.5cm diameter exhibits the lowest sensitivity of 0.0103 RIU^{-1}. The sensitivity performance is slightly lower than the previous optical planar D-shape sensor reported in [8] and the C-shape sensor reported in [9], which are 2.83 RIU^{-1} and 0.97 RIU^{-1} respectively. As for the linearity performance, all the sensors have a very good linearity which is higher than 0.9998. The linearity performance is comparable with the previous optical planar D-shape sensor reported in [8], which is 0.99.

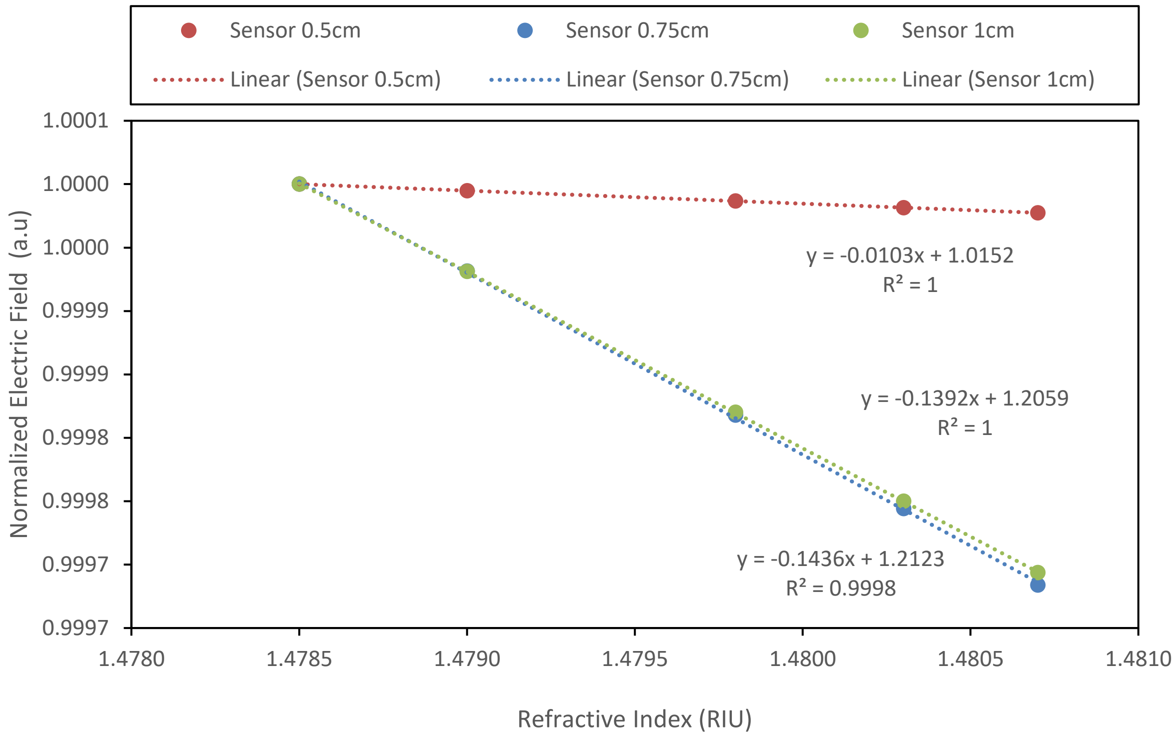


Fig. 4. The normalized electric field intensity

4. Conclusions

In conclusion, the investigation of a D-shaped POF sensor with curve surfaces using COMSOL Multiphysics software for transformer oil RI detection has been successfully conducted. The results show that the electric field distribution in the D-shaped POF sensor varied with the curve surface diameter, with a larger diameter resulting in a decreased field due to the dispersion effect. In the MFD analysis, the sensor's field intensity is influenced by the curve diameter and transformer oil RI, affecting the penetration depth of the evanescent wave, hence varying the sensor output intensity. Sensor with all curve diameters exhibits very good linearity which is above 0.9998. This study found that the 0.75cm diameter of the D-shaped POF sensor achieves the highest sensitivity with 0.1426 RIU^{-1} with 0.9998 linearity performance. This achievement proves the suitability of the proposed sensor to be adopted in transformer oil RI sensing applications.

Acknowledgement
This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through TIER1 (vot Q129) and GPPS (vot Q243).

References
[1] N'cho, Janvier Sylvestre, and Issouf Fofana. "Review of fiber optic diagnostic techniques for power transformers." *Energies* 13, no. 7 (2020): 1789. https://doi.org/10.3390/en13071789
[2] Mahanta, Deba Kumar, and Shakuntala Laskar. "Water quantity-based quality measurement of transformer oil using polymer optical fiber as sensor." *IEEE Sensors Journal* 18, no. 4 (2017): 1506-1512. https://doi.org/10.1109/JSEN.2017.2785498
[3] Lee, Byeong Ha, Young Ho Kim, Kwan Seob Park, Joo Beom Eom, Myoung Jin Kim, Byung Sup Rho, and Hae Young Choi. "Interferometric fiber optic sensors." *sensors* 12, no. 3 (2012): 2467-2486. https://doi.org/10.3390/s120302467

[4] Hisham, Hisham Kadhum. "Optical fiber sensing technology: basics, classifications and applications." *Am. J. Remote Sens* 6, no. 1 (2018): 1-5. https://doi.org/10.11648/j.ajrs.20180601.11

[5] Gandhi, MS Aruna, Yuanfang Zhao, Chenxingyu Huang, Yuan Zhang, H. Y. Fu, and Qian Li. "Highly sensitive refractive index sensor based on plastic optical fiber balloon structure." *Optics Letters* 47, no. 7 (2022): 1697-1700. https://doi.org/10.1364/ol.455562

[6] Wang, Shumin, Daming Zhang, Yan Xu, Siwen Sun, and Xiaoqiang Sun. "Refractive index sensor based on double side-polished U-shaped plastic optical fiber." *Sensors* 20, no. 18 (2020): 5253. https://doi.org/10.3390/s20185253

[7] Razzaq, Alaa, Hidayat Zainuddin, Farhan Hanaffi, Radhi M. Chyad, Anas A. Latiff, and H. R. A. Rahim. "Measurement of dissolved decay products of transformer oil using D-shaped plastic optical fibre as a sensor." *IET Science, Measurement & Technology* 14, no. 10 (2020): 901-905. https://doi.org/10.1049/iet-smt.2019.0399

[8] Sequeira, Filipa, Daniel Duarte, Lúcia Bilro, Alisa Rudnitskaya, Maria Pesavento, Luigi Zeni, and Nunzio Cennamo. "Refractive index sensing with D-shaped plastic optical fibers for chemical and biochemical applications." *Sensors* 16, no. 12 (2016): 2119. https://doi.org/10.3390/s16122119

[9] Razali, Nazirah Mohd, Sumiaty Ambran, Siti Nur Fatin Zuikafly, M. A. M. Yuzir, and H. H. J. Sapingi. "Design and Simulation of C-Shaped Optical Fiber Sensor." In *2021 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)*, pp. 109-110. IEEE, 2021. https://doi.org/10.1109/NUSOD52207.2021.9541425

[10] Razzaq, A., H. Zainuddin, F. Hanaffi, Y. Ying, Radhi M. Chyad, and H. A. Razak. "Transformer Oil Ageing Detection using Mach–Zender Interferometry Configuration as a Sensor." https://doi.org/10.35940/ijrte.b1153.0782s619

[11] Zubiate, Pablo, Jesus M. Corres, Carlos R. Zamarreño, Ignacio R. Matias, and Francisco J. Arregui. "Fabrication of optical fiber sensors for measuring ageing transformer oil in wavelength." *IEEE Sensors Journal* 16, no. 12 (2016): 4798-4802. https://doi.org/10.1109/JSEN.2016.2549562

[12] Mahanta, Deba Kumar, and Shakuntala Laskar. "Investigation of transformer oil breakdown using optical fiber as sensor." *IEEE Transactions on Dielectrics and Electrical Insulation* 25, no. 1 (2018): 316-320. https://doi.org/10.1109/tdei.2018.006855

[13] Razzaq, Alaa, Hidayat Zainuddin, Farhan Hanaffi, Radhi M. Chyad, Hanim Abdul Razak, and Anas Abdul Latiff. "Measurement of ester-based transformer oil aging using tapered single mode-multimode-single mode fiber structure." *Microwave and Optical Technology Letters* 62, no. 2 (2020): 559-564. https://doi.org/10.1002/mop.32096

[14] Zhao, Hongxia, Feng Wang, Zhuoyuan Wang, and Lu Chen. "Refractive index sensor based on a gradually hot-pressed flatted plastic optical fiber." *Optics Communications* 532 (2023): 129258. https://doi.org/10.1016/j.optcom.2023.129258

[15] Lopez, Juan David, Alex Dante, Regina Célia da Silva Allil, and Marcelo Martins Werneck. "The Influence of Geometric Shape on the Performance of Refractive Index Sensors Based on Plastic Optical Fibers: Simulations and Experimental Assessment." *IEEE Sensors Journal* 23, no. 6 (2023): 5803-5809. https://doi.org/10.1109/JSEN.2023.3240292

[16] Sulaiman, Nazrah Ilyana, Nor Hafizah Ngajikin, Nurfatihah Che Abd Rashid, Afiqah Yaacob, Maslina Yaacob, Mohd Haniff Ibrahim, and Noran Azizan Cholan. "Temperature sensing utilizing unclad plastic optical fiber with a balloon-like bent structure." *Applied Optics* 60, no. 13 (2021): 3895-3900. https://doi.org/10.1364/ao.419801 .

[17] Santos, D. F., Ariel Guerreiro, and José Manuel Baptista. "Numerical investigation of a refractive index SPR D-type optical fiber sensor using COMSOL multiphysics." *Photonic sensors* 3 (2013): 61-66. https://doi.org/10.1007/s13320-012-0080-5 .

[18] Teng, Chuanxin, Rui Min, Jie Zheng, Shijie Deng, Maosen Li, Li Hou, and Libo Yuan. "Intensity-modulated polymer optical fiber-based refractive index sensor: a review." *Sensors* 22, no. 1 (2021): 81. https://doi.org/10.3390/s22010081

[19] Handali, Jati Prima, Roer Eka Pawinanto, Budi Mulyanti, and Gandi Sugandi. "Simulation of de-cladding fiber optic sensor using MODE solutions for ammonia detection." In *2018 International Symposium on Electronics and Smart Devices (ISESD)*, pp. 1-4. IEEE, 2018. https://doi.org/10.1109/ISESD.2018.8605450 .

[20] Kumar, P., S. Kumar, J. Kumar, G. S. Purbia, O. Prakash, and S. K. Dixit. "Graphene-oxide-coated fiber Bragg grating sensor for ethanol detection in petrol." *Measurement Science and Technology* 31, no. 2 (2019): 025109. https://doi.org/10.1088/1361-6501/ab2d63