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Monitoring of Repeatedly Heated Cooking Oil Quality using Different Types of Optical Fiber Sensors

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ABSTRACT

In recent times, optical fiber sensors have seen widespread utilization in diverse sensing applications, marking a notable trend. These applications encompass the detection of changes in refractive indices, temperatures, pressures, and even biological compositions. Hence, the primary aim of this study is to evaluate the quality of cooking oil that undergoes repetitive heating using a variety of optical fiber sensors, including optical fiber tip, d-shaped optical fibers, and fiber Bragg gratings (FBGs). Several types of cooking oil, exposed to different cooking cycles, were meticulously prepared and subjected to analysis using these three distinct optical fiber sensor types, employing both dip-coating and drop-casting techniques. In the drop-casting method, an amplified spontaneous emission (ASE) source is utilized to transmit light through the D-shaped optical fiber to an optical spectrum analyser (OSA). On the contrary, the tip-coating approach involves an optical fiber circulator to split optical signals that travel in opposing directions. The obtained findings demonstrate a progressive reduction in optical power levels and shifts in wavelengths as the cooking cycles progress. These wavelength shifts serve as indicators of the refractive index changes in the cooking oil, suggesting that the cooking oil that undergoes repeated heating shows enhanced light absorption. This observation supports the conclusion that the D-shaped optical fiber sensor, FBG, and optical fiber tip are capable of distinguishing cooking oil quality. It can be observed that the sensitivity of the D-shaped optical fiber sensor is 0.9 dBm per unit of cooking oil cycles which is 9 times better than the optical fiber tip sensor. This is due to the exposed area of the D-shaped sensor being larger than the optical fiber tip sensor. In addition, the D-shaped sensor demonstrated higher levels of sensitivity and consistency when detecting cooking oil quality. In fact, greater light absorption might be linked to more pronounced degradation, implying a decline in oil quality. Thus, cooking oils exhibiting lower refractive indices (RIs) are indicative of superior oil quality.

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1. Introduction

An optical fiber, a cylindrical waveguide widely employed for long-distance and wideband communication, functions through the principle of total internal reflection, enabling the transmission of light signals between locations with minimal energy loss. Comprising three key components which include the core, the cladding, and the outer jacket, the fiber's core and cladding are often composed of glass, silica, or plastic materials [1]. The recent surge in interest surrounding fiber optic sensors (FOS) stems from their distinct advantages over conventional sensing mechanisms. These include swift response times, compact size, enhanced security, constancy, flexibility, remote monitoring capability, and resilience in harsh environments. Various methods and designs for optical fiber sensing fundamentals have been proposed by numerous FOS researchers. Optical fiber operates on the principle of total internal reflection, allowing light signals to be transmitted from one location to another with minimal energy loss. The development of the optoelectronics and fiber optic communications industries over the past 20 years has resulted in a revolution in product design. By enabling higher performance, and more stable telecommunication networks with practically falling bandwidth costs, the optical communications industry has transformed the telecommunications sector [2].

Numerous studies have been prompted by the phenomenon and as a result, new ideas aiming at employing optical fibers to fabricate sensing systems have emerged which have given rise to fiber-based sensing devices and components. Then the invention of in-line Bragg grating optical filters for optical communication led to the invention of fiber optic sensors. Fiber Bragg gratings, often known as FBGs, were soon discovered to provide excellent optical transducers for sensing a variety of different parameters [3]. The principle of FBG is shown in Figure 1. The FBG acts as a narrow band filter or wavelength-selective mirror. The light from the light source is injected into the optical fiber and there occurs the very narrow spectral width centered at Bragg wavelength, back-reflected by the gratings. The remaining light continues through the optical fiber to the next Bragg gratings without any loss.

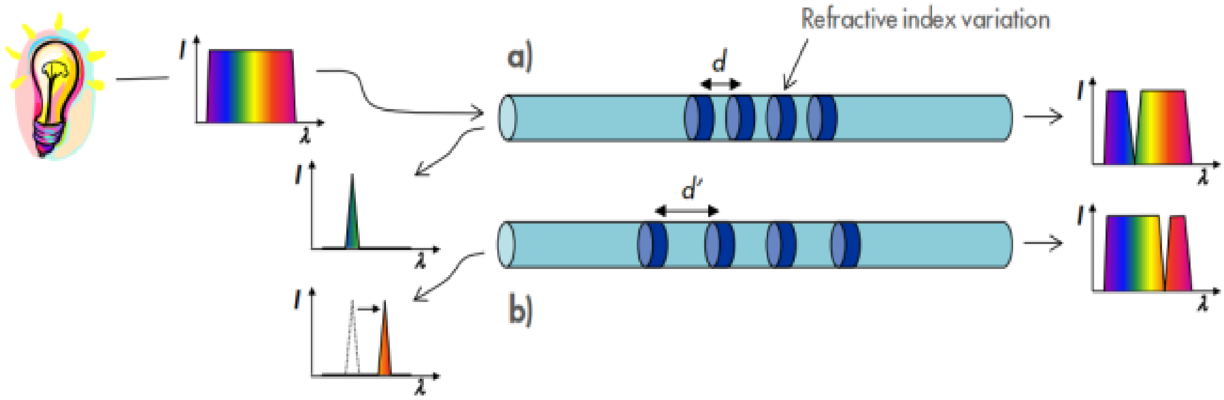


Fig. 1. The working principle of fiber Brag grating (FBG) [4]

The interaction between the evanescent wave with the surrounding medium is detected by the D-shaped optical fiber sensor (Figure 2). The foundation of this sensor is established through the meticulous side polishing of a single-mode fiber, thus exposing its cladding, core, and an additional metallic layer. D-shaped optical fibers, noted for their versatility, underpin an array of sensing applications that are inherently predicated on the tunability of two critical parameters within optical fiber transmission: the effective index and energy distribution. The modulation of optical power resulting from alterations in the refractive index serves as a pivotal tool for gauging environmental parameters, while variations in optical intensity facilitate the detection of changes in energy circulation.

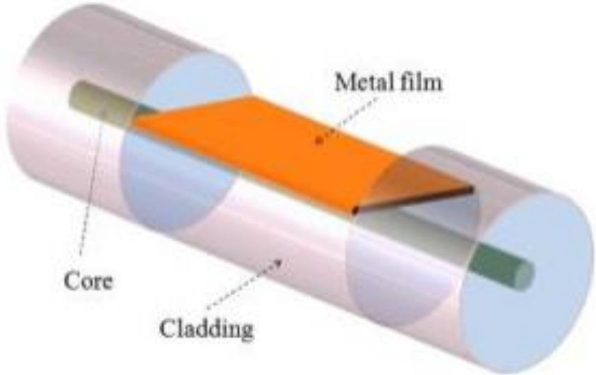


Fig. 2. The structure of D-shaped optical fiber [1]

In the sphere of health, the presence of supplementary polar compounds in commonly employed frying oils has been linked to an escalated susceptibility to hypertension. The iterative heating of cooking oil potentially exacerbates the risk of atherosclerosis, as the byproducts of lipid peroxidation expose endothelial cells to oxidative stress, thereby culminating in endothelial dysfunction and atherosclerosis progression [5-8]. Throughout the frying process, tangible modifications manifest in the physical attributes of cooking oil: color darkens, odor becomes increasingly disagreeable, and oil undergoes concentration. To quantify these transformations, the determination of the total concentration of free fatty acids hinges on referencing absorbance levels. A heightened absorbance value at specific wavelengths aligns with a greater concentration of free fatty acids [9-12].

Against the backdrop of the globalization era, cooking oil, whether synthetic, plant-derived, or animal-based, has been an essential component of food preparation. With escalating cooking oil prices, the practice of reusing cooking oil has become commonplace. However, the consumption of cooking oil that has undergone repetitive heating poses inherent risks [13]. The process of frying entails frequent exposure of cooking oil to elevated temperatures over extended durations, culminating in the formation of lipid peroxidation compounds that potentially jeopardize human health. Factors such as frying temperature, utensil cleanliness, oil turnover frequency, filtration practices, and the filtration process collectively influence the quality of frying oil. The deterioration of cooking oil quality is exacerbated by irregular heating and subsequent cooling, stemming from increased oxygen solubility as the oil cools from high frying temperatures. Moreover, the concentration of oil degradation products escalates as frying frequency increases [14]. Consequently, this study endeavours to gauge the quality of repetitively heated cooking oil through the application of diverse optical fiber sensors and methodologies. Currently, the investigation of cooking oil quality ultilising optical fiber sensors is still at a very minimal stage. The research investigating the degradation of transformer oil in power transformer using fiber Bragg grating sensor was conducted by Onn *et al.,* [15] the 1549.79nm sensing responses of the FBG sensor and 88% reflectivity are observed from optical spectrum analyser (OSA). The findings show that wavelength shift was detected by FBG due to the degradation of transformer oil.

The spectrum of applications for fiber optic-based sensors is vast within the optical industry, encompassing measurements, hazardous chemical identification, biosensing, and beyond. This study introduces a novel approach, employing a multipronged optical fiber sensor system to analyze and ascertain cooking oil quality predicated on power loss and wavelength shifts. Central to this assessment is the meticulous monitoring of the interaction between the evanescent wave and the surrounding medium, facilitated by a D-shaped optical fiber sensor. The overarching aim of this research is to present a straightforward methodology for evaluating potential health risks associated with repeatedly heated cooking oil, thereby contributing to an enhanced understanding of disease susceptibility. The combined utilization of a D-shaped optical fiber sensor, fiber tip sensor, and FBG sensor presents a streamlined and effective preliminary screening technique for assessing cooking oil quality, devoid of the need for intricate chemical analyses. This approach capitalizes on the inherent physical characteristics of cooking oil, thereby enabling the sensor to detect spectral variances and furnish optical power measurements that serve as a qualitative proxy for the oil's condition. By addressing the imperative need for robust methodologies to appraise the quality of repeatedly heated cooking oil and simultaneously raising awareness about cooking practices, this study proffers a tangible and effective solution.

2. Methodology

2.1 Cooking oil sample preparation

Five distinct cooking oil samples are meticulously prepared, each utilizing fresh ingredients such as raw chicken (Figures 3 and 4). The cooking oil samples are subjected to 2, 4, 6 and 8 consecutive cooking cycles. To ensure uniformity and consistency in heating, a standardized cooking method is employed, maintaining a consistent flame intensity for each cooking cycle [16,17]. This precautionary measure ensures that all samples are subjected to identical heating conditions. Subsequently, the refractive index of the cooking oil samples is ascertained using a refractometer, and the resulting data is meticulously documented, as depicted in Table 1.

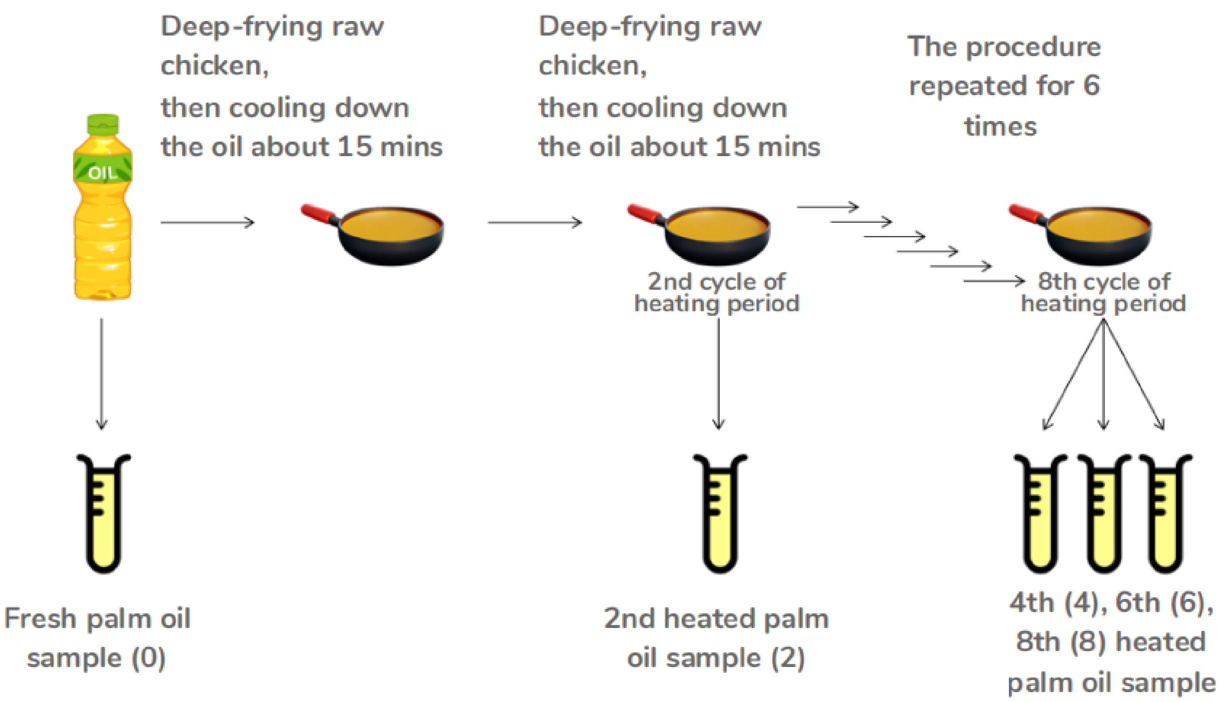


Fig. 3. Cooking oil sample preparation

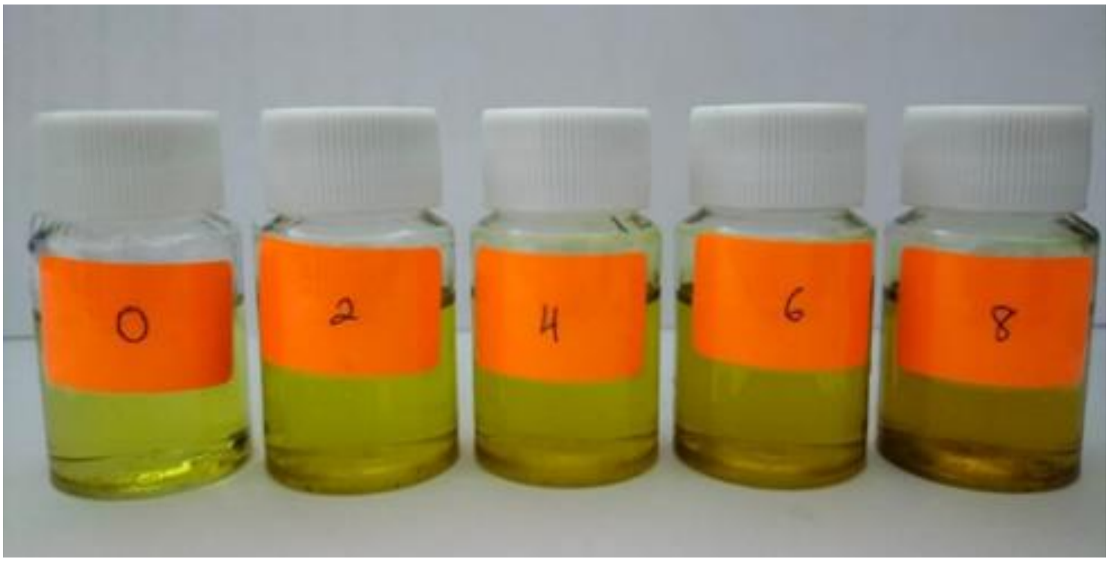


Fig. 4. Oil sample of different cooking cycles

2.2 Experimental setup

In accordance with conventional interrogation techniques, an optical spectrum analyzer (OSA) coupled with a broadband source is employed. The experimental setup is depicted in Figure 5 and Figure 6 below. The optical fiber circulator functions as a pivotal component, facilitating the division of optical signals propagating in opposite directions. The circulator is energized by an amplified spontaneous emission (ASE) light source (FiberLabs Inc., FL7004) featuring a wavelength range spanning from 1510 nm to 1660 nm. The tip of the fiber Bragg grating (FBG) and the optical fiber interface with the cooking oil sample. Subsequently, the circulator transmits the transduced light emanating from the sensing region to the optical spectrum analyzer (OSA; Yokogawa, AQ370D). The OSA, characterized by a resolution of 0.02 nm, is harnessed to visually represent the ensuing sensing response.

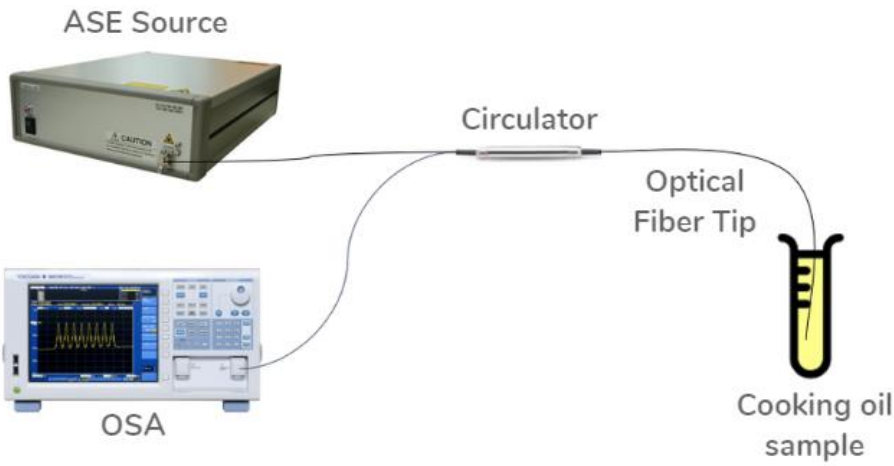


Fig. 5. Experimental setup of fiber tip sensor

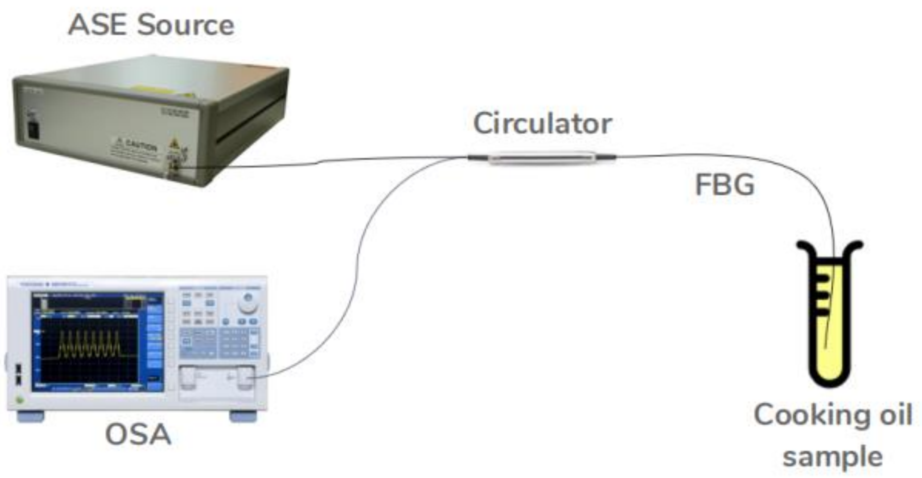


Fig. 6. Experimental setup of FBG sensor

The utility of D-shaped optical fiber sensors resides in their capacity to exploit optical power for the detection of alterations within the external environment (Figure 7). The process unfolds as amplified spontaneous emission (ASE) light is channelled into the D-shaped optical fiber sensor, encompassing a wavelength range spanning from 1510 nm to 1660 nm. The emitted light traverses the fiber's core, engendering an evanescent field at the core-cladding interface, extending into the adjoining medium. This evanescent field interfaces with the external surroundings, thereby inducing modifications in the optical power propelling through the fiber. The transduced light from the sensing region is subsequently relayed to the optical spectrum analyzer, and the resultant sensing response is delineated with a precision of 0.02 nm. The ensuing alterations in optical power are meticulously observed and documented.

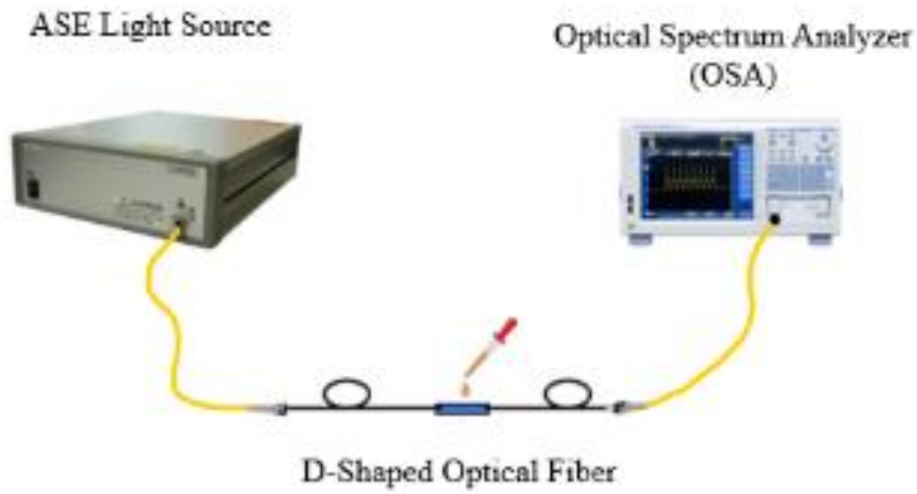


Fig. 7. Experimental setup of D-shaped optical fiber sensor

2.3 Drop-Casting Method

The drop-casting method (Figure 8), renowned for its simplicity and widespread utilization within various research circles, serves as an adept film-forming technique that obviates the requirement for specialized equipment. This technique involves the deposition of a solution containing the desired substance onto a substrate, followed by solvent evaporation [18,19].

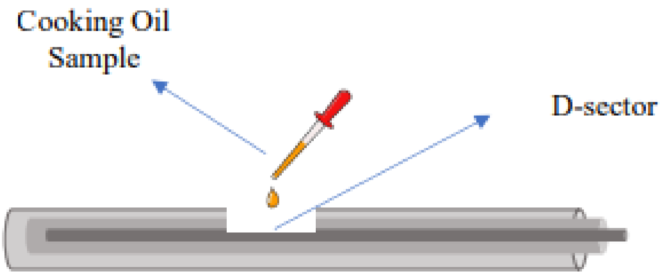


Fig. 8. The illustration of the drop casting method

3. Results

Table 1 shows a comprehensive overview of the refractive index measurements obtained from diverse qualities of cooking oils, meticulously assessed via a refractometer. The distinct qualities of cooking oil samples stem from their varying sequences of reheating, ranging from 0 to 8 cycles. The results underscore discernible deviations in refractive index across different qualities of cooking oil. A consistent rise in refractive index is observed, escalating from 1.4601 to 1.46285 over the initial 6 cycles of reheating, followed by a subsequent decline to 1.46195 during the 8th cycle. The anticipated linear relationship between refractive index and quality level encounters a deviation in the 8th cycle, possibly attributed to inadvertent inconsistencies during sample preparation.

Table 1
The refractive index of different reheated sequences of cooking oil

Cooking Cycle	Refractive Index
0	1.4601
2	1.46055
4	1.46235
6	1.46285
8	1.46195

3.1 Fiber Tip Sensor

The power spectrum of the optical fiber tip sensor in its endeavour to discern cooking oil quality. According to the graph, an initial increase in wavelength is observed, succeeded by a decrease as reheating cycles progress. Notably, cooking oil subjected to the 2nd reheating cycle exhibits the highest wavelength at 1560.208nm, while that of the 8th cycle plunges to 1558.609nm. Intriguingly, the results indicate a degree of instability in sensor performance, alluding to fluctuating sensor states.

3.2 Fiber Brag Grating (FBG) Sensor

Figure 9 captures the outcomes of the FBG sensor assessment across the five distinct cooking oil samples, thereby affirming the sensor's proficiency in discerning cooking oil quality. An observable shift in Bragg wavelength becomes evident with ascending levels of reheating, substantiating the FBG sensor's ability to gauge cooking oil quality. A correlation between Bragg wavelength shifts and refractive index emerges, affirming that superior cooking oil quality is associated with lower refractive indices (RI). Intriguingly, it is noteworthy that the exact alignment of the Bragg wavelength shift with the cooking oil's RI is not exact. Specifically, during the 8th cycle, the RI value falls between the 2nd and 3rd cycles of reheated cooking oil. This may be caused by some inappropriate procedure during the sample preparation or an uncertain factor or condition that occurs in the experiment.

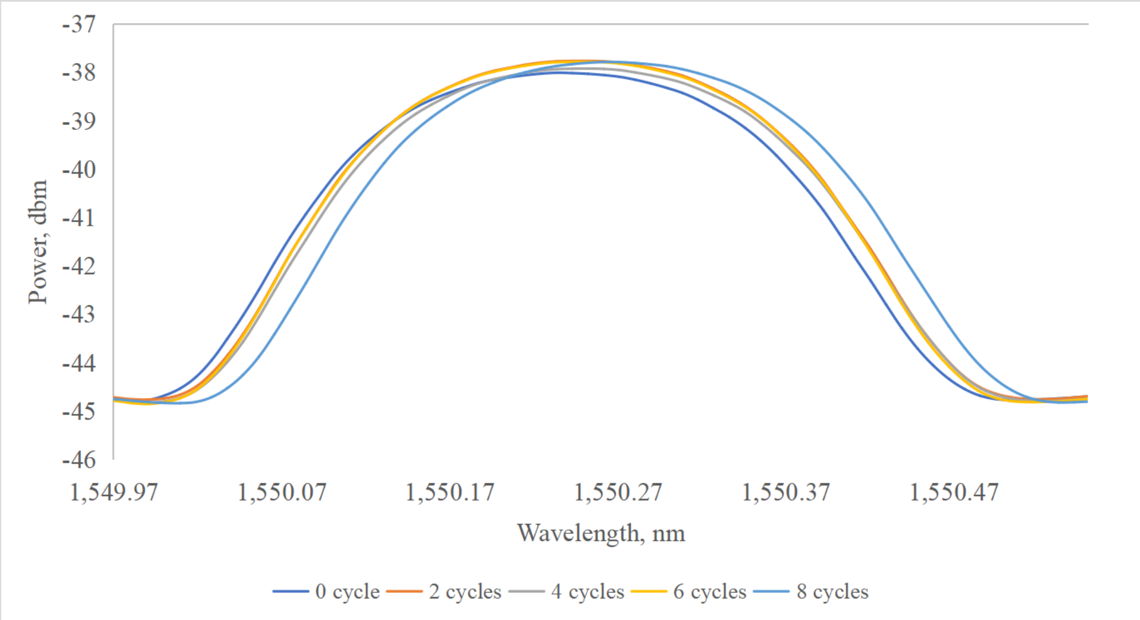


Fig. 9. Bragg wavelength shift detected by FBG sensor

The wavelength shift of the FBG sensor is depicted in Figure 10. When comparing the performance of the optical fiber tip sensor and FBG sensor, the optical fiber tip sensor has a higher sensitivity which is 0.1 dBm per unit cycle, but it was unstable. Although the optical fiber tip sensor exhibits higher sensitivity compared to the FBG sensor, its instability compromises its utility. Conversely, the FBG sensor, while less sensitive which was only 0.001 nm per unit cycle, offers heightened consistency. To mitigate the FBG sensor's reduced sensitivity, optimization avenues such as adjusting the cladding thickness of Bragg gratings are feasible. Notably, the FBG sensor's sensitivity is influenced by its dip coating exposure to cooking oil samples, which avoids direct contact due to challenges in polishing the FBG tip, potentially affecting sensitivity.

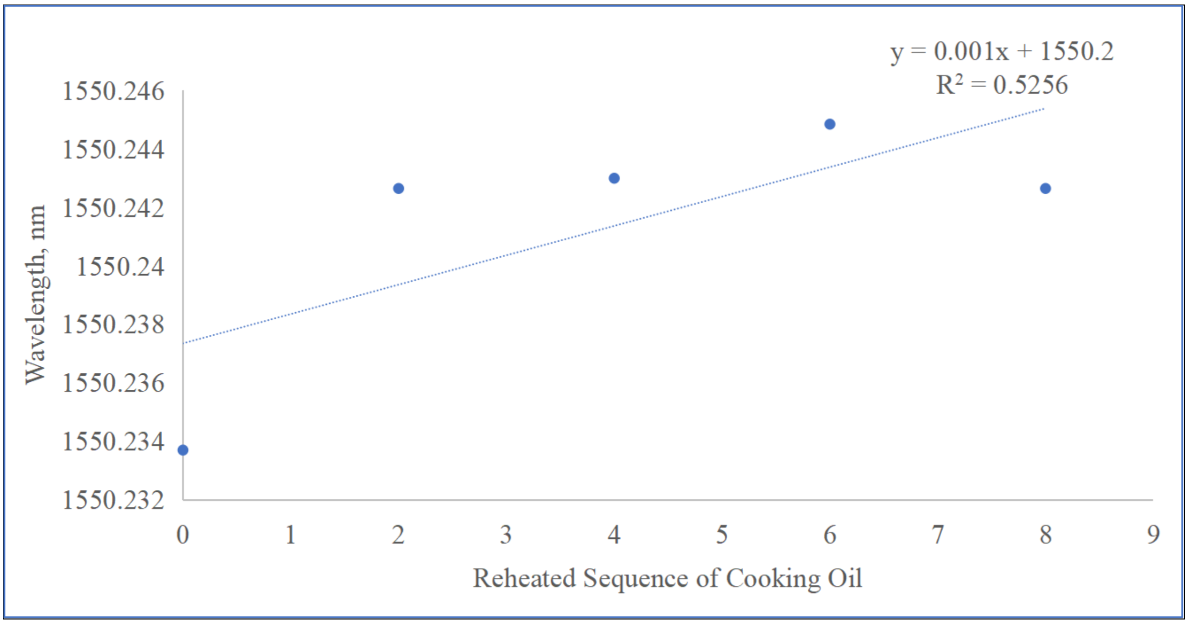


Fig. 10. The wavelength shift response of FBG sensor to detect the cooking oil quality

3.3 D-shaped Optical Fiber Sensor

Figure 11 presents the optical power levels of a D-shaped optical sensor across distinct cooking cycles for reheated palm cooking oil, offering indirect insight into light absorbance— an attribute linked to the oil's capacity to absorb light energy. As cycles progress, a discernible decline in power levels suggests heightened light absorption or scattering properties in repeatedly heated cooking oil. Power levels ascend until the 4th cooking cycle, followed by a decline in the 6th cycle, and a subsequent rise during the 8th cycle. The fluctuation, possibly stemming from sample preparation uncertainties, does not undermine the sensor's ability to detect cooking oil changes.

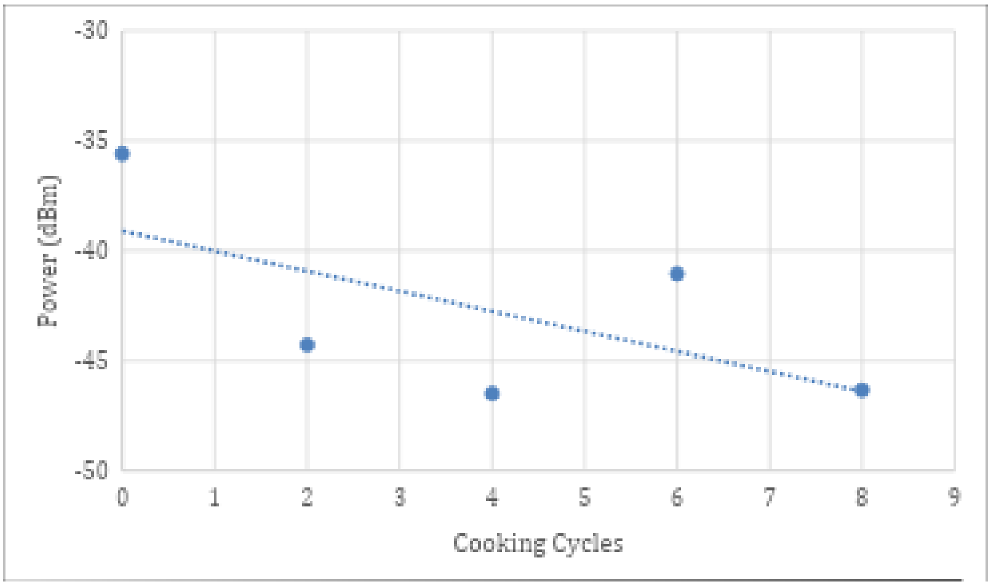


Fig. 11. The power spectrum of D-shaped optical fiber sensor

Peak wavelength values range between approximately 1558.83 nm and 1559.43 nm, while optical power levels fluctuate from -46.5 dBm to -35.6 dB with increasing cooking cycles. Repeated heating engenders chemical transformations, potentially leading to degradation or by-product formation.

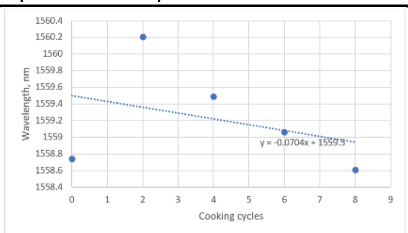
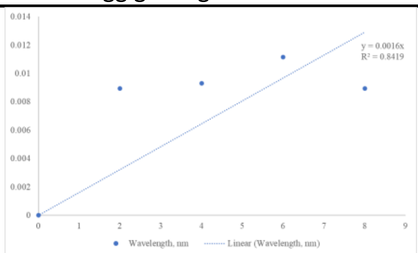
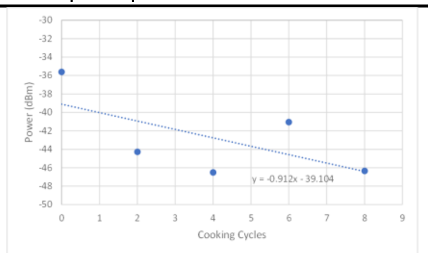
The sensitivity of the D-shaped optical fiber sensor to such chemical changes translates to power level shifts at specific wavelengths [20,21]. The sensitivity of D-shaped sensor is 0.91 dBm per unit cycle which is 9 times better than optical fiber tip sensors. Variations in measured power levels across wavelengths are indicative of modifications in light-fiber interaction precipitated by cooking oil alterations.

4. Discussion

The D-shaped optical fiber sensor exhibits superior sensitivity in contrast to both the fiber tip sensor and FBG sensor. This heightened sensitivity can be attributed to the D-shaped optical fiber's enhanced exposure to the sample, surpassing the capabilities of the other sensors. Consequently, its adeptness in capturing alterations in repeatedly heated cooking oil proves invaluable for assessing cooking oil quality. The elevated sensitivity of the D-shaped optical fiber sensor facilitates effective interaction with and measurement of variations in the optical characteristics of repeatedly heated palm cooking oil.

In direct comparison, the FBG sensor lags behind in terms of sensitivity when detecting changes in cooking oil. This can be seen from the sensitivity of the FBG sensor which is only 0.001 nm per unit cycles. This discrepancy arises from the FBG sensor's indirect exposure to the sample. Despite its diminished sensitivity, the FBG sensor still demonstrates a commendable capacity to detect transformations in repeatedly heated cooking oil. A comprehensive summary of the sensors' performance is provided in Table 2, offering a clear comparative insight into their respective capabilities.

Table 2
The comparison of the optical fiber sensors' performance

Optical fiber tip sensor	Fiber Bragg gratings sensor	D-shaped optical fiber sensor
		
High sensitivity but low consistency	Lower sensitivity but high consistency	Higher sensitivity and high consistency
The sensor is unstable while the higher sensitivity showed the sensor is sensitive to the changes of chemical composition in cooking oil which resulting a wavelength shift for different quality levels of cooking oil	The sensor is stable but the lower sensitivity showed the sensor is only slightly sensitive to the changes of chemical composition in cooking oil which resulting a wavelength shift for different quality levels of cooking oil	The sensor is stable and it has a higher sensitivity. It is sensitive to the changes of chemical composition in cooking oil, which results in shifts in the measured power levels at specific wavelengths

4. Conclusions

This study has unveiled the operational effectiveness of optical fiber sensors in assessing the quality of cooking oil. The sensors employed for this purpose encompassed the optical fiber tip sensor, the D-shaped sensor, and the FBG sensor. Notably, the FBG sensor showcased its ability to exhibit wavelength shifts towards longer wavelengths when subjected to varying qualities of cooking oil. In contrast, the D-shaped sensor showcased alterations in optical power levels corresponding to different cooking cycles. The primary objectives of this research were to evaluate the performance and effectiveness of several optical fiber sensors. The evaluation of sensor performance was conducted with a specific focus on sensitivity and consistency. Within the scope of this study, the D-shaped sensor demonstrated higher levels of sensitivity with 0.91 dBm per unit cycle and better consistency when detecting cooking oil quality. This showed that the sensitivity of the D-shaped sensor was 9 times better than optical fiber tip sensors. The introduced sensor configuration offers simplicity and versatility, serving as a chemical sensor capable of accurately gauging cooking oil quality. This study contributes to the advancement of optical fiber-based sensing techniques, particularly in the context of evaluating cooking oil quality.

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References

[1] Ying, Yu, Guang-yuan Si, Fang-jun Luan, Ke Xu, Yuan-wei Qi, and Hong-nan Li. "Recent research progress of optical fiber sensors based on D-shaped structure." *Optics & laser technology* 90 (2017): 149-157. https://doi.org/10.1016/j.optlastec.2016.11.021

[2] Yin, Shizhuo, Paul B. Ruffin, and Francis T. S. Yu. 2017. Fiber Optic Sensors. Google Books. CRC Press. https://books.google.com.my/books?hl=en&lr=&id=5KdCOguH9CsC&oi=fnd&pg=PP1&dq=Yin. https://doi.org/10.1201/9781420053661

[3] Udd, Eric, and William B. Spillman Jr, eds. *Fiber optic sensors: an introduction for engineers and scientists*. John Wiley & Sons, 2024. https://doi.org/10.1002/9781119678892

[4] “Fibre-Optic Sensing for Application in Oil and Gas Wells.” n.d. Accessed December 8, 2019. https://doi.org/10.6100/IR769555

[5] Haroon, Hazura, Muhamad Naeem Mohd Nazri, Siti Khadijah Idris, Hanim Abdul Razak, Anis Suhaila Mohd Zain, and Fauziyah Salehuddin. "Comparative study of solution concentration variations for polymer optical fibers sensor." *Malaysian Journal of Fundamental and Applied Sciences* 16, no. 2 (2020): 140-144. https://doi.org/10.11113/mjfas.v16n2.1451

[6] Guillaume, C., F. De Alzaa, and L. Ravetti. "Evaluation of chemical and physical changes in different commercial oils during heating." *Acta Scientific Nutritional Health* 2, no. 6 (2018): 2-11.

[7] Yee, T., Radhika Loganathan, and Teng Kim Tiu. "Oxidative changes in repeatedly heated vegetable oils." *Journal of Oil Palm Research* 30, no. 4 (2018): 635-641.

[8] Ng, Chun-Yi, Xin-Fang Leong, Norliana Masbah, Siti Khadijah Adam, Yusof Kamisah, and Kamsiah Jaarin. "Heated vegetable oils and cardiovascular disease risk factors." *Vascular pharmacology* 61, no. 1 (2014): 1-9. https://doi.org/10.1016/j.vph.2014.02.004

[9] Phiri, Gabriella, Peter Mumba, and Agnes Mangwera. "The quality of cooking oil used in informal food processing in Malawi: a preliminary study." *International journal of consumer studies* 30, no. 6 (2006): 527-532. https://doi.org/10.1111/j.1470-6431.2006.00513.x

[10] Chen, Jiapeng, and Hongbing Liu. "Nutritional indices for assessing fatty acids: A mini-review." *International journal of molecular sciences* 21, no. 16 (2020): 5695. https://doi.org/10.3390/ijms21165695

[11] Nayak, Prakash Kumar, U. M. A. Dash, Kalpana Rayaguru, and Keasvan Radha Krishnan. "Physio-chemical changes during repeated frying of cooked oil: A Review." *Journal of Food Biochemistry* 40, no. 3 (2016): 371-390. https://doi.org/10.1111/jfbc.12215

[12] Atinafu, Dimberu G., and Belete Bedemo. "Estimation of total free fatty acid and cholesterol content in some commercial edible oils in Ethiopia, Bahir DAR." *Journal of Cereals and Oil seeds* 2, no. 6 (2011): 71-76. https://doi.org/10.5897/JCO11.025

[13] Szabo, Zoltan, Tamas Marosvölgyi, Eva Szabo, Viktor Koczka, Zsofia Verzar, Maria Figler, and Tamas Decsi. "Effects of repeated heating on fatty acid composition of plant-based cooking oils." *Foods* 11, no. 2 (2022): 192. https://doi.org/10.3390/foods11020192

[14] [14] Azman, A, S Mohd Shahrul, S X Chan, A P Noorhazliza, M Khairunnisak, M F Nur Azlina, H M S Qodriyah, Y Kamisah, and K Jaarin. n.d. “Level of Knowledge, Attitude and Practice of Night Market Food Outlet Operators in Kuala Lumpur Regarding the Usage of Repeatedly Heated Cooking Oil.”

[15] Onn, B. I., P. T. Arasu, Yusser Al-Qazwini, A. F. Abas, N. Tamchek, and A. S. M. Noor. "Fiber Bragg grating sensor for detecting ageing transformer oil." In *2012 IEEE 3rd international conference on photonics*, pp. 110-113. IEEE, 2012. https://doi.org/10.1109/ICP.2012.6379520
[16] Hassanien, M. F. R., and A. M. Sharoba. "Rheological characteristics of vegetable oils as affected by deep frying of French fries." *Journal of food measurement and characterization* 8 (2014): 171-179. https://doi.org/10.1007/s11694-014-9178-3
[17] Mariana, Rina Rifqie, Titi Mutiara Kirana, and Laily Hidayati. "Analysis on the quality change of tempeh, catfish and fried chicken as the effect of the repetitive used cooking oil." *Journal of Food Research* 3, no. 1 (2014): 96. https://doi.org/10.5539/jfr.v3n1p96
[18] Zuo, Chuantian, Andrew D. Scully, and Mei Gao. "Drop-casting method to screen Ruddlesden–Popper perovskite formulations for use in solar cells." *ACS Applied Materials & Interfaces* 13, no. 47 (2021): 56217-56225. https://doi.org/10.1021/acsami.1c17475
[19] Kumar, Archana Kaliyaraj Selva, Yifei Zhang, Danlei Li, and Richard G. Compton. "A mini-review: How reliable is the drop casting technique?." *Electrochemistry Communications* 121 (2020): 106867. https://doi.org/10.1016/j.elecom.2020.106867
[20] Yusoff, S. F. A. Z., M. H. Mezher, I. S. Amiri, N. Ayyanar, D. Vigneswaran, H. Ahmad, and R. Zakaria. "Detection of moisture content in transformer oil using platinum coated on D-shaped optical fiber." *Optical Fiber Technology* 45 (2018): 115-121. https://doi.org/10.1016/j.yofte.2018.07.011
[21] Salleh, W. S., W. F. Muhamat, S. Nurulain, M. R. Salim, and H. Manap. "A spectroscopy study of heated palm cooking oil using an open path optical method for Free Fatty Acids concentration measurement." *Materials Today: Proceedings* 109 (2024): 7-11. https://doi.org/10.1016/j.matpr.2023.03.743