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SENSITIVITY OF REFRACTIVE INDEX SENSORS MADE USING NO-CORE TAPERED FIBRE: A COMPARATIVE ASSESSMENT

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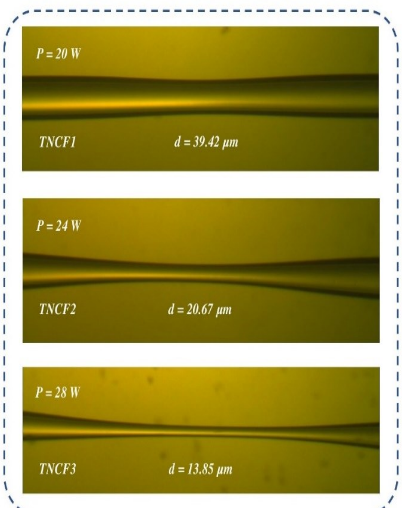
Graphical abstract



Abstract

In this research paper, the authors discuss the development, structure and evaluation of a sensor system, for measuring index that is based on a tapered no core fibre (TNCF). To enhance the TNCF diameter's effectiveness various CO_2 input powers were utilized to develop optical-based refractive index sensor. The tapered fibre waist of the TNCF design enables interaction with the surrounding medium thereby enhancing sensor sensitivity. Optimal taper shape selection was crucial in achieving sensitivity and a low limit of detection (LoD) in the TNCF design process. A CO_2 laser was employed in the fabrication process to reduce the waist diameter for the TNCF. The sensor performance was evaluated by monitoring wavelength shift as a function of the surrounding medium refractive index. Experimental findings demonstrated that the TNCF-based refractive index (RI) sensor exhibited a LoD value of 0.127 RIU compared to NCFs 0.171 RIU and a higher sensitivity at 150.00259 ± 6.77632 nm/RIU versus NCFs sensitivity, at 42.30713 ± 1.20951 nm/RIU. Better performance was demonstrated by the TNCF-based RI sensor in terms of sensitivity, LoD, repeatability, and reversibility. This research advances the development of highly effective and versatile optical-based RI sensors for a wide range of real-time applications, thereby contributing to the ongoing advancement in fields like chemical analysis, biomedical diagnostics, and environmental monitoring. These sensors offer a significantly improved sensitivity and lower limit of detection compared to conventional sensors.

Keywords: Tapered NCF, CO_2 laser, refractive index, sensor

Abstrak

Dalam kertas penyelidikan ini, kami membincangkan pembangunan, struktur dan penilaian sistem sensor, untuk mengukur indeks yang berasaskan gentian tanpa teras (TNCF). Untuk meningkatkan keberkesanan diameter TNCF pelbagai kuasa input CO_2 telah digunakan untuk mencipta penderia indeks berdasarkan optik. Pinggang gentian tirus reka bentuk TNCF membolehkan interaksi dengan medium sekeliling sekali gus meningkatkan sensitiviti sensor. Pemilihan bentuk tirus yang optimum adalah penting dalam mencapai sensitiviti dan had pengesanan (LoD) yang rendah dalam proses reka bentuk TNCF. Laser CO_2 digunakan dalam proses fabrikasi untuk menentukan diameter pinggang untuk TNCF. Prestasi sensor dinilai dengan memantau perubahan dalam panjang gelombang keluaran sebagai fungsi indeks sederhana sekeliling. Penemuan eksperimen menunjukkan bahawa penderia indeks biasan berasaskan TNCF mempamerkan nilai LoD 0.127 RIU berbanding NCFs 0.171 RIU dan kepekaan yang lebih tinggi pada 150.00259 ± 6.77632 nm/RIU berbanding sensitiviti NCFs 42.30713 ± 1.20951 nm/RIU. Prestasi cemerlang ditunjukkan oleh sensor indeks biasan berasaskan TNCF dari segi kepekaan, LoD, kebolehulangan dan kebolehbalikan. Penyelidikan ini memajukan pembangunan penderia indeks biasan berasaskan optik yang sangat berkesan dan serba boleh untuk pelbagai aplikasi masa nyata, dengan itu menyumbang kepada kemajuan berterusan dalam bidang seperti analisis kimia, diagnostik bioperubatan dan pemantauan alam sekitar. Penderia ini menawarkan sensitiviti yang dipertingkatkan dengan ketara dan had pengesanan yang lebih rendah berbanding dengan penderia konvensional.

Kata kunci: NCF tirus, laser CO2, indeks biasan, penderia

1.0 INTRODUCTION

A basic fibre optic system comprises three key components; a light source, a fibre optic cable, and a detector. In this system, a laser can be employed as the light source, directing a light beam into the fibre optic cable. Fibre-based sensors have garnered significant attention in the past decade [16, 20]. Because of the consistent and regulated photonic behaviour of light, fibre optic sensors in particular have benefits over electrical and electronic sensing techniques. These sensors can operate effectively in hazardous environments, including those with a high risk of explosion [1]. Furthermore, they are immune to electromagnetic interference caused by nearby electronic devices. Optical fibre sensors are currently being explored for various measurement applications, thanks to their straightforward and secure installation and operation [17, 18].

In this system, the laser is the source of light and its ray is guided inside the fibre optic cable. The cable is made up of tiny reflective strands that are sheathed in a protected casing. The reflective coating enables light to be reflected back and forth inside the cable; thus, light is trapped inside the cable and the original light is not permitted to escape. At the receiving end, the detector decodes the light which has gone through the fibre optic line. The detector next turns the light signal into an electrical signal which the computer or other electronic devices will then use to process.

Several sensors utilizing silica optical fibre, plastic optical fibre, and polymer optical microfibres have been developed and demonstrated for various detection applications. Challenging production techniques have hindered the advancement of these sensors [2]. Before this, several studies by other researchers have explored different types of fibre probe sensor structures, including small-core fibre [3], hollow-core fibre [4], and Mech-Zehnder interferometer (MZI) [5]. However, these previous studies suffered from low sensitivity values and high LoD. Moreover, they are also vulnerable to environmental fluctuations including temperature and mechanical vibrations which cause noise and drift into measurements, as such, the resultant accuracy and reliability of measurements is also compromised. Another critical characteristic of sensors is the LoD, which represents the ability of a sensor to detect the smallest variation in analyte concentrations [6]. It can be calculated as:

$$LoD = \frac{3\sigma}{Sensitivity} \quad (1)$$

where σ is the fibre standard deviations.

The parameter σ, a basic statistical measure that expresses the standard deviation and measures the variability or dispersion in a collection of data points. σ holds significant physical relevance as it characterizes the intrinsic variability or noise associated with the fibre structure, particularly for both the conventional no core fibre (NCF) and tapered no core fibre (TNCF).

The variations, in the fibre structure properties are evident through the values of σ = 1.7822 for NCF and σ = 8.7125 for TNCF. These differences arise from the variability in the manufacturing process fluctuations, in laser power and external factors contributing to this unpredictability. To put it simply, a higher σ means that the qualities of the fibre are noisy.

The relationship between σ and the sensor development is crucial. It directly impacts the calculation of the LoD, as expressed in Equation (1). When σ is higher, the denominator becomes larger. So, a lower LoD is generated. In this respect, the role that σ could play is to monitor the variability of the fibre structure and the value of this factor is associated with the type of fibre (TNCF and NCF) that is used in the experiment. Such a standard deviation of the test and the sensitivity of the sensor define the LoD that is highly relevant to the sensor's performance.

A better sensitivity of the sensor can be assessed with a smaller LoD in this study, leading to the detection of smaller fluctuations in the change of sample concentration. With that being thus, assessing the efficiency and treatment of the sensors in practical applications will entail a comparison of the values of σ for both NCF and TNCF.

So, in this case, the sensing region was represented by NCF. NCF - i.e. coreless fibre - is both the core as well as the cladding [7, 22]. Today, it is commonly used in sensing applications including coatings, evanescent wave absorption and multimode interference self-imaging. This is because of its special structures [8]. Compared to more conventional optical fibre sensors, this kind of sensor has the following benefits: immunity to electromagnetic interference, small size, fast response, and remote distributed real-time monitoring [9,21]. The operating principle of NCF is based on its distinct design of a hollow core that is different from the traditional single-mode or multimode fibres. In these fibres, the light can be guided due to a thorough reflection at the boundary between the coreless region and the surrounding cladding.

Using the diameter of the fibre to enhance light interaction with its surroundings is a crucial parameter in this research. The method selected for fibre tapering in this study is the use of a CO_2 laser. Tapered optical fibres provide an effective means to adjust the cladding diameter, allowing more core light leakage into the fibre cladding. The coupling coefficient and effective refractive index of each mode in NCF change with external, refractive index value. Previous researchers have employed various techniques such as fusion splicing [10], chemical etching [11], and flame torches [12] to construct tapered optical fibres. However, flame torches suffer from low repeatability and waist diameter variation due to flame instability.

In contrast, the CO_2 laser provides a controlled process with minimal time consumption and can achieve a clean and symmetrical taper. It also offers a regulated process that mitigates the effects of external air rheology, unlike flame torches, fusion splicing and chemical etching [13]. Additionally, a greater percentage of evanescent waves can interact with their environment thanks to tapering fibres, which increases sensitivity. Therefore, tapered fibres have a lot of potential for use in sensing applications.

TNCFs play their role in the optics industry among other things substantially, while holding some benefits. Due to their smaller central size compared to that of other materials, as a result of which the exchange of the light energy with the surrounding material is improved, the particular application of this fibre type in sensing makes it particularly interesting. Tapered fibres are one of the prominent features along with the ones like miniaturised optical systems, evanescent field sensing and light mode conversion. They play a major role in optical fibre links that they play in compensating for the crosstalk, allowing optical component coupling, and providing wavelength tunability and low absorption losses. Their compact size and good working conditions make fibre-optic endoscopy suitable for medical operations. Their high capabilities in dealing with non-linear impacts, rapid adaptability and transforming them into a potent and efficient tool in a wide spectrum of uses ranging from telecommunications, and medicine to catering to the needs of different fields of study.

This study's primary objective is to develop and optimise a TNCF for refractive index measurement using a sample of an ethylene glycol-water solution. To maximise the sensor system's sensitivity, it seeks to ascertain the best TNCF diameter and nanofiber sensing region length.

2.0 METHODOLOGY

2.1 Preparation of SMF-NCF-SMF (SNCS)

The fabrication of sensors comprises several phases one after another. Starting from stripping the fibre, then cleaning the fibre, then aligning the fibre, and finally, optical fibre fusion joints and sensor cables are protected. In step one, the protective serving of single mode fibre (SMF) and no core fibre (NCF) is very carefully and slowly removed from the ends of the SMF. The stripping is done with a fine soft fibre stripper, and for the different lengths we can prepare fibres from 0.5 cm to 2.5 cm. When the stripping is finished, the fibre is washed deeply. It is cleaned with isopropyl alcohol and a lint-free cloth to remove different contaminants (dirt, oil, and debris) which could affect how it functions. Secondly, fibre cutting is being performed. The finisher is a fibre cleaver which is used to sharpen the fibre end, yet making it as flat and smooth as possible. This is a key component for precise jointing in the fusion splicer.

The phase of fibre alignment and fused splicing is done on a fusion splicer machine equipped with a microscope. The machine crafter precisely positions SMF and NCF ends to make them contiguous and systematic. With an electric arc, the fibre ends can be melted and then fused. Thus, the fusion process is repeated to achieve a secure permanent connection between the two strands as a result of the low loss. In the last step for the sensor fibre fabrication, a glass slide was used. Being cautious, the technician sets the glass slide down on the fabricated sensor fibre which is just as another covering layer. This stage is aimed at preventing the degradation of the fibre and conservation of its core characteristics. By completing the following step, we are obtaining a high-efficiency and well-bonded fibre connection therefore the quality and reliability of the sensor system is desirable.

2.2 Preparation of Ethylene Glycol-Water Solution

In this research, the concentration of ethylene glycol used will vary from 100 % to 0 % with a decrement of

20 % for each subsequent sample, resulting in a total volume of 5 ml. The process begins by combining water and ethylene glycol. Start by adding the prescribed amount of water to a clean container [19]. Then, add the designated amount of ethylene glycol to the same container. It is important to ensure that the ethylene glycol completely dissolves in the water. The mixture is gently stirred to facilitate dissolution.

By measuring the refractive index of the ethylene glycol-water solution using a refractometer, Then, a certain number of fluid samples are put onto the refractometer's glass surface and then covered with the transparent cover plate. The cover plate prevents the liquid from being out of the thin plane on the surface. The refractive index of the solution then determines the direction of the light beam as it passes through the layer. The refraction angle is measured by the refractometer usually either on the visual scale or the electronic detector and then this value is used to obtain the refractive index by a calibration process. six different compositions are prepared, as presented in Table 1.

Table 1 Varied refractive index for six ethylene–water solutions

Solution Ratio	Ethylene Glycol (%)	Water (%)	Refractive Index (RIU)
100:0	100	0	1.4290
80:20	80	20	1.4146
60:40	60	40	1.3978
40:60	40	60	1.3739
20:80	20	80	1.3512
0:100	0	100	1.3313

2.3 Tapering Process by CO_2 Laser

Utilizing isopropyl alcohol as a cleaner only, we cleaned the stripped and dirty area before tapering. Using the CO_2 laser, we tapered the stripped section of the optical fibre at 20 W, 24 W, and 28 W input powers. However, the laser power of CO_2 is an indicator of the amount of energy that the lasing device produces in a single unit of time. The energy grows linearly with the CO_2 laser power. The CO_2 laser's energy is absorbed by the silica optical fibre and transformed into thermal energy [14]. Varying the CO_2 laser power resulted in different waist diameters of the fibres [15].

Subsequently, the TNCFs were visually documented using an AmScope optical microscope. The fibre was carefully positioned to ensure that the stripped area could be heated by the CO_2 laser beam, employing a precision motorized translation stage. Two highly precise stepper motors operating at a speed of 700 rpm were utilized to pull the fibre while it was being heated. The taper-based optical fibres were then securely stored in a sealed container to ensure their integrity. Figure 1 illustrates the experimental set-up used for the fibre tapering process utilising the CO_2 laser technique.

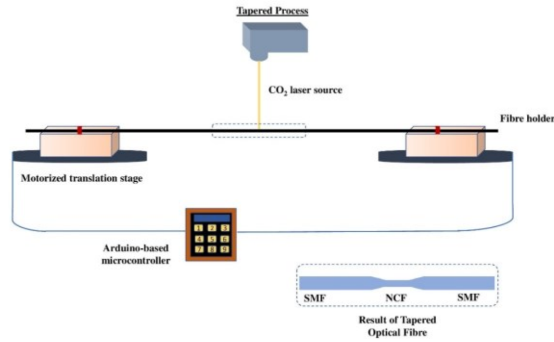


Figure 1 Experimental set-up for tapering process by CO_2 laser

The taper waist diameters attained with CO_2 lasers operating at 20 W, 24 W, and 28 W, respectively, are shown in Figure 2. It displays the tapered fibre pictures along with the appropriate acronyms. The figures clearly show that every taper has symmetrical shapes. The TNCF, designated as TNCF1, has a waist diameter of 39.42 μm and was created with a 20 W CO_2 laser. Similarly, TNCF2 designates the TNCF created by the CO_2 laser at 24 W power, and so on, with a waist diameter of 20.67 μm. This controlled and precise waist diameter achieved using the CO_2 laser is one of the advantages over other techniques, such as the flame brush tapering technique, where controlling the longitudinal shape and waist diameter of the tapered optical fibres is more challenging [16, 17].

To get the diameter of a TNCF using the AmScope MT500 microscope, put the fibre sample on the microscope examination stage first. So that the fibre stands out in sharp contrast, move the coarse and fine focusing controls on the microscope. Use a high-magnification objective lens once the fibre is in view to make adjustments for more accurate measures. Set the microscope up using a fixed measurement stage micrometre. Position the micrometre on the stage and bring the eyepiece reticle to coincide with the micrometre divisions. Take away the stage micrometre and replace it with the TNCF, and with the calibrated reticule measure the diameter of the fibre. Measured the lengths of the fibre three times to get the accurate results with the scale of 1 cm equal to 21.30 μm. Record the readings and calculate the average diameter of the fibre using a uniform scale.

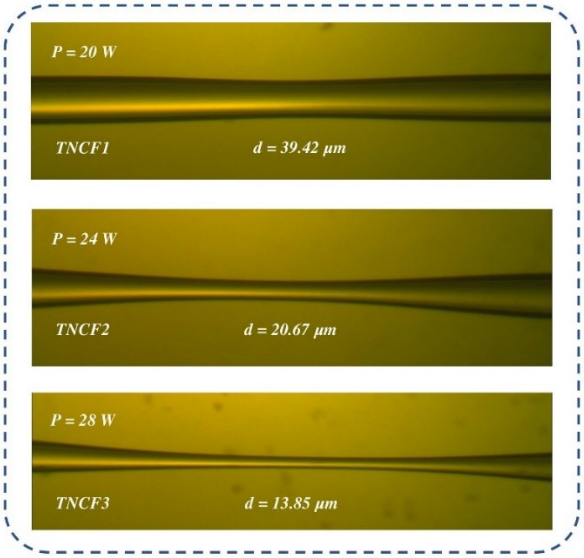


Figure 2 Diameter of TNCF

2.4 Refractive Index Sensor by NCF and TNCF

The NCFs and TNCFs were subjected to refractive index sensing testing using ethylene glycol as the sample. Figure 3 illustrates the experimental setup employed for this purpose. To ensure complete submersion of the ethylene glycol-water solutions (RI ranging from 1.33 to 1.43) into the sensing region of the sensor, The optical fibre's tapered portion was inserted into a sample holder. With an output power of 6.0 mW, the halogen tungsten white light source was utilised as the light source in this experiment. Using a spectrometer to identify a light source and pick up the light signal from the light source, the process normally entails analyzing the light's spectrum to learn about its composition and intensity at various wavelengths.

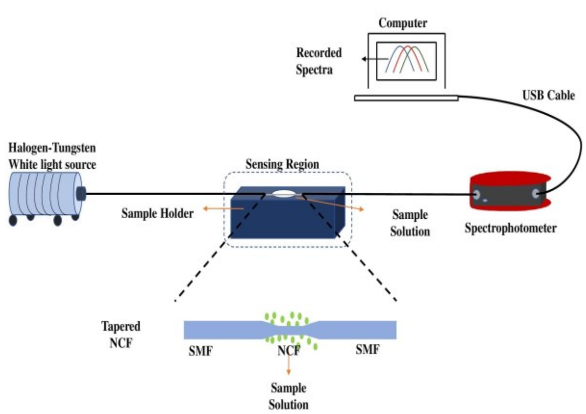


Figure 3 Experimental set-up for refractive index measurement

A sensitivity value comparison is required for the application of the optimal diameter or level of the sensor NCF. To compare sensor sensibility between a wavelength shift vs. refractive index and a graph of wavelength shifts down vs. refractive index, show the graphics separately for each sensor, calculate the sensitivity as the straight part of each graph slope, unify the units, and compare these sensitivity values. The sensor's higher sensitivity indicates its ability to detect tiny deviations in refractive index which is required for more precise applicability. Compared to sensors, it is critical to take into account variables such as probability, ambient conditions and ambient conditions, together with the required accuracy and detection limits.

3.0 RESULTS AND DISCUSSION

3.1 Optimization of NCFs Length

The sensing region utilized optical fibres known as NCFs, varied in length from 0.5 cm to 2.5 cm with an increment of 0.5 cm. The SNCS sensor configuration was employed for detecting changes in the refractive index of the sample. To determine the optimal length of the NCF, preliminary measurements were conducted, and the length yielding the best sensitivity was chosen. The measurements involved detecting changes in the refractive index of the ethylene glycol-water solution.

Figure 4 displays the result of the optical spectra obtained from the optimum length of NCF, which was 2.0 cm.

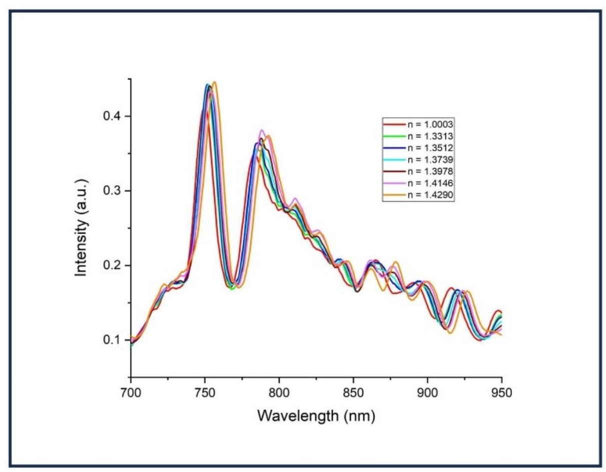


Figure 4 Optical spectra for 2.0 cm length of NCF

The spectra provide insights into the changes in light intensity and wavelength, allowing for the analysis of the sensor's response to variations in the refractive index of the sample. The effect of the change of light intensity as it passes through solvent or any other fluid with various refractive index values is due to several physical forces. At an interface between two media some light is reflected and some is transmitted and more bounces of being reflected and little transmission with a greater refractive index difference will occur, therefore resulting in the loss of intensity. Furthermore, refraction modifies the light traveling path and inside the material intensity reduction occurs as well as by lateral component from particles dispersed within the medium light scattering still.

The sensitivity values for the 0.5 cm, 1.0 cm, 1.5 cm, 2.0, and 2.5 cm lengths of NCF were 31.60, 28.13, 38.37, 42.30, and 38.43 nm/RIU, respectively. The data reveals that the 2.0 cm length of NCF exhibits the highest average sensitivity of 42.30713 nm/RIU, indicating its greater responsiveness to changes in the refractive index. These values demonstrate the varying levels of sensitivity achieved by different NCF lengths in the sensor system.

Figure 5 illustrates the fitting graph generated from the results obtained using the 2.0 cm length of NCF, which exhibited the highest sensitivity among the tested lengths. The graph represents the relationship between the wavelength shift and the corresponding change in the refractive index of the sample, ranging from 1.33 to 1.43, respectively. The data points on the graph showcase the observed wavelength shifts, allowing for the fitting of a curve to analyze the relationship.

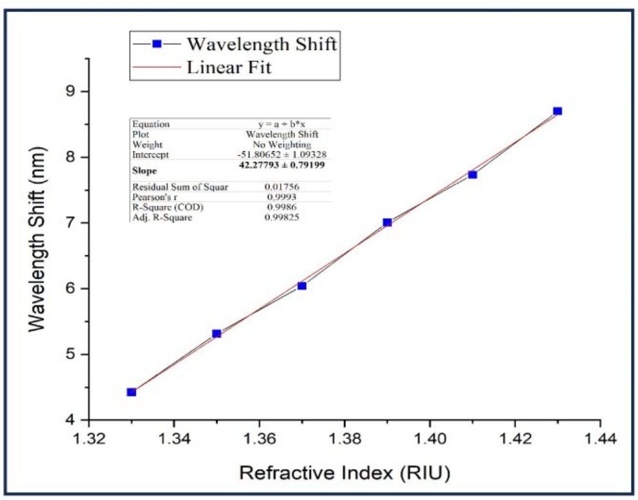


Figure 5 Sensitivity value obtained from 2.0 cm of NCF

Considering the excellent sensitivity displayed it has been selected as the optimal length for the tapering process. This choice enables a comparison of the results between the NCF and the TNCF, providing valuable insights into the performance enhancement achieved through tapering.

3.2 Refractive Index Sensing by TNCFs

For the detection of changes in the refractive index of the ethylene glycol-water solution, different diameters of TNCFs were utilized as the sensor. The obtained results will be used for the comparison of sensitivity between the non-tapered NCF and the TNCF. Figures 6 (a) to (c) present the optical spectra results obtained from three different diameters of TNCF which are 39.42 µm, 20.67 µm, and 13.85 µm. These spectra showcase the changes in light intensity and wavelength, providing valuable data for evaluating the performance and sensitivity of the TNCF sensor compared as compared to the non-tapered NCF sensor.

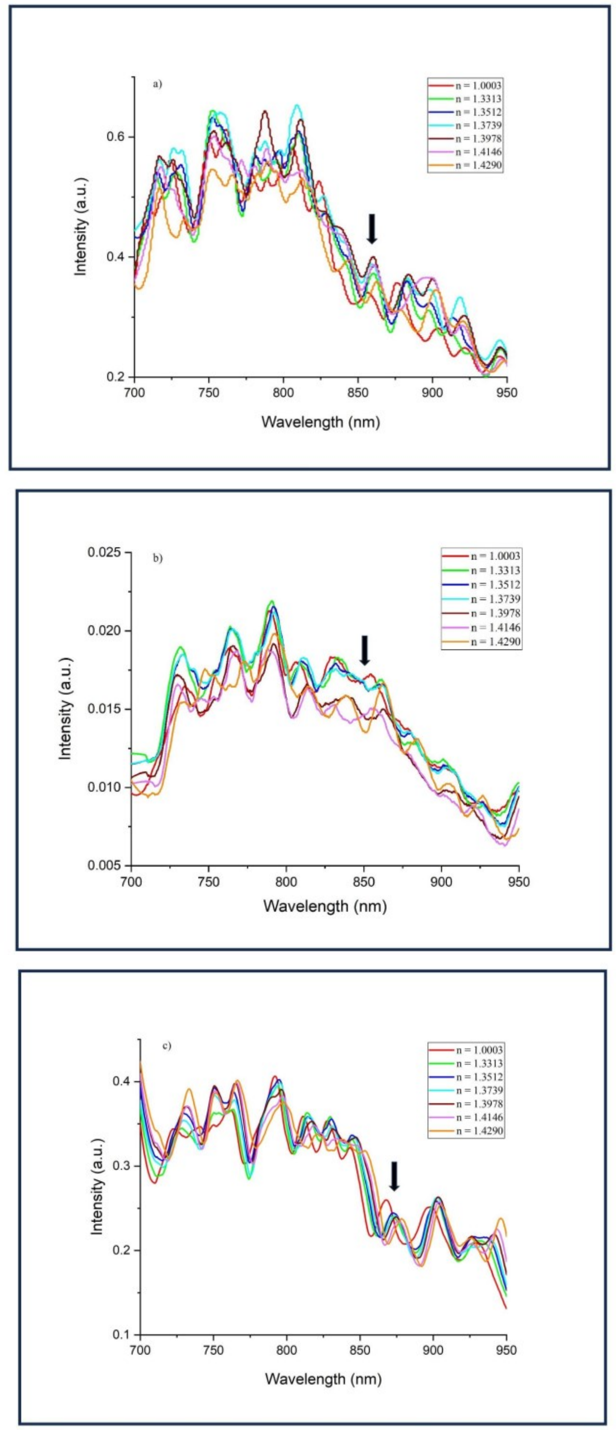


Figure 6 Optical spectra for three different diameters of TNCF

Figures 7(a) to (c) display the fitting graphs generated from the results obtained by using three different diameter sizes of TNCF as the sensing region.

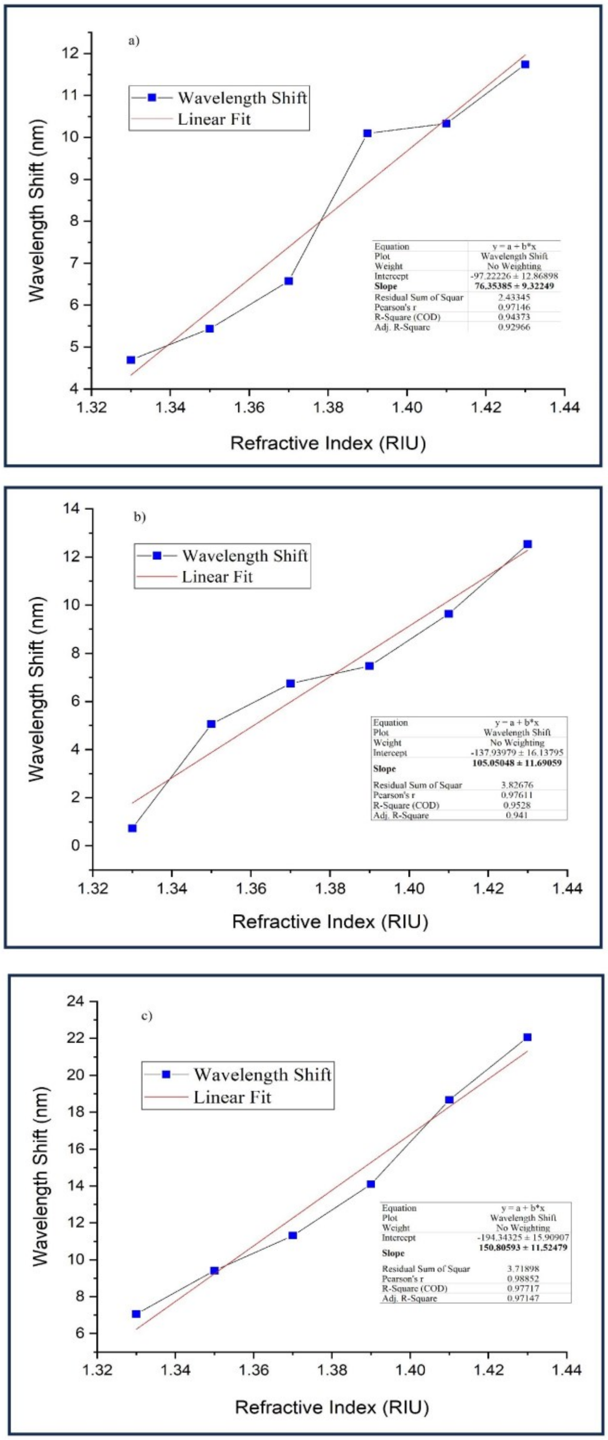


Figure 7 Sensitivity value obtained from the three different diameters of TNCF

3.3 Reproducibility, Reusability and Reversibility Tests

In this section, the reproducibility, reusability, and reversibility of the TNCF sensor probe were further tested. The results of these tests are presented in Figures 8 (a) to (c).

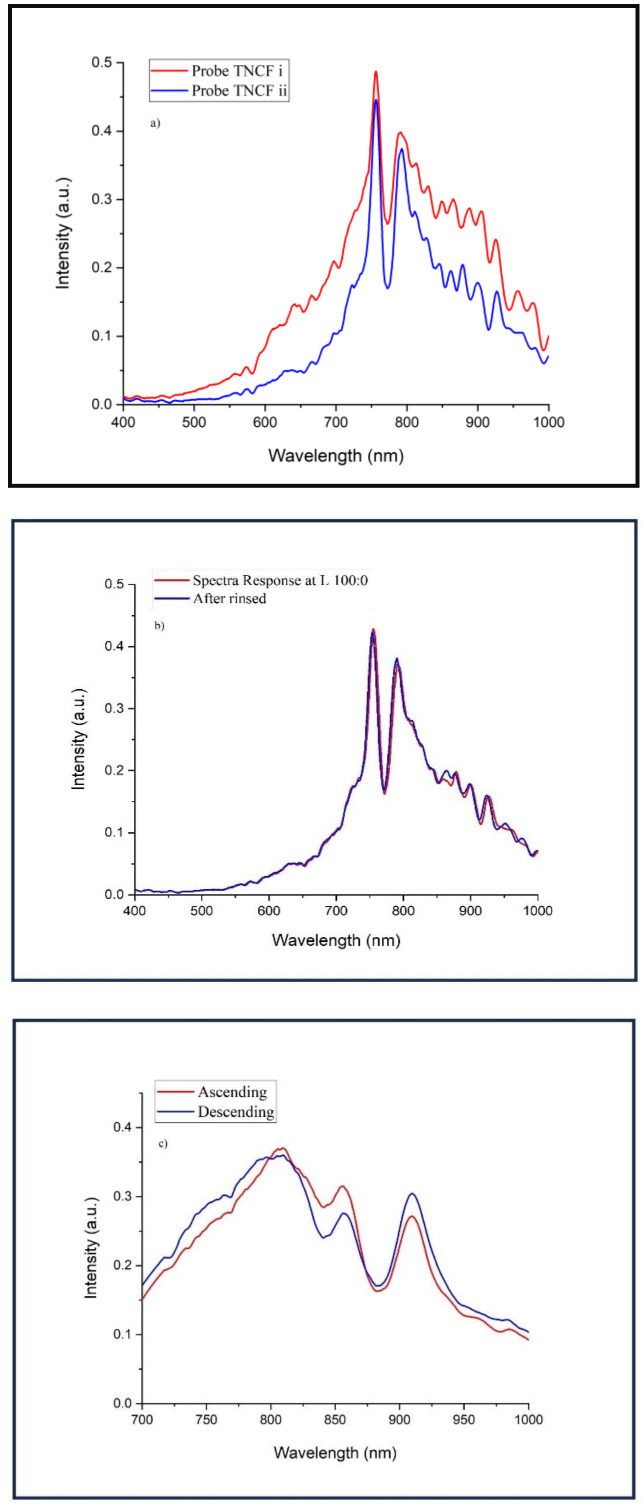


Figure 8 (a) Reproducibility test, (b) reusability test and (c) reversibility test of the proposed sensor probe of 13.85 µm diameter of TNCF

Since the 13.85 µm diameter of TNCF exhibited the best performance among all three TNCF sensor probes, these tests were conducted using the 13.85 µm diameter TNCF sensor probe exclusively. For the reproducibility test, two different sensor probes were tested using the same concentration of ethylene glycol-water solution (100 % EG). The intensity fluctuations between the two sensing probes can primarily be attributed to manufacturing and connection losses. To assess the reusability of the sensor, its performance was tested twice with the ethylene glycol-water solution (100 % EG), with the sensor being rinsed with deionized water between the two tests. In the reversibility test, the sensor underwent measurements starting from the initial value of the sample until it reached the final value, and then it was reversed back to the initial value. Reversibility is an important quality for a sensor, particularly in applications where the sensor undergoes multiple measurement cycles, and the property being monitored is expected to fluctuate over time. Regarding reversibility, reversible sensors are those that trace changes in the recorded property and then return to their initial configuration when the setting is back to its initial state. Overall, the performance of the proposed sensor in terms of reproducibility, reusability, and reversibility was found to be satisfactory in these three cases, indicating its reliability and suitability for practical application.

4.0 CONCLUSION

Briefly, the CO_2 laser technique was applied to decrease NCF diameter. This process shows advantages like clean, regular steps and a short processing time, which is possible with a microprocessor. As for the most sensitive sensor, three unique TNCF sensor sizes were checked. The results reveal that the tapered NCF sensor has higher electrochemical sensitivity than the commonly-used non-tapered NCFs. Besides this fact, TNCF with a 13.85 µm diameter is the biggest contributor to refractive index change detection. The sensor's LoD of 0.127 RIU and a sensitivity of 150.00259 ± 6.77632 nm/RIU indicate that very small changes in the refractive index are within its range. TNCF contains good reversibility, repeatability, and reusability properties as well. It is the most suitable option for practical use and can be repeated consistently due to these excellent properties. Finally, for precise detection of changes in refractive index through this particular TNCF sensor the recommended size of its diameter is optimal. Forming a TNCF for a uric acid sensor will contribute to both science and medicine, as small changes in the solution's refractive index can be detected. A new highly sensitive and portable sensor can revolutionize point-of-care diagnostics which could help to identify and track urate imbalance-related diseases in the early stages. This discovery and improvement could help disease control, reduce healthcare expenses, and impact global health, especially in regions with limited resources. Beyond its immediate use, the technology advances scientific understanding, creativity, and discoveries that could be used in a range of domains, such as biomedical research and environmental monitoring.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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