



Tapered and Coated Optical Fiber with Fe₃O₄ Nanoparticles and Magnetic Fluid for Magnetic Field Detection

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Abstract: In this work, an optical fiber sensor was developed for magnetic field detection. Single-mode and multi-mode fibers were used based on two main processes: chemical etching using hydrofluoric acid (HF) and coating with Fe₃O₄ nanoparticles. The nanoparticle layer was deposited using pulsed laser deposition (PLD) with an Nd:YAG laser operating at a wavelength of 1064 nm and 70 pulses, achieving a thickness of 49.4 nm in the sensing region. This work demonstrates the use of Fe₃O₄ nanoparticles in the coating process through two different techniques within the optical fiber system. In the first technique, the nanoparticles were deposited as a solid coating via pulsed laser deposition (PLD), achieving a thickness in the nanoscale range of 40–60 nm, which provides an effective surface for interaction. In the second technique, Fe₃O₄ nanoparticles were used in the preparation of a magnetic fluid that acts as a liquid coating, forming a stable and magnetically responsive medium. This dual use of Fe₃O₄ in both solid and liquid coatings provides more effective interaction than the use of a single coating technique. The magnetic fluid was prepared by dispersing 5 g of Fe₃O₄ powder in 13 g of paraffin oil. The experimental results showed that increasing the etching time during the chemical etching process using hydrofluoric acid (HF) led to a reduction in the optical fiber diameter, accompanied by a decrease in the transmitted optical power. These results are consistent with previous studies, which have shown that the tapering process using hydrofluoric acid (HF) transforms a conventional optical fiber into a sensitive element capable of responding to external variations. Therefore, this approach provides a suitable way to improve fiber sensitivity and enables its use in magnetic field sensing applications.

Keywords: Optical fiber sensor, tapered optical fiber, Oil-based magnetic fluid, Fe₃O₄ nanoparticles, Pulsed laser deposition (PLD).

1. Introduction

Optical fiber technology is widely used for data transmission and in communications technology [1, 2]. Optical fiber sensing systems have seen rapid development thanks to their superior sensing performance, and their applications have expanded significantly in recent years due to several advantages, including low cost, small size, light weight, high sensitivity and resistance to electromagnetic interference (EMI) [3, 4, 5]. In optical communication systems, external interference is minimized to ensure reliable signal transmission and reception [2]. In contrast, optical fiber sensing systems are specifically designed to



enhance their sensitivity to external disturbances, allowing changes in light radiation to serve as measurable indicators of environmental changes [3, 4]. The light signal propagating through the fiber is typically modulated before transmission [2]. In sensing applications, however, the optical fiber itself acts as the modulator [3, 4]. Furthermore, as a transducer, it converts physical parameters such as temperature, stress, strain, rotation, electric current, and magnetic field into corresponding changes in optical properties, including intensity, phase, wavelength, and polarization [3, 4, 5]. Despite their advantages, conventional fiber optic sensors often suffer from limited sensitivity, restricting their performance in sensing applications [6, 7]. Recent studies have not adequately explored the integration of chemically etched fiber optics using hydrofluoric acid (HF) [8, 9], pulsed laser deposition (PLD) of Fe_3O_4 thin films [10, 11, 12], and an oil-based stable magnetic fluid within a single fiber optic sensing architecture [13, 14]. Therefore, this paper presents an improvement in the sensitivity of a conventional fiber optic sensor. The sensor is used in magnetic field detection applications, as well as in medical and biological applications (biosensing) and sensing in hazardous environments (environmental applications) [15, 16].

2. Materials and Methods

The experimental process involved fabricating tapered optical fibers using controlled chemical etching. The tapering process was carried out in two main stages. In the first stage, the optical fiber was mechanically clamped and integrated into an optical meter. One end of the fiber was connected to a laser light source operating at a wavelength of 1550 nm, while the other end was connected to a photometer to enable continuous monitoring of the output light energy during the etching process. In the second stage, tapering was achieved by localized etching of the sensing area of the fiber using a 40% hydrofluoric acid (HF) solution prepared at a 1:5 mixing ratio (HF:H₂O). The acid was applied using a plastic needle to ensure precise and localized control of fiber diameter reduction. After the etching process was complete, the acid was removed, and the fiber was immediately immersed in distilled water for 5 min, with the water being changed twice to ensure complete termination of the chemical reaction. Laboratory safety precautions were strictly observed during the tapering process using hydrofluoric acid (HF). The chemical etching process was carried out inside a fume hood to provide a safe working environment. Protective gloves were worn throughout the experiment to avoid direct contact with the acid. In addition, glass containers were avoided because HF reacts with glass; therefore, suitable plastic containers were used. The experimental setup of the optical fiber tapering process is shown in Figure 1.

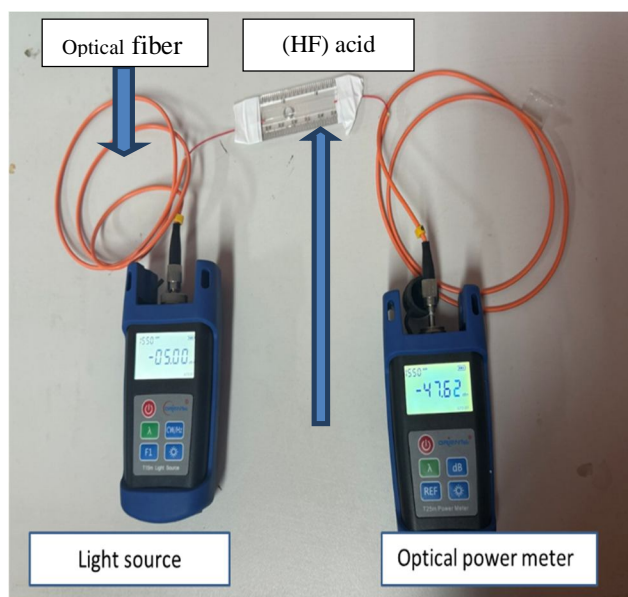


Fig. 1: The experimental setup of the optical fiber tapering process.

2.1. Functional Fiber Coating with Fe_3O_4

Functional coating included the following steps: preparation of the target material (Fe_3O_4) and pulsed laser deposition (PLD).

2.2. Preparation of Fe_3O_4 Target

Fe_3O_4 powder (2g) was used to prepare the deposition target in the form of a pellet. The powder was compressed using a 20-ton hydraulic press under a pressure of 20 bar for 10 min to obtain a dense and mechanically stable target suitable for laser ablation. The use of dense pellet targets is a standard requirement in pulsed laser deposition (PLD) to ensure stable ablation and reproducible thin-film growth. The prepared Fe_3O_4 pellet used as the deposition target is shown in Figure 2.



Fig. 2: The (Fe_3O_4) pellet.

2.3. Pulsed Laser Deposition (PLD) Process

The deposition process was carried out inside the vacuum chamber of a pulsed laser deposition (PLD) system under controlled vacuum conditions, maintaining a chamber pressure of 0.8 Torr. Both the optical fiber substrate and the Fe_3O_4 target were fixed inside the chamber, with the target mounted on a rotating bracket to ensure uniform ejection during deposition. An Nd:YAG laser was used to eject the Fe_3O_4 target, focusing the beam directly onto the target surface. A fixed number of laser pulses (70 pulses) were applied to each deposition sample. The deposition parameters included a wavelength of 1064 nm, a pulse time of 11.7 s, a pulse energy of 500 mJ, and a frequency of 6 Hz. The literature has extensively reported the use of Nd:YAG lasers in the deposition of thin films of oxides, including Fe_3O_4 , as providing controlled and reproducible growth under suitable discharge conditions. Safety precautions were also observed during the PLD process. The deposition was carried out within the designated deposition system while ensuring the safe operation of the laser. Appropriate protective eyewear was worn to avoid direct exposure to the laser beam or its reflections. The PLD setup used for the deposition process is shown in Figure 3.



Fig. 3: (A) The PLD setup

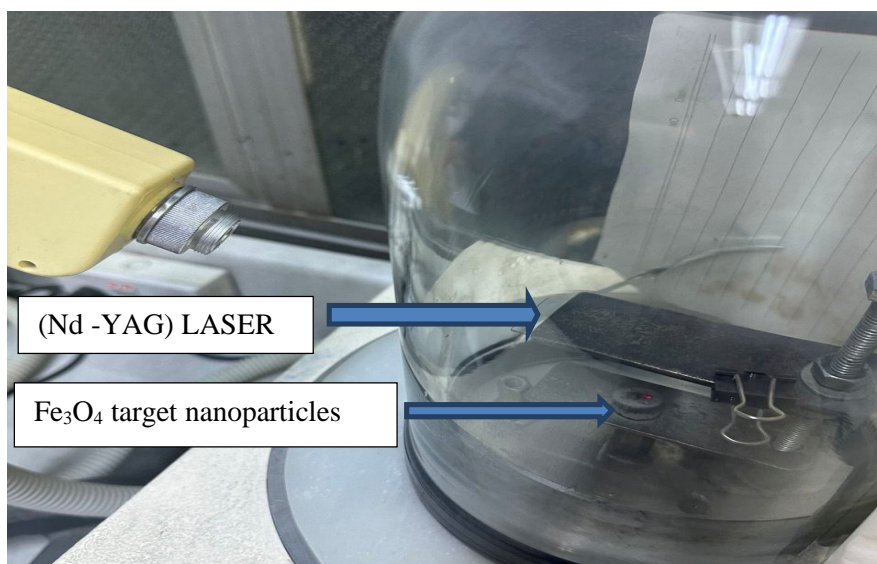


Fig.3: (B) The quartz chamber

2.4. Preparation of Oil-Based Magnetic Fluid

An oil-based magnetic fluid was prepared by dispersing 5 g of magnetite powder (Fe_3O_4) in 13 g of paraffin oil (5:13 \approx 1:2.6 ratio), using oleic acid (OA) as a surfactant to improve particle stability. Ethanol 70% was used as a temporary dispersing solvent to enhance nanoparticle distribution and ensure homogeneity of the mixture. The mixture was stirred manually to ensure uniform dispersion of the Fe_3O_4 particles and then left for 15–20 min to allow the ethanol to evaporate completely. After the ethanol had evaporated, paraffin oil was gradually added while continuing to stir manually until a homogeneous magnetic fluid was obtained. The prepared magnetic fluid was then applied to the modified (tapered) part of the optical fiber using the drop-casting technique. A carefully measured microscopic droplet was placed on the sensitive area to ensure uniform coverage of the conical surface. The coated fibers were

then kept at room temperature to allow the magnetic liquid layer to stabilize. Figure 4 shows the prepared oil-based magnetic fluid.

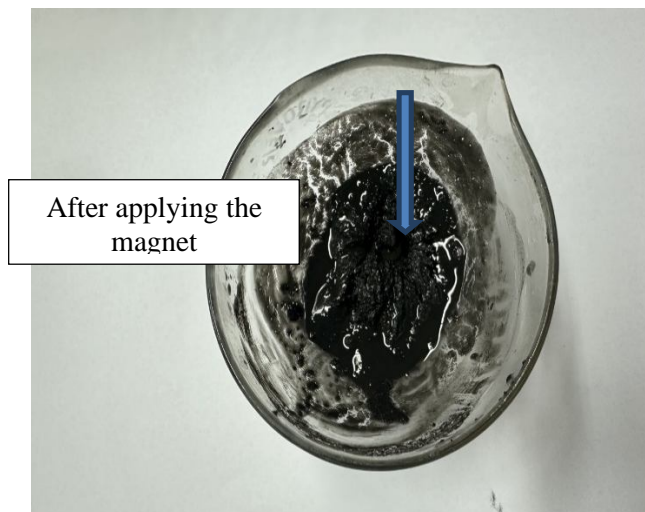
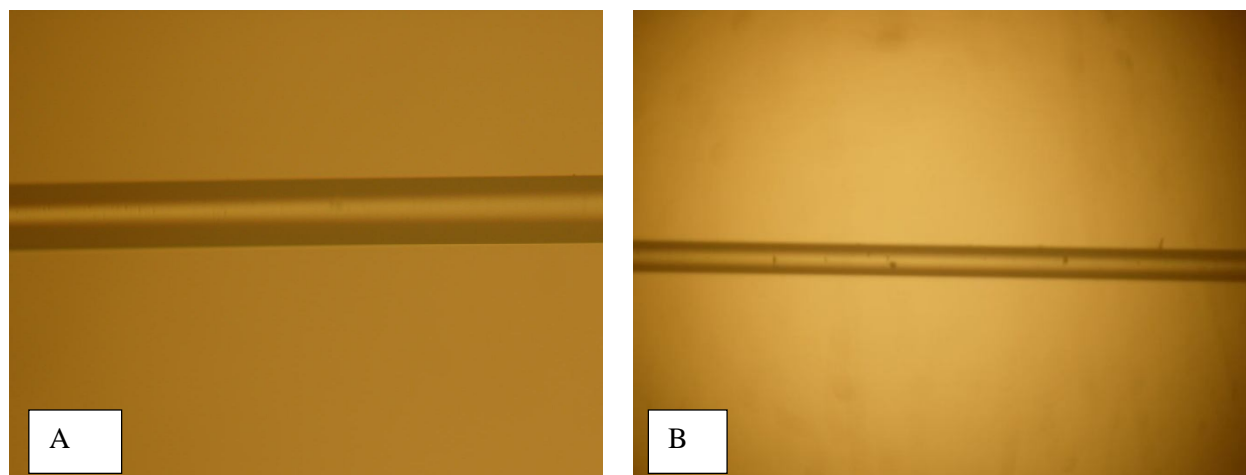


Fig. 4: Oil-Based magnetic fluid

3. Results and Discussion

3.1 Tapered Optical Fiber Diameter Measurement

The reported diameter values in Fig. 5 and Fig. 6 represent the average measurements obtained at multiple positions along the etched region (before and after tapering) using an optical microscope with a magnification of $50\times$. These measurements correspond to an etching duration of 60 min, which was selected based on a time-dependent etching process conducted at 30, 40, and 60 min. The reduction in optical fiber diameter is attributed to the chemical reaction between hydrofluoric acid (HF) and silica (SiO_2), which is the primary constituent of the optical fiber. The etching process predominantly affects the cladding layer, where HF progressively removes portions of the cladding. Consequently, this partial removal leads to a continuous decrease in fiber diameter with increasing etching time.



(A) Fig. 5: The diameter of multi-mode fiber before and after tapering. (A) Before tapering ($121.4\ \mu\text{m}$) (B) After tapering ($65.1\ \mu\text{m}$) at 60 min.



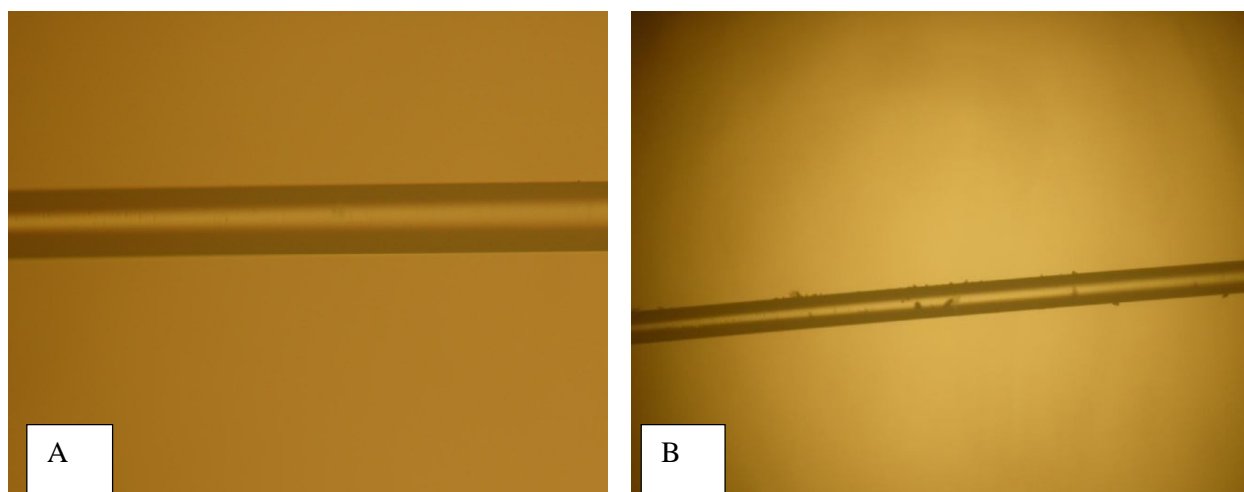


Fig. 6: The diameter of single-mode before and after tapering (A) Before tapering ($121.4 \mu\text{m}$) (B) After tapering ($48.41 \mu\text{m}$) at 60 min

3.2. The Results of Tapered Optical Fiber Output Power Measurement

Fig. 7 shows the variation of the output power of the multimode optical fiber with increasing etching time. Multimode fiber supports multiple propagation modes that allow light to travel through different paths within the core. During the tapering process, the reduction in fiber diameter weakens the confinement of these modes, causing a portion of the optical power to extend into the surrounding medium in the form of an evanescent field. Although some modes continue to propagate, mode redistribution occurs within the tapered region, leading to increased propagation losses. As a result, the transmitted power gradually decreases with increasing etching time. This gradual reduction is attributed to the distribution of optical power among multiple modes, which reduces the overall sensitivity of multimode fiber to diameter changes compared to single-mode fiber.

This behavior is attributed to the reduction in fiber diameter, which weakens the confinement of light within the core and enhances the evanescent field, leading to increased optical losses. The obtained results were compared with previously published studies. In her study entitled "Performance Improvement of the Endoscope by Coating with Antimicrobial Agent," Huda Sahi Raham (2023) reported similar findings, where tapered optical fibers were fabricated using chemical etching with hydrofluoric acid (HF). The study demonstrated that the output power decreases with increasing etching time due to the reduction in fiber diameter and the associated increase in optical losses. This behavior is in good agreement with the present results. Due to the presence of only one propagation mode, the single-mode fiber is highly sensitive to structural changes, resulting in a rapid decrease in output power.

This calibration enabled accurate control of the film thickness by adjusting the number of laser pulses. Accordingly, 70 pulses resulted in a film thickness of approximately 49.4 nm, with a corresponding deposition time of about 11.7 s at a repetition rate of 6 Hz. The observed linear dependence between film thickness and pulse number is consistent with standard pulsed laser deposition behavior reported for oxide thin films under fixed deposition conditions, where the growth rate remains nearly constant and thickness control is achieved through pulse counting. Fig. 8 shows the variation of output power of the single-mode optical fiber with increasing etching time. It can be observed that the transmitted power decreases significantly as the etching time increases. Figure 9 shows that the deposition rate was calibrated using a film thickness of 97.4 nm obtained at 138 laser pulses, yielding an average deposition rate of approximately 0.706 nm/pulse based on the relation $r = t/N$.



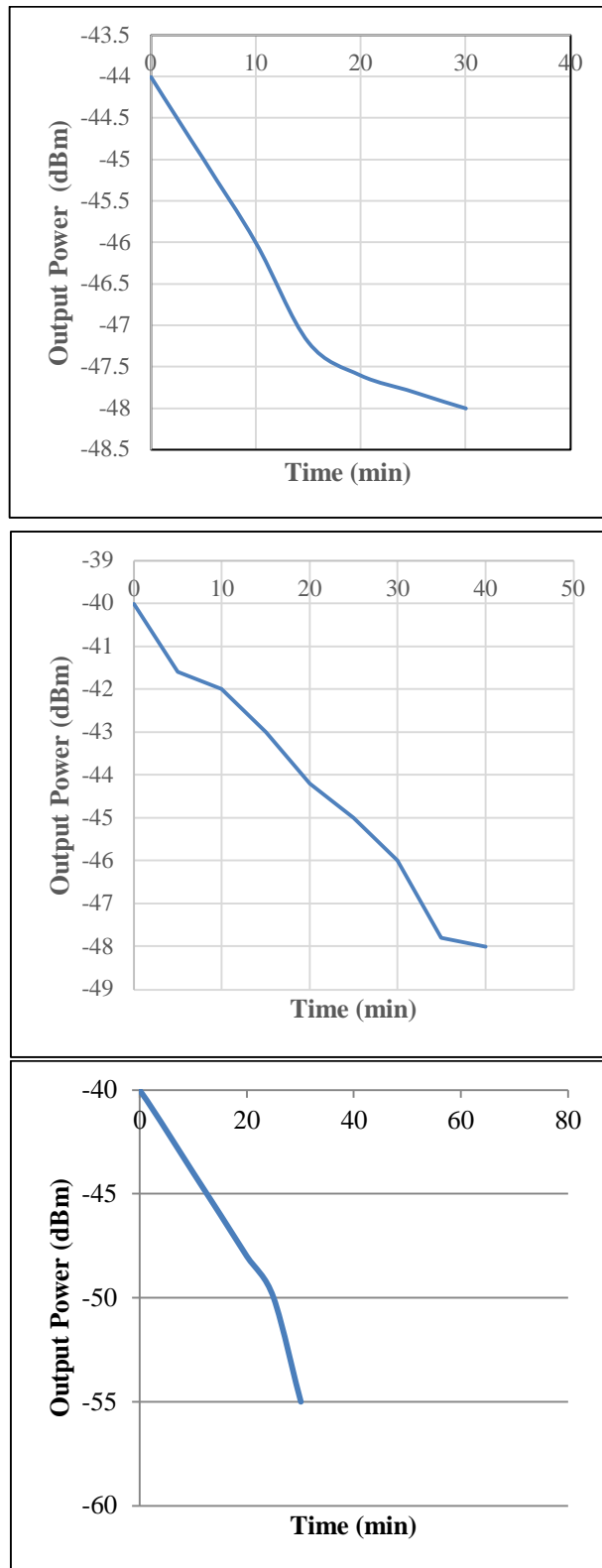


Fig. 7: (A) Output power for the multi-mode fiber at (30 min), (B) Output power for the multi-mode fiber at (40 min), (c) Output power for the multi-mode fiber at (60 min).

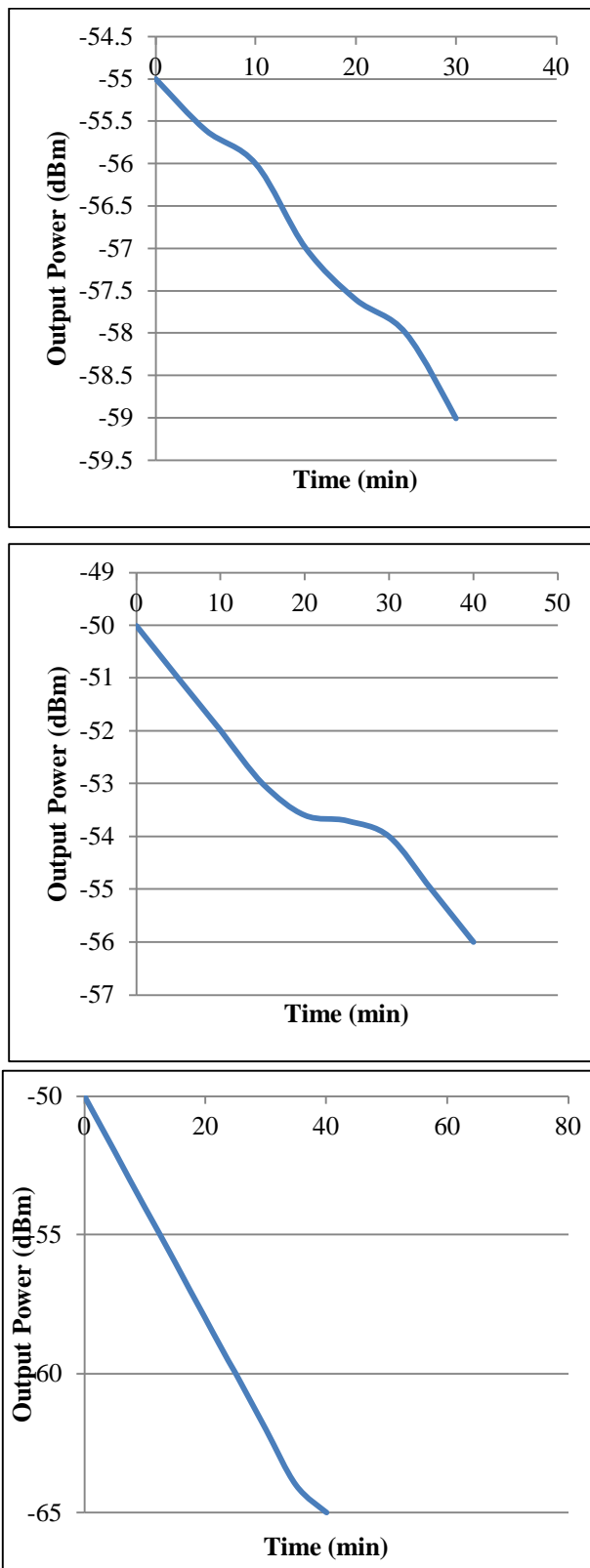


Fig. 8: (A) Output power for the single-mode fiber at (30min), (B) Output power for the single-mode fiber at (40 min), (c) Output power for the single-mode fiber at (60 min)



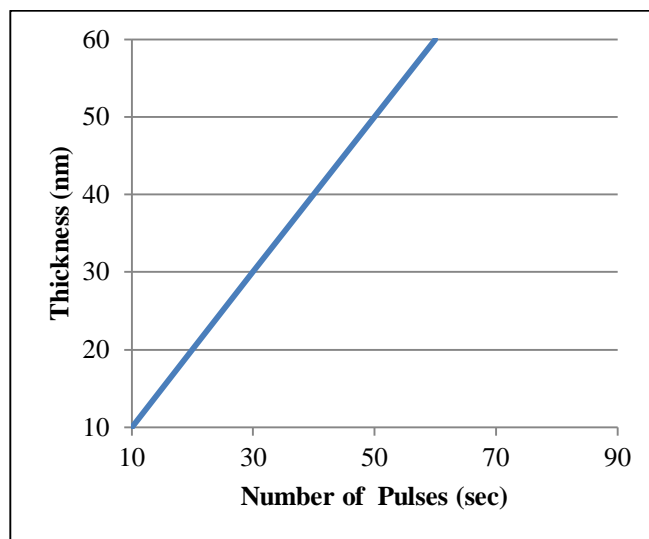


Fig. 9: Thickness of the Fe_3O_4 as a function of pulses in (sec).

4. Conclusion

The tapering process successfully modified the optical fiber geometry in both single-mode and multimode fibers, reducing the fiber diameter and transmitted optical power because of weaker light confinement and increased evanescent-field-related losses. In addition, a thin Fe_3O_4 layer with a thickness of approximately 49.4 nm was successfully deposited onto the tapered region by pulsed laser deposition, while a paraffin oil-based magnetic fluid containing Fe_3O_4 nanoparticles was prepared and applied to create a magnetically responsive sensing medium. The combined use of the solid coating and magnetic fluid improved the sensitivity of the optical fiber sensor. Overall, the developed optical fiber structure demonstrates strong potential for compact, low-cost, and highly sensitive magnetic field sensing, with promising applications in magnetic field monitoring, environmental sensing, and industrial measurement systems.

Author Declaration

The authors declare that this manuscript is original, has not been published before, and is not under consideration for publication elsewhere.

Author's Contributions

The first author performed the experimental work, collected and analyzed the data, and wrote the manuscript. The second author supervised the work, contributed to the interpretation of the results, and revised the manuscript. All authors approved the final manuscript.

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ألياف بصرية مدببة ومطلية بجسيمات نانوية من أكسيد الحديد (Fe₃O₄) وسائل مغناطيسي للكشف عن المجال المغناطيسي

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الخلاصة: في هذا العمل تم تطوير مستشعر ألياف بصرية للكشف عن المجال المغناطيسي حيث تم استخدام ألياف أحادية النمط ومتعددة الأنماط اعتمادا على عمليتين رئيسيتين، هما الحفر الكيميائي باستخدام حامض الهيدروفلوريك (HF) وترسيب طبقة من جسيمات أكسيد الحديد (Fe_3O_4) تم ترسيب الجسيمات النانوية باستخدام تقنية الترسيب بالليزر النبضي (PLD) باستخدام ليزر من نوع (Nd:YAG) بطول موجي قدره 1064 نانومتر وعدد 70 نبضة، حيث تم الحصول على سمك يقارب 49.4 نانومتر في منطقة الاستشعار. يوضح هذا العمل استخدام جسيمات (Fe_3O_4) في عملية الطلاء من خلال تقنيتين مختلفتين ضمن منظومة الألياف البصرية حيث تم في التقنية الأولى ترسيب الجسيمات النانوية كطبقة صلبة باستخدام تقنية (PLD) مما أتاح الحصول على سمك ضمن المدى النانوي (40-60 نانومتر) حيث يوفر سطحا فعالا للتفاعل. أما في التقنية الثانية، فقد تم استخدام جسيمات (Fe_3O_4) في تحضير سائل مغناطيسي يعمل كطبقة طلاء سائلة، مكونا وسطا مستقرا ومستجيبا للمجال المغناطيسي. إن هذا الاستخدام المزدوج للطلاء الصلب والسائل يوفر تفاعلا أكثر كفاءة مقارنة باستخدام تقنية طلاء واحدة فقط. تم تحضير السائل المغناطيسي عن طريق تشتيت 5 غرام من مسحوق (Fe_3O_4) في 13 غرام من زيت البارافين. وأظهرت النتائج التجريبية أنه مع زيادة زمن الحفر الكيميائي باستخدام (HF) ينخفض قطر الليف البصري ويصاحب ذلك انخفاض في القدرة الضوئية المنقلة. وتتفق هذه النتائج مع دراسات سابقة، والتي بينت أن عملية التخصير باستخدام حمض الهيدروفلوريك (HF) تحول الليف البصري التقليدي إلى عنصر حساس قادر على الاستجابة للتغيرات الخارجية. وبذلك يوفر هذا النهج المقترح طريقة فعالة لتحسين حساسية الألياف البصرية مما يجعلها مناسبة للاستخدام في تطبيقات استشعار المجال المغناطيسي.

