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Research Article

Highly Sensitive Plasmonic Sensor for Moisture Detection in Transformer Oil Using Silver-Coated D-Shaped Optical Fiber

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ABSTRACT

Transformer oil plays a critical role in maintaining the insulation and cooling functions of power transformers. However, its performance is significantly affected by moisture contamination, which reduces dielectric strength, accelerates material degradation, and increases the risk of catastrophic failures. This study presents a highly sensitive and cost-effective optical sensing device based on a D-shaped optical fiber coated with silver nanoparticles (Ag-NPs) to detect moisture levels in transformer oil. The sensor makes use of plasmonic homes of Ag-NPs to expand sensitivity and affords real-time moisture detection with a decrease detection restriction of 15 ppm. Fabrication of the sensor became carried out through electron beam evaporation, and its overall performance was optimized the usage of advanced simulations, inclusive of finite detail evaluation and the Drude model. Experimental effects confirmed a sturdy correlation between moisture degrees and transmitted strength changes, demonstrating a sensitivity of 0.4097 dB/ppm. Comparisons with conventional strategies, which include Karl Fischer titration and capacitance sensors, suggest that the proposed sensor gives superior accuracy, quicker reaction times, and lower fabrication charges. These findings underscore the capability of this sensor for enhancing transformer protection strategies and stopping operational failures.

Keywords: Moisture Detection, Transformer Oil, D-shaped Fiber, Silver Nanoparticles, Plasmonic Sensing

INTRODUCTION

Transformer oil serves as a vital insulating and cooling medium in power transformers. However, its performance is considerably stimulated by means of moisture contamination, that can result in reduced dielectric power, increased degradation of insulating substances, and accelerated threat of catastrophic failures[1, 2]. Maintaining moisture degrees under 10 ppm is important for ensuring the operational reliability and durability of transformers. Despite the availability of traditional detection strategies which includes Karl Fischer titration and capacitance sensors, those strategies regularly lack the real-time sensitivity and precision required for advanced programs[3, 4].

Recent advancements in nanotechnology have delivered innovative sensing mechanisms that address those boundaries. Silver nanoparticles (Ag-NPs), in particular, have received substantial attention because of their fantastic plasmonic homes. These houses, which get up from localized floor plasmon resonance (LSPR), allow sturdy light scattering and absorption, making Ag-NPs fairly powerful in optical sensing [5, 6]. By leveraging those plasmonic properties, Ag-NPs can be tailored for diverse packages, inclusive of biosensors, optoelectronic gadgets, and environmental tracking[7-9]. However, the utility of these superior substances for moisture detection in transformer oil stays an underexplored place with sizable capacity. To in addition explore advancements on this place, recent studies have investigated various sensing techniques, which might be reviewed below.

Detection of moisture in transformer oil is an important area of research, as it directly affects the reliability and efficiency of transformers Traditional methods, such as Karl Fisher titration, provide accurate but time-consuming moisture measurements, lack monitoring capabilities in real time and requires robust techniques Advanced methods for optical and fiber plasmonic sensing have been investigated.

Optical fiber sensors have come to be distinguished because of their high sensitivity, immunity to electromagnetic interference, and potential to offer actual-time monitoring. For instance, Yusoff et al. (2018) evolved a D-fashioned optical fiber sensor covered with platinum for moisture detection in transformer oil. The sensor utilized the evanescent area interaction to obtain more desirable sensitivity, making it powerful for precise moisture measurements in dynamic conditions[4]. Similarly, Zhang and Webb (2016) proposed a polymer optical fiber Bragg grating (FBG) sensor for detecting moisture stages in transformer oil. The sensor leveraged the swelling residences of the polymer in reaction to moisture, providing a cost-powerful and sensitive solution[10].

Plasmonic sensors have also been extensively researched for his or her ability to decorate sensitivity the usage of surface plasmon resonance (SPR). Shakya and Singh (2023) brought a hexa-slotted plasmonic sensor able to detecting refractive index adjustments as a result of moisture in transformer oil. Their paintings confirmed excessive sensitivity in the near-infrared region, making it appropriate for enterprise monitoring programs[11]. In some other look at, S. Karthikeyan et al. (2019) evolved an optical waveguide sensor with Graphene oxide coatings, which provided stability and high sensitivity in detecting moisture under sensible running conditions[12].

This observe proposes a D-shaped optical fiber sensor lined with Ag-NPs as a cost-effective and tremendously touchy answer for real-time moisture detection. The D-fashioned fiber layout exposes the evanescent field, improving interplay with the surrounding medium, while the plasmonic residences of the Ag-NPs expand sensitivity and detection accuracy. Advanced simulation strategies, consisting of finite element evaluation and the Drude version, were hired to optimize the layout and validate the functionality of the proposed sensor. This studies no longer handiest highlights the advantages of the D-fiber sensor however also provides a complete assessment with present technology, showcasing its potential to revolutionize moisture detection in transformer oil.

METHODOLOGY

This section describes the systematic approach adopted for the design, fabrication, and evaluation of a D-shaped optical fiber sensor covered with silver nanoparticles (Ag-NPs) to discover moisture content material in transformer oil. By leveraging the plasmonic houses of Ag-NPs, the sensor well-knownshows greater sensitivity, permitting accurate, real-time detection.

2.1 Fabrication of D-Shaped Optical Fiber

The fabrication process began with the use of monomodal optical fibers (SMF-28, Corning) with a core diameter of 8.2 µm and a cladding diameter of 125 µm to fabricate the D-shaped structure to secure its position during the mechanical polishing process Used to be used. A 1500 nm red laser was used to monitor the polishing progress. Using 1200-grit sandpaper, a section of the cladding turned into cautiously eliminated until the middle become partially exposed. This ensured powerful interplay among the evanescent area and the encompassing medium, a key feature of the sensor's capability. The polishing intensity was optimized to approximately 15% of the center diameter to stability sensitivity and structural integrity [4, 13]. The experimental setup consisted of a broadband light supply coupled into the optical fiber, with a photodetector measuring the transmitted power as shown in Fig.1. Transformer oil samples of excessive purity had been used, and moisture content material become incrementally brought to simulate real-global conditions. The resulting changes in transmitted energy were recorded and analyzed to determine the sensor's sensitivity.

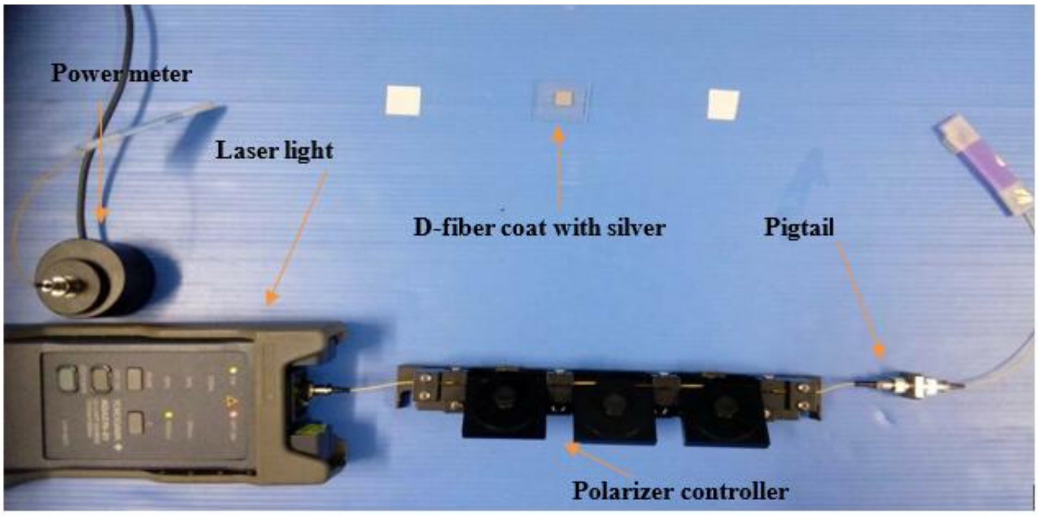


Fig. 1 Experimental set-up of silver coating on D-shape optical fiber water sensor

2.2 Simulation of D-Shaped Optical Fiber

The simulation phase of this study involved designing and analyzing two models of a D-shaped optical fiber using COMSOL Multiphysics[14]. The goal was to evaluate the optical performance and plasmonic properties of the fiber, both with and without a silver nanoparticle coating. This approach enabled a comprehensive understanding of the fiber's behavior under different configurations and operating conditions. Two distinct models were created:

1. **Bare D-Shaped Fiber**: A standard D-shaped optical fiber with no additional layers. The geometry consisted of a core with a refractive index of 1.48 and a cladding with a refractive index of 1.45. The core width was 8.2 µm, while the cladding width was 125 µm. The exposed flat surface of the fiber served as the sensing region, allowing interaction with external media.
2. **Silver-Coated D-Shaped Fiber**: A 30 nm thin silver layer was added to the exposed flat surface of the fiber to enhance its plasmonic properties. The silver layer was modeled with a complex refractive index to account for plasmonic losses and field enhancements.

The propagation of light through the optical fiber was modeled using Maxwell's equations, which are fundamental for simulating electromagnetic wave behavior in optical systems[15].

$$\nabla \times E = -j\omega\mu H \dots\dots\dots\dots\dots (1)$$

$$\nabla \times H = J + j\omega\epsilon E \dots\dots\dots\dots\dots (2)$$

Where, E and H are the electric and magnetic fields, ϵ and μ are the permittivity and permeability, $\omega = 2\pi f$ is the angular frequency.

For the silver-coated model, the plasmonic effects were incorporated using the Drude model for the silver's refractive index[16], a widely used approach for analyzing the optical behavior of metals in plasmonic applications.

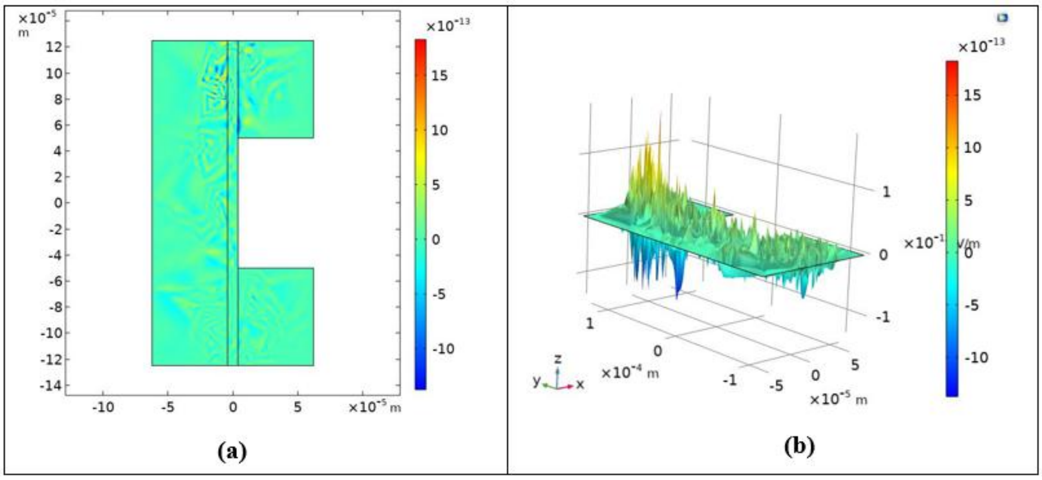
$$n_{Ag} = \sqrt{\epsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\gamma\omega}} \dots\dots\dots\dots\dots (3)$$

where: ϵ_∞ is the high-frequency dielectric constant, ϵ_∞ is the plasma frequency and γ is the damping coefficient.

The simulations were carried out using the Electromagnetic Waves, Beam Envelopes module in COMSOL Multiphysics. A triangular mesh was applied to ensure high-resolution calculations, particularly at the silver-core interface. The operational wavelength range was set from 1.55 µm to 1.561 µm, covering the region of interest for the plasmonic resonance.

2.2.1 Simulation Results

The electric field distribution in the bare D-shaped fiber was analyzed to understand its optical behavior. The simulation results, as shown in Fig.2, The cross-sectional view demonstrates the presence of an evanescent field at the flat sensing surface of the D-shaped fiber, while the side view of the field distribution highlights the strong confinement of the guided light within the core, ensuring efficient propagation with low optical losses. This evanescent field enables the fiber to interact with external media, making it suitable for sensing applications.



(a) (b)

Fig.2 Electric field distribution. (a) cross-sectional and (b) z-component (side view) in the bare D-shaped fiber.

The reflectance, transmittance, and loss properties of the bare D-shaped fiber were evaluated over the wavelength range of 1.559 µm to 1.5605 µm, as shown in **Fig. 3**. The results indicate a gradual increase in reflectance and transmittance with an increase in wavelength. The reflectance remains relatively low, starting at approximately 0.896 and reaching 0.913 at the higher wavelength. This trend demonstrates the fiber's high transmission efficiency, with minimal losses throughout the wavelength range. The transmittance, which correlates closely with the reflectance curve, confirms the efficient optical wave propagation within the core. These properties make the bare D-shaped fiber an excellent candidate for sensing applications, where high transmittance and low reflectance are critical for maintaining signal quality[17].

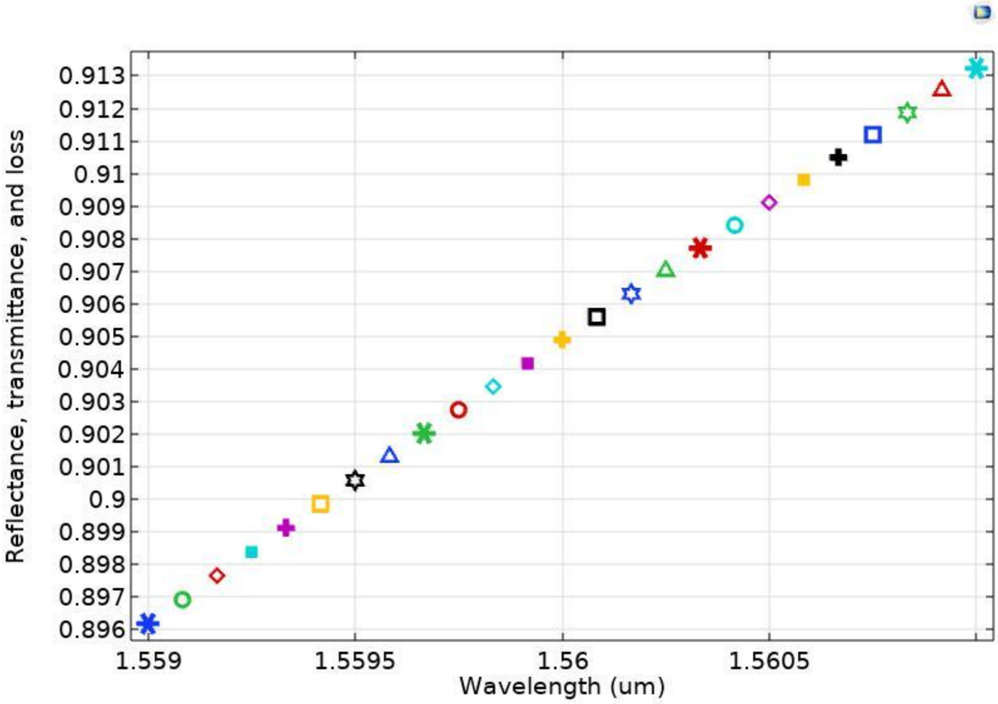


Fig.3 the reflectance, transmittance, and loss characteristics of the bare D-shaped

The simulation results for the D-fashioned fiber with a 30 nm silver coating spotlight the full-size impact of the metal layer on the optical behavior of the fiber. Fig. 4(a) illustrates the two-dimensional distribution of the electric field, displaying better field confinement on the middle-metallic interface because of the excitation of surface plasmon polaritons (SPPs). This enhancement is further emphasised in the 3-dimensional visualization in Fig. 4(b), in which the sphere intensity peaks near the silver-covered area, indicating strong plasmonic effects. These results verify that the inclusion of the silver layer amplifies the evanescent area, thereby growing the fiber's sensitivity to changes inside the surrounding refractive index.

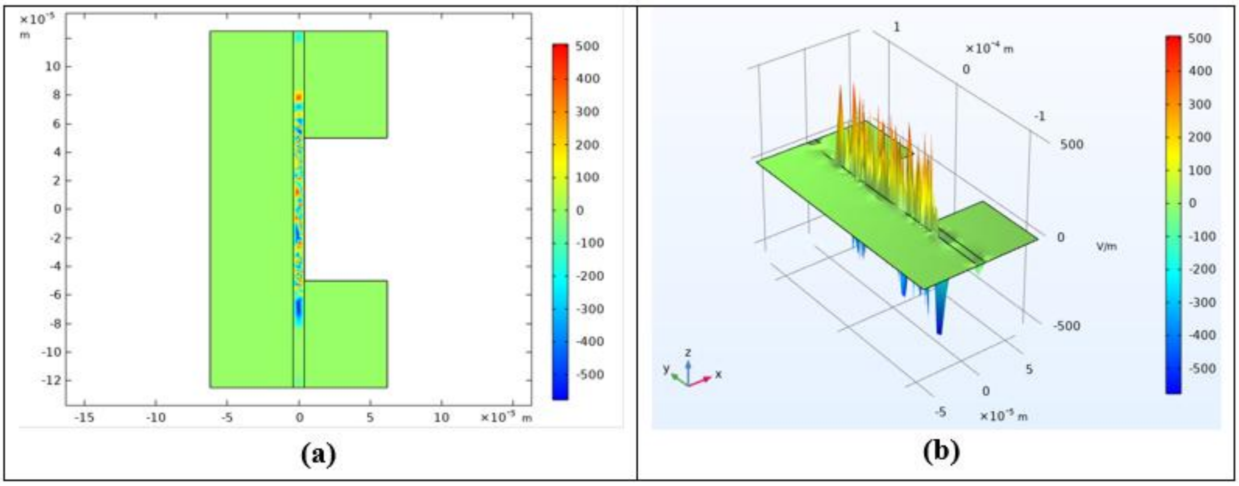


Fig.4 Electric field distribution. (a) cross-sectional and (b) z-component (side view) in the D-shaped fiber with 30 nm silver layer.

Additionally, as shown in **Fig. 5**, the reflectance, transmittance, and loss characteristics of the silver-coated fiber reveal a distinct dip in transmittance near the plasmonic resonance wavelength of 1.56 μm, with a corresponding increase in reflectance. This behavior demonstrates the efficient interaction of light with the silver layer, making the coated fiber suitable for plasmonic sensing applications such as biosensing, refractive index measurement, and environmental monitoring[18].

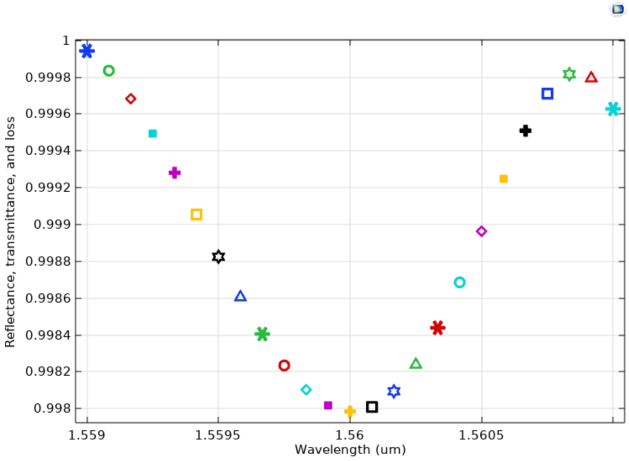


Fig.5 the reflectance, transmittance, and loss characteristics of the D-shaped fiber coating silver layer

2.3 Sample Preparation and Characterization

The silver (Ag) coating on the polished D-shaped optical fiber was prepared using an electron beam evaporation technique. During the deposition process, the optical fiber was placed in a vacuum chamber at a pressure of 3×10^{-5} Torr to ensure a contamination-free environment. A controlled deposition current of 35 mA was applied, resulting in a uniform silver layer with a thickness of 30 nm. This precise deposition process is critical for achieving consistent plasmonic properties across the coated surface[18, 19].

Following deposition, the coated fiber underwent annealing at 270°C for two hours to improve the adhesion and crystallinity of the silver layer. The annealing process promotes the formation of uniformly distributed silver nanoparticles, essential for enhancing localized surface plasmon resonance (LSPR) effects. Field Emission Scanning Electron Microscopy (FESEM) analysis confirmed the formation of nanoparticles with an average size of 29 nm and a density of 327 ± 12 μm^{-2} over an area of 500 × 500 nm^2, as shown in Fig.6.

The selection of a 30 nm silver layer aligns with previous studies, which demonstrated that this thickness optimizes plasmonic interactions for sensing applications. A. Philip and A. R. Kumar (2022) observed that silver coatings of similar dimensions significantly enhance LSPR effects, improving sensor sensitivity by amplifying the interaction between the evanescent field and the surrounding medium[20]. Furthermore, Sharma and Gupta (2022) emphasized that precise control over deposition parameters, such as vacuum pressure and deposition current, is crucial for achieving reliable optical performance in plasmonic sensors[21].

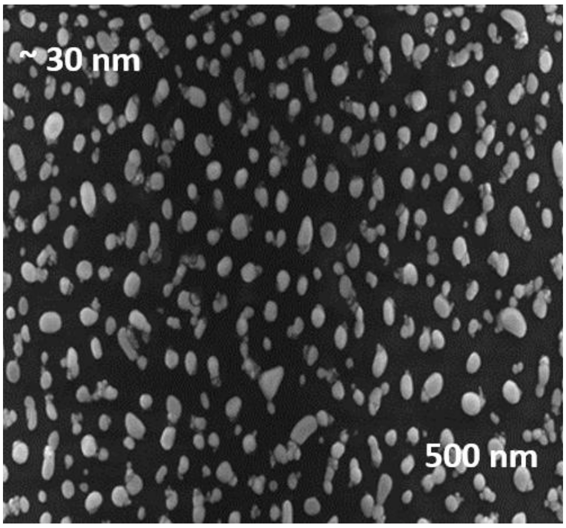


Fig.6 FESEM image demonstrates the uniform deposition of silver nanoparticles with an average size of 30 nm.

Table 1: Specifications of Silver nanoparticles (Ag-NPs)

Silver nanoparticles annealing at temperature of 270°C (2 hours for Ag)

Material	**Sample Thickness (nm)**	**Average Size of Particles (nm)**	**Average of nanoparticle distribution in (500 x 500) nm^2**	**Density (□m^2) = average of nanoparticle per area (500 x 500) nm^2**
Silver (Ag)	**30**	**29**	**82**	**327 ± 12**

RESULTS AND DISCUSSION

3.1 UV-Vis Analysis of Silver Nanoparticles

The optical traits of the silver nanoparticles used to coat the D-fiber have been analyzed using UV-Vis spectroscopy. The absorption spectra showed that the silver nanoparticles exhibited robust plasmonic resonance at approximately 440 nm, as shown in Fig. 7. This peak corresponds to the localized floor plasmon resonance (LSPR) of the silver nanoparticles, indicating their suitability for plasmonic programs. The located LSPR peak aligns with previous research, which document similar resonance conduct for silver nanoparticles with similar sizes and fabrication situations[22], confirming their potential for boosting sensor sensitivity in various application

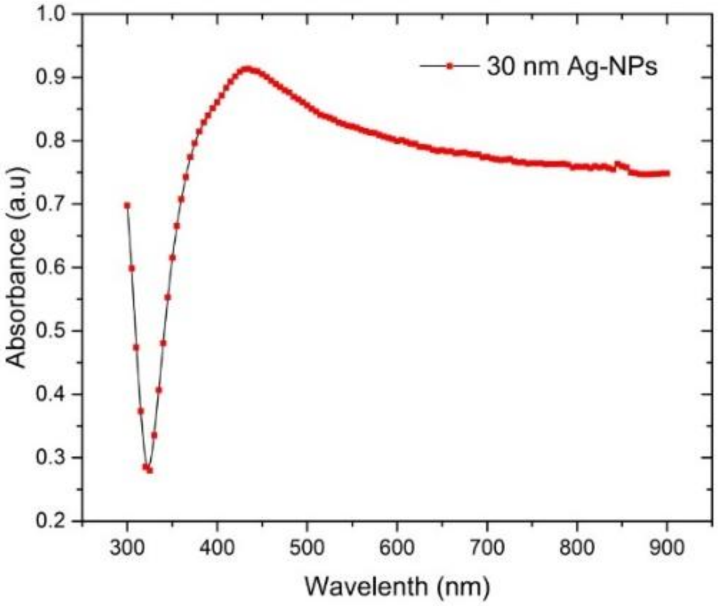


Fig. 7 Absorption spectra of Ag-NPs (~30 nm).

3.2 **FESEM Analysis of D-Shaped Fiber**

Field Emission Scanning Electron Microscopy (FESEM) was used to analyze the polished D-shaped optical fiber [23], as shown in Fig.8. The image revealed a smooth and uniform polished surface with a clearly exposed core region, demonstrating precise control over the polishing process. The intact cladding, except for the polished area, maintained the fiber's structural stability. These features ensure effective evanescent field interaction and strong coupling with silver nanoparticles, confirming the fiber's suitability for plasmonic sensing applications.

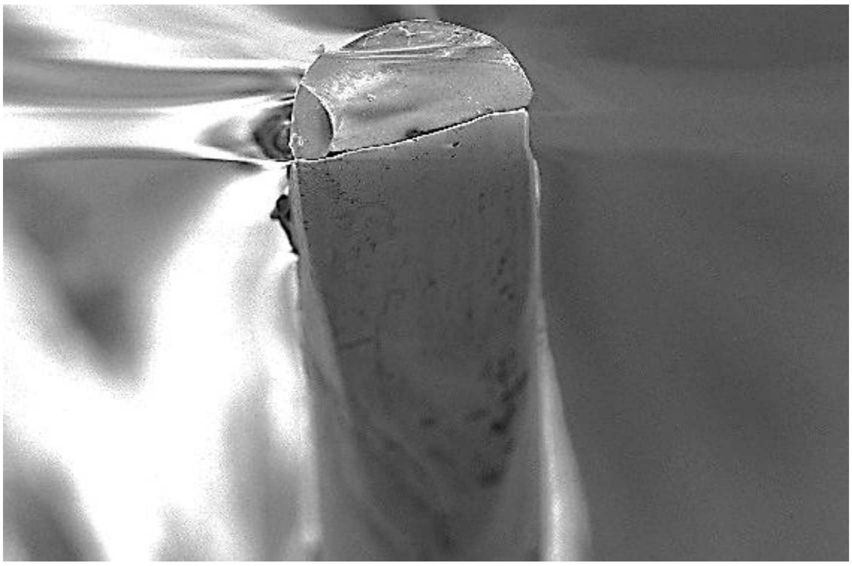


Fig. 8 FESEM image of the polished D-shaped optical fiber

3.3 Sensor Performance and Response to Moisture Content

The first experiment involved applying transformer oil samples with varying moisture content to the D-shaped fiber sensor. The moisture levels ranged from 0 ppm to 15 ppm, with measurements taken at intervals. The sensor's response was observed as a change in transmitted power, which decreased as the moisture content in the oil increased. The sensor's change in transmitted power for different moisture levels (0 ppm, 5 ppm, 10 ppm, and 15 ppm) was measured over time. As shown in Fig. 9, a sharp drop in transmitted power was observed immediately after applying the oil sample. The magnitude of the power drop increased as the moisture content of the oil increased, with the 15-ppm sample exhibiting the most significant decrease (~ 6.15 dB) in transmitted power.

The decrease in transmitted power through the fiber sensor due to several reasons. First, water has light absorption properties, which increase the overall absorption of light. Second, water causes additional light scattering within the oil due to changes in its composition. Additionally, the presence of water alters the oil's refractive index, leading to uneven light refraction. Moreover, interactions between the fiber and the water-oil mixture can reduce the efficiency of light transmission. Finally, moisture contributes to the degradation of the oil and increases its electrical conductivity, which disrupts the oil's ability to transmit light effectively.

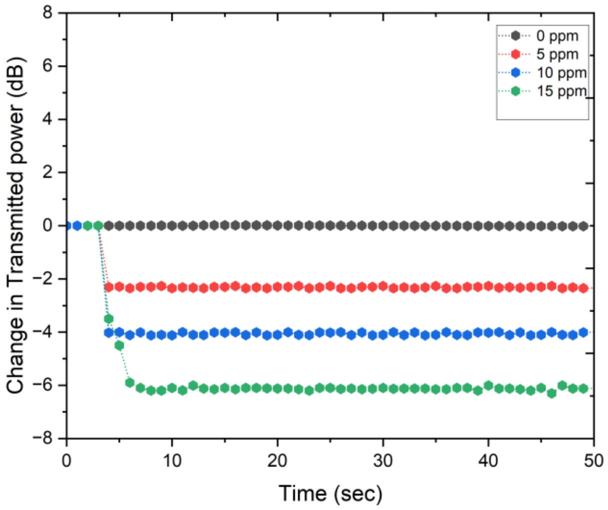


Fig. 9 Change in transmitted power (dB) over time for different moisture concentrations.

A calibration curve was generated by plotting the change in transmitted power (dB) against the moisture content (ppm) in transformer oil as shown in Fig 10. The slope of the calibration curve represents the sensitivity of the sensor. This indicates that for every 1 ppm increase in moisture content, the transmitted power decreases by 0.4097 dB. Therefore, the sensitivity of the senso is 0.4097dB/ppm.

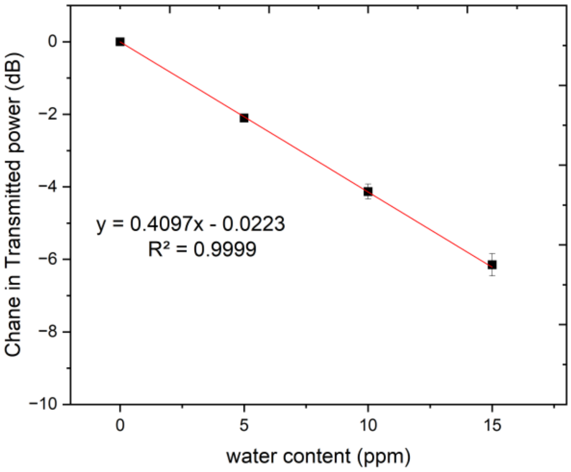


Fig.10 Linear relationship between water content (ppm) and change in transmitted power (dB).

The experimental results established that the silver-covered D-formed optical fiber well-knownshows excessive sensitivity and brilliant linearity in detecting moisture content material in transformer oil. The calibration curve (Fig. 10) indicates a sensitivity of 0.4097 dB/ppm with a sturdy correlation coefficient (R^2 = zero.9999), confirming the sensor's reliability.

This sensitivity surpasses the performance of polymer-primarily based sensors, together with those reported by using Zhang and Webb (2016)[10], wherein decrease sensitivity and correlation have been determined due to fabric swelling results.

Moreover, the robustness of the silver-coated D-shaped fiber under varying conditions, which includes temperature and humidity, positions it as a more stable opportunity in comparison to other metal-coated fibers. For example, platinum-coated designs, as said by Yusoff et al. (2018), confirmed lower sensitivity and stability, highlighting the blessings of the silver-covered configuration for actual-time programs in transformer oil monitoring [4].

CONCLUSIONS

In this look at, a extraordinarily sensitive plasmonic sensor based on a silver-coated D-shaped optical fiber become successfully developed for actual-time moisture detection in transformer oil. The optimized sprucing depth (15% of the core diameter) and the uniform silver nanoparticle coating considerably enhanced the evanescent discipline interaction and plasmonic residences, leading to advanced sensor sensitivity and stability. The experimental effects validated a high sensitivity of 0.4097 dB/ppm and an first rate linear relationship between transmitted energy loss and moisture content, with a correlation coefficient of $R^2 = 0.9999$. These findings surpass the performance of traditional polymer-based totally and platinum-coated sensors, showcasing the prevalence of the silver-lined design in phrases of precision, balance, and robustness beneath various environmental conditions.

Simulations using COMSOL Multiphysics and the Drude model confirmed the presence of an improved applied electric field at the core-metal interface, further validating the plasmonic behavior of the sensor The sensor exhibited exceptional potential for application requiring precise real-time monitoring, such as transformer oil quality monitoring and predictive maintenance in power systems

This research provides a foundation for further exploration of plasmonic sensors in industrial applications. Future studies could focus on extending the sensor's capabilities to detect other impurities in transformer oil, enhancing its multi-functional performance, and improving its integration with IoT systems for smart monitoring solutions.

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