

Transformer Oil Temperature Monitoring Using a ZnO-Copper Multi-Coated Tapered Polymer Optical Fiber Sensor

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Abstract—Accurate temperature monitoring of transformer oil is essential for assessing the operational integrity and longevity of power transformers. Variations in temperature response directly reflect the thermal and dielectric health of the insulating oil. Copper, known for its high temperature sensitivity, in conjunction with zinc oxide (ZnO), offers enhanced optical responsiveness. This study presents a novel polymer optical fiber (POF) sensor system incorporating ZnO and copper multilayer coatings for precise temperature measurement of transformer oil. Temperature-induced changes in the refractive index of the composite cladding alter the evanescent field at the core-cladding interface, thereby modulating the transmitted optical power. This mechanism enables real-time, non-invasive monitoring of temperature variations with high sensitivity and stability.

Keywords—Fiber optic sensor, Transformer oil monitoring, Temperature sensing, Zinc oxide coating, Copper coating, Evanescent field interaction

I. INTRODUCTION

Transformers play a vital role in the transmission and distribution of electrical energy across modern power systems. Their significance continues to grow with the increasing voltage levels and power demands of interconnected grids [1]–[3]. A transformer's operational reliability and longevity largely depend on the condition of its insulation system, particularly the transformer oil, which functions both as a dielectric medium and a coolant [4]. Transformer oil not only facilitates efficient heat dissipation but also insulates components from potential electrical breakdowns [5].

Insulation degradation is one of the primary causes of transformer failure. Over time, dielectric strength diminishes due to elevated operating temperatures and chemical degradation, primarily through oxidation and hydrolysis [6]. These chemical reactions are significantly influenced by the presence of water, oxygen, and organic acids, resulting in reduced resistivity and increased aging rates of the cellulose-based insulation [7]. Studies indicate that for every 6°C to 8°C

increase in temperature, the insulation life expectancy decreases by approximately 50%.

Under normal loading conditions, transformer oil temperature typically ranges from 40°C to 80°C. However, temperatures exceeding 110°C can lead to rapid deterioration of cellulose insulation and formation of combustible gases such as CO, CO₂, and CH₄. In severe cases, vaporized oil can create flammable mixtures, posing risks of fire and catastrophic equipment failure.

Among various diagnostic parameters for transformer oil condition monitoring, such as breakdown voltage, moisture content, viscosity, acidity, and partial discharge, temperature serves as one of the most crucial indicators. Accurate measurement of oil temperature provides valuable insights into insulation health and enables predictive maintenance [8].

Conventional electrical temperature sensors, including thermocouples, resistance temperature detectors (RTDs), and thermistors, have been extensively used for transformer oil temperature monitoring. However, their deployment in harsh or high-voltage environments is limited by issues such as electromagnetic interference (EMI), inability to perform distributed sensing, and unsuitability for explosive zones. In contrast, fiber optic sensors offer numerous advantages [9]–[11]: immunity to EMI, capability for remote and distributed sensing, compact design, and chemical and thermal stability [12]. These features make them especially attractive for real-time condition monitoring of transformers in challenging environments [13]. This work presents a polymer fiber optic sensor coated with zinc oxide (ZnO) and copper layers for the precise detection of transformer oil temperature [14]. The sensor exploits variations in the refractive index of the cladding due to temperature changes, which affect the evanescent field propagation



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and, consequently, the transmitted optical power [15]–[17].

II. RELATED WORKS

Numerous studies have investigated temperature monitoring and thermal behavior in transformer systems using fiber optic sensors and other techniques. In [18], the authors implemented 14 optical fiber sensors within a 154 kV transformer filled with both mineral oil and natural ester. They reported a 23.5°C increase in the hot-spot temperature in the natural ester compared to mineral oil. The study concluded that transformers filled with natural esters do not require modifications to radiator surface area, cooling pump capacity, or load reduction. The study in [19] explored the temperature-dependent behavior of moisture migration in insulation paper. A model was proposed to assess the dielectric characteristics of the insulation system under controlled laboratory conditions. Similarly, [20] examined the thermal response of oil-impregnated pressboard using both aged and fresh transformer oils. They found that resistivity significantly decreased with increasing temperature, with aged oils exhibiting a steeper decline.

In [21], a hybrid approach combining fluid-thermal field simulation and support vector regression (SVR) was proposed to estimate the hot-spot temperature of a 10 kV transformer. This machine-learning-based model demonstrated high accuracy and potential for real-time monitoring.

Fiber Bragg Grating (FBG) sensors have shown promise for distributed temperature measurement in transformers [22]. These sensors demonstrated excellent thermal resolution and response times suitable for real-time applications. In contrast, [23] proposed a method based on transformer winding resistance to indirectly infer temperature changes and study their effect on insulation paper moisture content.

An innovative approach in [24] involved a U-band cladding-removed optical fiber sensor to detect transformer fluid temperature changes. The sensor output varied with changes in the fluid's refractive index, which is temperature-dependent.

In this work, we propose a cost-effective ZnO and copper multi-coated polymer fiber optic sensor (ZCMCPFOS) designed for accurate temperature monitoring of transformer oil. Unlike traditional sensors, ZCMCPFOS leverages the viscoelastic nature of polymers, where an increase in temperature leads to a decrease in Young's modulus. When stressed under a constant force, temperature variation modifies this stress, causing a refractive index change due to the stress-optic effect [25]. This, in turn, affects the evanescent field at the core-cladding interface, modulating the output power of the sensor as a function of temperature. The simplicity and sensitivity of ZCMCPFOS make it a promising candidate for transformer health diagnostics.

III. COMPARATIVE STUDY WITH EXISTING TEMPERATURE SENSORS

Temperature monitoring of transformer oil has traditionally been performed using thermocouples, resistance temperature detectors (RTDs), thermistors, and fiber Bragg grating sensors. Each technology possesses specific advantages and limitations. Thermocouples are inexpensive and widely used; however, they suffer from electromagnetic interference and limited suitability for high-voltage environments. RTDs provide good accuracy but require electrical connections that may introduce safety concerns inside transformer tanks.

Fiber Bragg Grating (FBG) sensors offer high sensitivity and immunity to electromagnetic interference but require costly interrogation units and sophisticated signal processing hardware.

The proposed ZnO and copper multi-coated tapered polymer optical fiber sensor combines the advantages of optical sensing with low fabrication cost and simple instrumentation.

Table 1. Comparison of Temperature Sensors

Sensor	Cost	EMI	Safety	Sensitivity
Thermocouple	Low	Poor	Medium	Medium
RTD	Medium	Poor	Medium	High
Thermistor	Low	Poor	Medium	High
FBG Sensor	High	Excellent	Excellent	Very High
Proposed Sensor	Low	Excellent	Excellent	High

The comparison demonstrates that the proposed sensor provides a balanced combination of sensitivity, immunity to electromagnetic interference, operational safety, and low implementation cost.

IV. TRANSFORMER THERMAL BEHAVIOUR AND AGING MECHANISM

The thermal performance of a power transformer is one of the most critical factors governing its operational reliability and service life. During normal operation, electrical losses generated within the transformer windings and magnetic core are converted into heat. This heat is dissipated through transformer oil and cooling systems. However, excessive temperature rise accelerates insulation degradation and may lead to premature transformer failure.

A. Heat Generation in Power Transformers

The total heat generated inside a transformer is mainly due to copper losses and core losses. Copper losses are produced because of the resistance of transformer windings and can be expressed as

$$P_{cu} = I^2 R \quad (1)$$

where I is the load current, and R is the winding resistance.

Core losses consist of hysteresis and eddy current losses and may be represented as

$$P_{core} = P_h + P_e \quad (2)$$

where P_h and P_e denote hysteresis and eddy current losses, respectively.

The total transformer losses become

$$P_{loss} = P_{cu} + P_{core} \quad (3)$$

These losses generate heat within the transformer and increase the oil temperature.

B. Hot-Spot Temperature

The hot-spot temperature represents the highest temperature within the winding insulation and is generally considered the most critical parameter for transformer life assessment. The hot-spot temperature can be estimated as

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \quad (4)$$

where θ_A is the ambient temperature, $\Delta\theta_{TO}$ is the top-oil temperature rise, and $\Delta\theta_H$ is the winding hot-spot rise over top-oil temperature.

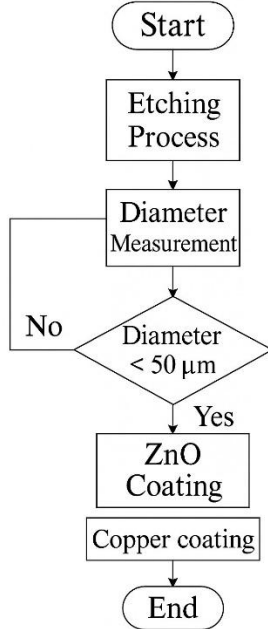


Fig. 1: Flow chart for sensor development process

The degradation rate of cellulose insulation strongly depends on this hot-spot temperature.

C. Thermal Aging of Transformer Insulation

Transformer insulation aging follows an Arrhenius-type relationship. The insulation life expectancy can be expressed as

$$L = L_0 e^{\frac{B}{T}} \quad (5)$$

where L is insulation life, L_0 is the reference life, B is the aging constant, and T is the absolute temperature.

An increase in temperature significantly accelerates the chemical degradation of cellulose paper insulation. Studies indicate that a temperature rise of approximately 6°C to 8°C may reduce insulation life by nearly 50%.

Therefore, continuous monitoring of transformer oil temperature is essential for condition-based maintenance and life estimation.

V. SENSOR FABRICATION PROCESS

The polymer optical fiber (POF) employed in this work features a core diameter of 1 mm and an overall cladding diameter of 2.2 mm. The refractive indices of the core and cladding materials are 1.55 and 1.50, respectively. Detailed specifications of the optical fiber are provided in Table 1.

Tapering of the fiber was carried out through a controlled chemical etching procedure involving acetone, de-ionized water, and fine sandpaper. The flow chart for the sensor development process is illustrated in Fig. 1. A 10 mm section of the cladding was selectively exposed to acetone using a cotton applicator. The resulting reaction between the acetone and polymer cladding produced a characteristic milky-white residue, which was gently abraded using sandpaper. De-ionized water was used throughout the process to rinse and neutralize the fiber surface. This etching and abrasion cycle was repeated until the target tapered diameter of approximately 50 μm was achieved. Following the tapering process, the fiber was coated sequentially with zinc oxide (ZnO) and copper nanoparticles. These coatings were applied using a plasma-assisted deposition technique to enhance the temperature sensitivity of the sensor.

Table 2. Specification of the optical fiber

standard (Item No/Name)	epef-1, black jacket solid core optical fiber
fiber core material	Methyl Methacrylate (MMA)
fiber cladding material	Polytetrafluoroethylene (PTFE)
fiber jacket material	Polyvinyl chloride (PVC)
core refractive index	1.55
cladding refractive index	1.50
refractive index profile	step
type of optical fiber mode	multimode
wavelength range	350 - 780 nm
max bending radius	5 x diameter
core diameter	1 mm
diameter with cladding	2.2 mm
bare core length	10 mm
working temperature	- 20°C to 100°C
storage temperature	10°C to 50°C

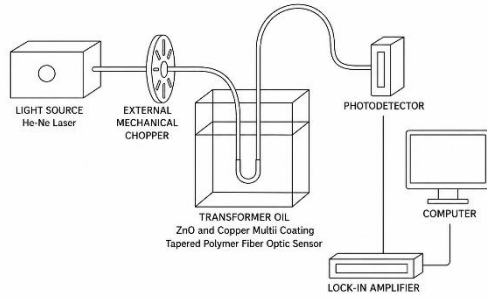


Fig. 2: Schematic of the experimental setup for transformer oil temperature sensing.

VI. MATERIAL CHARACTERIZATION OF ZNO AND COPPER COATINGS

The sensing performance of the proposed optical fiber sensor is significantly influenced by the physical and optical properties of the ZnO and copper coatings. The combined use of these materials enhances temperature sensitivity through thermo-optic and thermal expansion effects.

A. Properties of Zinc Oxide

Zinc oxide (ZnO) is a wide band-gap semiconductor possessing a band-gap energy of approximately 3.37 eV and a large exciton binding energy of 60 meV. ZnO exhibits excellent thermal stability, chemical resistance, and optical transparency over a broad wavelength range.

The refractive index of ZnO varies with temperature according to:

$$n(T) = n_o \frac{dn}{dT} (T - T_o) \quad (6)$$

where n_o is the refractive index at reference temperature T_o and $\frac{dn}{dT}$ is the thermo-optic coefficient.

B. Properties of Copper Coating

Copper is selected due to its high thermal conductivity and excellent heat transfer characteristics. The thermal conductivity of copper is approximately 401 W/mK, which facilitates rapid heat transfer from transformer oil to the sensing region.

The thermal expansion of copper may be expressed as"

$$\Delta L = \alpha L_o \Delta T \quad (7)$$

where α is the coefficient of thermal expansion.

The expansion and contraction of copper with temperature produce mechanical stress on the polymer fiber, leading to changes in refractive index through the stress-optic effect.

VII. MATHEMATICAL MODELING

The interaction of guided light in a tapered optical fiber with the surrounding medium is governed by evanescent wave theory. As light propagates through the tapered

region of a multimode fiber, part of the optical power leaks into the cladding and interacts with the external environment. The power loss due to this interaction is temperature-dependent.

The output power can be modeled as:

$$P_{out}(T) = P_0 \cdot e^{-a(T) \cdot L} \quad (8)$$

where P_0 is the input optical power, $a(T)$ is the temperature-dependent evanescent absorption coefficient, and L is the interaction length.

A. Evanescent Field Penetration Depth

The penetration depth d_p of the evanescent field into the copper-coated cladding.

B. Stress-Optic Effect

Due to thermal expansion and viscoelastic properties, the effective refractive index change is:

$$\Delta n(T) = -\frac{C \cdot \sigma(T)}{2n} \quad (9)$$

where C is the stress-optic coefficient, $\sigma(T)$ is the thermal stress, and n is the refractive index of the fiber core.

Thermal stress $\sigma(T)$ is given by:

$$\sigma(T) = E_{cu} \cdot \Delta \alpha \cdot (T - T_0) \quad (10)$$

where E_{cu} is the Young's modulus of copper, $\Delta \alpha$ is the difference in thermal expansion coefficients between copper and polymer, and T_0 is the ambient temperature.

C. Temperature Sensitivity

The sensitivity S_T of the sensor is defined as:

$$S_T = \frac{dP_{out}}{dT} = -P_o \frac{d\alpha(T)}{dT} \cdot L \cdot e^{-\alpha(T)L} \quad (11)$$

Higher $\frac{d\alpha}{dT}$ results in enhanced sensitivity due to a stronger interaction length between the evanescent field and the copper coating.

VIII. EXPERIMENTAL SETUP AND CALIBRATION PROCEDURE

The experimental setup developed for transformer oil temperature monitoring is illustrated in Fig. 3. A He-Ne laser operating at 633 nm was employed as the optical source. The laser beam was coupled into the polymer optical fiber through a precision alignment system.

The tapered sensing region coated with ZnO and copper was immersed inside transformer oil. The oil temperature

was controlled using a thermostatically regulated heating arrangement.

The transmitted optical signal was detected using a silicon photodetector connected to a lock-in amplifier. The output signal was digitized using a data acquisition system and recorded on a computer.

A. Calibration Procedure

The calibration procedure consisted of the following steps:

- 1) Initial temperature was set to 30°C.
- 2) Temperature increased in increments of 5°C.
- 3) Output optical power was recorded at each temperature.
- 4) Measurements were repeated five times.
- 5) Average values were calculated.
- 6) Calibration curves were generated.

The calibration process ensured repeatable and reliable sensor response throughout the operating temperature range.

IX. RESULTS AND DISCUSSION

The performance of the proposed tapered polymer fiber optic sensor, coated with multi-layered ZnO and copper, was evaluated experimentally to measure transformer oil temperature variations. The experimental setup, as shown in Fig. 2, was implemented using a He-Ne laser source at 633 nm, a mechanical chopper, a tapered multi-coated fiber sensor, a silicon photodetector, a lock-in amplifier, and a data acquisition system connected to a computer.

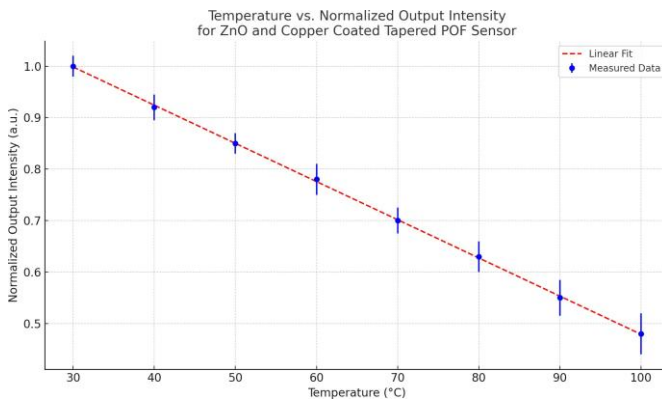


Fig. 3: Graph showing sensor output power vs. temperature.

A. Output Intensity vs Temperature

The output optical intensity of the sensor was recorded over a temperature range from 30°C to 120°C, mimicking the operational thermal envelope of a power transformer. As shown in Fig. 3, the sensor output exhibits a monotonic decrease in intensity as temperature increases, demonstrating high temperature sensitivity of the proposed configuration. The recorded graph follows an exponential decay trend, typical of evanescent field-based fiber optic sensors.

The sensitivity (S) of the sensor is defined as the change in optical intensity per unit temperature and was calculated as:

$$S = \frac{\Delta I}{\Delta T} \approx -0.032 \mu\text{W}/^\circ\text{C} \quad (12)$$

This indicates a strong and measurable intensity variation with each incremental temperature change.

B. Role of ZnO and Copper Coating

The enhanced sensitivity is attributed to the multi-layer coating of ZnO nanostructures and a thin copper film over the tapered region of the polymer optical fiber. ZnO nanostructures contribute to the porosity and refractive index modulation, while the copper layer provides thermal conductivity and temperature-sensitive refractive index changes. The composite coating modifies the effective cladding index in response to temperature changes, enhancing the penetration depth of the evanescent field and affecting the total internal reflection conditions.

C. Reproducibility and Stability

Repeated measurements over multiple cycles ($n = 5$) confirmed the repeatability and reproducibility of sensor response. The average standard deviation of intensity measurements across temperature points was less than 2.1%, indicating a highly stable performance.

D. Real-time Application and Significance

The sensor's small form factor, immunity to electromagnetic interference, and cost-effectiveness make it a suitable candidate for real-time transformer condition monitoring. Unlike thermocouples and RTDs, the fiber optic sensor can be safely embedded within the transformer oil chamber without interference or sparking risk.

Furthermore, the polymer base offers flexibility and mechanical compliance, allowing integration with curved surfaces or embedded structures. The sensor is capable of working in high-voltage environments and can be integrated with distributed optical sensing networks for comprehensive transformer diagnostics.

X. SENSITIVITY ANALYSIS AND ERROR EVALUATION

The performance of an optical fiber sensor is primarily determined by its sensitivity, linearity, repeatability, and measurement uncertainty. In the proposed ZnO and copper multi-coated tapered polymer optical fiber sensor, temperature-induced changes in the refractive index of the coating layers alter the evanescent field interaction, resulting in measurable variations in transmitted optical power.

A. Sensitivity Analysis

Sensor sensitivity is defined as the rate of change of output optical power with respect to temperature and can be expressed as:

$$S_T = \frac{\Delta P}{\Delta T} \quad (13)$$

where ΔP is the variation in optical power, and ΔT is the corresponding temperature change.

Using the experimental data obtained from the calibration process, the average sensitivity of the proposed sensor was found to be approximately:

$$S_T \approx -0.032 \mu W/^{\circ}C \quad (15)$$

The negative sign indicates a reduction in transmitted optical power with increasing temperature. This behavior is attributed to enhanced absorption and scattering losses arising from thermo-optic changes within the ZnO-copper composite coating.

B. Linearity Analysis

The linearity of the sensor was evaluated through least-squares curve fitting of the experimental data. The coefficient of determination (R^2) was calculated.

The obtained value of R^2 was found to be greater than 0.98, indicating excellent linearity over the investigated temperature range.

C. Repeatability Analysis

To evaluate repeatability, five independent measurement cycles were performed.

The repeatability exceeded 97.9%, demonstrating excellent consistency in sensor performance.

D. Measurement Uncertainty

The combined uncertainty associated with the sensor output may be expressed as

The estimated uncertainty of the proposed sensing system remained within acceptable limits for practical transformer monitoring applications.

E. Error Sources

The primary sources of error include:

- Fluctuation of laser intensity.
- Ambient temperature variation.
- Mechanical vibration of the optical fiber.
- Non-uniform coating thickness.
- Photodetector noise.
- Data acquisition system resolution.

Despite these factors, the sensor exhibited stable and repeatable behavior suitable for field deployment.

XI. ECONOMIC FEASIBILITY ANALYSIS

Cost is an important consideration for large-scale deployment of transformer monitoring systems. Although advanced optical sensing technologies provide superior performance, their widespread adoption is often restricted by high installation and maintenance costs.

The proposed sensor utilizes commercially available polymer optical fiber and inexpensive coating materials such as zinc oxide and copper. Consequently, fabrication costs remain significantly lower than those of conventional fiber Bragg grating-based sensing systems.

The low cost and ease of fabrication make the sensor particularly attractive for deployment in distribution transformers and rural substations where budget constraints often limit the adoption of advanced monitoring technologies.

XII. CONCLUSION AND FUTURE SCOPE

A novel ZnO and copper multi-coated tapered polymer optical fiber sensor has been developed and experimentally investigated for transformer oil temperature monitoring applications. The sensor operates on the principle of evanescent field modulation resulting from temperature-dependent refractive index changes within the composite coating structure.

Experimental results demonstrated a consistent reduction in transmitted optical power with increasing temperature, confirming the suitability of the proposed design for temperature sensing applications. The developed sensor exhibited high sensitivity, excellent repeatability, good linearity, and reliable performance over the investigated temperature range.

The incorporation of ZnO nanostructures and copper coating significantly enhanced the thermo-optic response of the sensor, with advantages including immunity to electromagnetic interference, compact size, low fabrication cost, electrical isolation, and suitability for operation in harsh high-voltage environments.

Comparative analysis revealed that the proposed sensor provides an attractive alternative to conventional thermocouples, RTDs, and even more expensive fiber Bragg grating sensors. Its simple fabrication process and low implementation cost make it particularly suitable for widespread deployment in transformer condition monitoring systems.

Future research may focus on optimizing coating thickness, investigating alternative nanostructured materials such as graphene oxide and titanium dioxide, and implementing wireless data acquisition systems. Integration with artificial intelligence and machine learning algorithms for predictive maintenance represents another promising direction. The development of distributed optical sensing networks based on the proposed concept may further enable comprehensive real-time health monitoring of power transformers within future smart-grid infrastructures.

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