

Polymer-Based Acousto-Optic Ultrasonic Sensor for Non-Destructive Evaluation of Dielectric Insulation

Krishanlal Adhikari^{1*}, Chiranjib Koley², Nirmal Kumar Roy³

Abstract

A dual-polymer fiber-optic sensor for monitoring partial discharge (PD) activity in high-voltage polymeric insulation is presented in this work for non-destructive evaluation and dielectric testing applications. Dielectric weakness within polymeric insulation leads to partial discharge activity, generating ultrasonic acoustic waves that propagate through the medium. The developed sensing assembly comprises a conical polymer-based horn that gathers and concentrates the ultrasonic acoustic emission energy generated by dielectric weakness, and a single-mode fiber (SMF)–polymer–SMF interferometric cavity that converts the resulting stress into optical signal modulation. Because the horn is fabricated from a dielectric polymer, the acoustic front end can be positioned near energized high-voltage terminals without disturbing local electric field conditions, making it suitable for dielectric condition monitoring of polymeric insulators. When the concentrated acoustic pressure from the polymeric horn is applied to a compliant polymer gap between two single-mode fibers, the cavity's optical path length is modulated through thickness deformation and photoelastic index variation, producing an interference response that is directly interrogated by a photodiode. Different promising polymer combinations are evaluated through optimized modeling of the polymeric horn and cavity architecture, from which the epoxy horn–PDMS cavity configuration is identified as the most suitable. The performance of the developed sensor is experimentally investigated and validated against the standard electrical detection method, with testing carried out on polymeric silicone rubber samples and insulators under controlled partial discharge conditions as a proof-of-concept demonstration. An average sensitivity of $-75.7 \text{ dB re } 1 \text{ V}/\mu\text{bar}$ and a signal-to-noise ratio of approximately 24.6 dB are achieved, confirming that optical transduction within the polymer cavity and mechanical amplification provided by the polymer horn enable effective detection of low-level PD-induced ultrasonic signatures. The results demonstrate the effectiveness of polymer-based fiber-optic acoustic sensors for long-term condition monitoring of polymeric insulators in high-voltage environments.

Keywords: Dielectric weakness, non-destructive evaluation, partial discharge, polymer-based sensors, polymeric insulator, proof-of-concept development, ultrasonic, and acoustic emission

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INTRODUCTION

Partial discharge is a crucial indicator of the overall dielectric weakness in any high-voltage (HV) power application. Early detection of partial discharge is essential to ensure the reliable functioning of any power utility [1]. Hence, condition-based monitoring by partial discharge detection is crucial.

In electrical power systems, polymeric insulators are considered essential components of power utilities [2]. The long-term stability of polymeric insulators is lower than that of conventional insulators, such as glass and porcelain, despite their growing use [3]. For this reason, an efficient non-destructive assessment of dielectric health for the

polymeric insulator is required. These insulators are exposed to environmental pollution [4] from both natural and industrial contaminants, which form a conductive coating on their surfaces, causing leakage currents and the corresponding ultrasonic and acoustic signals to occur when excited with high voltage. Moisture in the environment can cause dry bands, leading to insulation breakdown and failure [5]. Salem et al. [6]. measured electrical properties of contaminated polymer-based insulators and modeled the surface electric field distribution across various insulator geometries. The findings indicate that polymeric design influences electric field stress significantly. Fahmi et al. [7]. investigated the effect of fly ash, salt, and algae contamination on the dielectric behavior of polymer insulators. This necessitates ongoing research into different methods to monitor the dielectric health of this power equipment.

There are several conventional and non-conventional methods for testing the dielectric strength of insulation. The IEC 60270-based standard electrical detection method [8] is considered a traditional laboratory-based diagnostic technique that detects the impulsive current pulse associated with PD events using the direct contact method. Several other conventional sensor-based methods exist, such as PD detection using a high-frequency current transformer [9] and transient earth voltage sensors [10]. However, these sensors are susceptible to interference and have limited sensitivity in detecting internal PD events. On the other hand, the conventional detection method, which involves investigating PD-generated gases dissolved in oil using dissolved gas analysis [11], is a contemporary offline method with no scope for online or onsite PD monitoring. In this context, non-conventional methods, i.e., ultra-high-frequency sensors [12], optical sensors [13], and ultrasonic acoustic sensors [14], provide the facility for invasive online-on-site detection. Electromagnetic detection is based on detecting ultra-high-frequency signals from PD using different types of antennas; however, its susceptibility to surrounding electromagnetic waves limits its application in HV applications [12]. The optical sensors are highly sensitive to the PD-generated light, which varies from infrared to ultraviolet [13], but require an optical transparent path, which is generally difficult to achieve within the complex architecture of high-voltage apparatus.

Acoustic detection using various types of invasive and non-invasive acoustic ultrasonic sensors is widely employed, but it primarily suffers from a low signal-to-noise ratio [15]. Recently, optical fiber-based acoustic sensors have gained attention due to their compactness, high sensitivity, and suitability for high-voltage environments [16]. Various types of optical fiber sensors exist, including interferometric sensors (Michelson [17], Sagnac [18], Mach-Zehnder [19], and Fabry-Pérot [20]), which offer excellent sensitivity but face limitations such as complexity and temperature sensitivity. Fiber Bragg grating (FBG)-based sensors [21] are robust but have moderate sensitivity to partial discharges, although recent enhancements like phase-shifted FBGs [22] and distributed feedback fiber lasers [23], have improved performance but still suffer from temperature sensitivity and spectral drift. Emerging microstructure-based intensity-modulated sensors [24] provide advantages such as compact design, easy installation, immunity to electromagnetic interference, and simple signal demodulation, making them appealing for high-voltage monitoring.

These sensor architectures have become increasingly useful in recent years due to the incorporation of polymeric materials [25]. Since the majority of polymers are inherently insulating and inherently dielectric, polymeric sensing devices can be placed near high-voltage components without interfering with nearby electric fields [26]. Moreover, polymers help in building strong sensor assemblies due to their mechanical durability, resistance to corrosion, and tolerance to extreme environmental conditions. These characteristics make polymer-assisted microstructured fiber sensors attractive options for stable performance in electrical and environmental applications [27].

Due to their adaptable properties, polymeric materials are widely utilized in various sensing applications, particularly in partial discharge (PD) detection, enabling the development of advanced sensors. Testa et al. [28]. demonstrates that Fabry-Perot microcavities constructed entirely from

polymers are capable of achieving both excellent optical performance and useful functionality. The findings suggest that polymer microcavities provide a practical and affordable approach for integrating biolaser systems and disposable photonic sensors. Chen et al. [29]. demonstrated the direct application of polymeric structures in sensing processes by all-polymer microcavity fiber acoustic sensors for PD detection in power equipment. Similar to this, fluorescent polymer optical fiber sensors (F-POF) are represented by Adhikari et al. [30]., establishing a significant improvement, particularly in PD detection under high-voltage conditions. Zhang et al. [31]. explains a self-assembled microbottle resonator hydrogen sensor developed by coating a single-mode fiber with a Pd-WO₃ sensitive layer and an outer PDMS polymer layer, which exhibits high hydrogen sensitivity while resisting humidity, temperature disturbances.

Furthermore, polymer membranes, such as polypropylene or polyethylene terephthalate, are used as reflectors in optical acoustic PD detection systems, yielding sensitive and promising sensor designs. Although polymer films and elastomeric coatings have improved the overall performance of the Fabry-Perot and interferometric fiber sensors [32], they mainly employ the polymer as a mechanical interface or as an optical transduction medium. Limited research has been conducted on the potential for integrating both functions into a single sensor – employing polymers to both shape and convert the incoming acoustic field into optical interference.

In this research, we examine the dual-purpose concept employing a fiber-optic sensor that integrates polymer components at two essential transduction stages, as shown in Figure 1. At the acoustic front end, ultrasonic waves generated by the PD events are gathered and focused utilizing a conical polymeric horn. The horn can be positioned in close proximity to the high-voltage terminals, where acoustic coupling is most pronounced, due to its construction from a dielectric polymer. A compliant polymer gap situated between two single-mode fibers receives the amplified acoustic field, forming an SMF–polymer–SMF interferometric cavity. The photodiode directly detects the dynamic variation in optical path length caused by the simultaneous elastic deformation and photoelastic index modulation within this polymeric cavity. This work primarily focuses on polymer and polymer-composite materials, with material selection and design as the key scientific contributions, which govern the overall sensor performance.

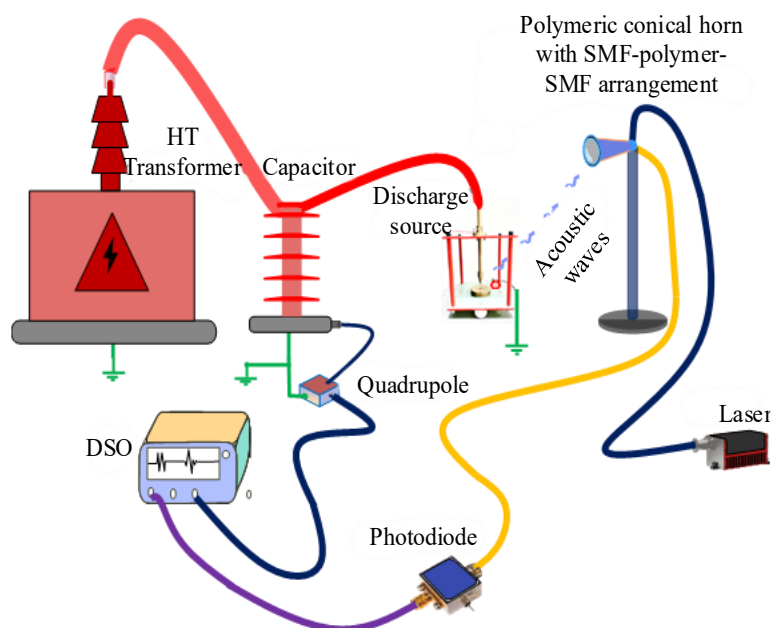


Figure 1. schematic representation of the dual-polymer fiber-optic sensor-based PD detection in polymeric silicone rubber sample.

The noble contribution of the study is mentioned below.

- To design and develop a 3D-printed polymer-based acoustic concentrator integrated with a novel sensing architecture based on a soft, photoelastic polymer cavity that effectively converts PD-generated ultrasonic waves into optical intensity modulation
- To cross-check and evaluate the sensitivity of the proposed sensor by systematically varying the polymer material used for the acoustic horn, as well as the soft elastic polymer forming the SMF–SMF cavity
- Laboratory experimentation for investigating and validating the performance of the designed sensor on artificially aged and contaminated polymeric silicone rubber insulator against the standard electrical detection method

The subsequent part of the study is structured as follows. Section II describes the fundamental principle behind the proposed methodology. Section III elaborates on the optimized design and development of the polymeric conical horn structure, along with the architecture of the SMF–polymer–SMF arrangement. Section IV outlines the experimental setup employed for sensitivity verification and laboratory-based performance assessment of the proposed dual polymeric sensor. Section V discusses the results obtained from the laboratory experiments, while Section VI concludes the study by summarizing the key findings.

FUNDAMENTAL PRINCIPLE BEHIND THE PROPOSED METHODOLOGY

In high-voltage power devices like polymeric insulators, partial discharge produces transient ultrasonic pressure waves that travel across the medium with many frequency components. A correctly built acoustic sensor can detect the mechanical energy associated with these ultrasonic pressure waves. In the suggested approach, the mouth of the polymeric conical horn gathers the PD-generated ultrasonic waves, which are then focused towards the neck and projected into a specifically made polymer cavity between two single-mode optical fibers.

When the incident acoustic wave interacts with the polymeric cavity, a time-varying mechanical stress is induced within the cavity material. This stress induces axial deformation, resulting in local changes in material density. This led to modulation of the refractive index of the polymeric cavity, following the photoelastic effect, causing a time-varying optical path length experienced by the guided light. This acousto-optic modulation within the polymeric cavity is generally described in terms of phase modulation of the optical fields. The instantaneous phase shift accumulated by the optical wave due to acoustically induced refractive index perturbation ($\theta(t)$) is expressed as Equation 1.

$$\theta(t) = k_0 \int_0^L \Delta n(z, t) dz \quad (1)$$

Where $k_0 = \frac{2\pi}{\lambda}$ is the optical wavenumber, L is the cavity length, and $\Delta n(z, t)$ represents the time-dependent refractive index variation along the axial direction of the polymer cavity.

The refractive index perturbation induced by the PD-generated acoustic ultrasonic field can be expressed as in Equation 2.

$$\Delta n(z, t) = n_0 \cdot \eta \cdot p(z, t) \quad (2)$$

Where n_0 is the unperturbed refractive index of the polymer, $\eta = \partial n / \partial p$ is the pressure–optic coefficient of the polymer, and $p(z, t)$ denotes the acoustic pressure distribution within the cavity.

For a harmonic acoustic excitation, the pressure field inside the polymer cavity can be approximated as expressed in Equation 3.

$$p(z, t) = P_a \cdot \sin(k_a \cdot z - \omega_a \cdot t) \quad (3)$$

Where P_a is the acoustic pressure amplitude, k_a is the acoustic wavenumber, and ω_a is the angular frequency of the acoustic wave.

In addition to refractive index modulation, the acoustic pressure also produces a small axial deformation of the polymer cavity, leading to a time-varying cavity length $L(t)$. The total optical phase modulation ($\Delta\varphi(t)$), therefore, arises from the combined contributions of refractive index change and cavity length variation, and can be expressed as follows

$$\Delta\varphi(t) = k_0 \left[\int_0^L \Delta n(z, t) dz + n_0 \cdot \Delta L(t) \right] \quad (4)$$

This time-varying phase modulation is converted into proportional intensity modulation in the output, caused by the interference of the optical field transmitted across the polymeric cavity. Subsequently, the PD-induced acoustic ultrasonic waves cause a significant temporal variation in the detected optical intensity, which can be monitored using a suitable photodiode. The strong photoelastic response of the polymer, along with the pressure-concentrating horn, enables the effective and efficient conversion of weak PDF-generated ultrasonic signals into detectable optical intensity variations.

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DESIGN OF THE POLYMERIC SENSOR

There are two fundamental steps in the development of the suggested dual polymeric sensor. In the first step, a polymer-based conical horn is designed and fabricated, and in the second step, the SMF–polymer–SMF sensing arrangement is constructed.

Design, Optimization, and Simulation of the Polymeric Conical Horn

During the propagation of acoustic ultrasonic waves generated by PD events through a medium, the energy of these waves decays rapidly, which creates a challenge for acoustic sensors to detect weak PD activity. Therefore, improving the sensitivity is essential. In this study, to improve the overall sensitivity of the sensor, a polymeric conical horn-based passive structure is designed to capture and concentrate acoustic energy. The polymeric materials are selected for fabricating the conical horn because they offer acoustic impedance values that are better matched to air and the compliant polymer sensing element than metals, along with being lightweight and electrically passive. These properties ensure efficient coupling of ultrasonic waves, reducing losses caused by reflection at the material interface. The wide mouth area of the conical horn enables the collection of acoustic energy from a larger surface area and gradually converges it towards the throat, compressing the wave and increasing local acoustic pressure. This enhancement in pressure amplifies mechanical excitation on the polymeric cavity-based sensing region. The horn geometry is designed based on fundamental acoustic properties, keeping polymer-specific behavior such as material compliance and internal damping in mind. The horn length (L_h) is an important geometric parameter that governs the effective transfer of acoustic energy from the mouth to the throat as expressed in Equation 5.

$$L_h = \frac{M-m}{2\tan\theta_{eff}} \quad (5)$$

Where θ_{eff} is the effective flare angle, and d_m and d_t are the mouth and throat dimensions, respectively. Moderate flare angles are ideal for polymer-based horns because they offer efficient acoustic focusing without causing significant attenuation or mechanical stress. Another crucial design factor is the mouth diameter, which controls how well acoustic energy is transferred from the surrounding medium into the horn. When taking impedance continuity into account, the mouth diameter can be roughly calculated using Equation 6.

$$M = \left(\frac{\lambda_a}{2} \right) \times \sqrt{\frac{2\pi\zeta}{\rho c}} \quad (6)$$

where c is the speed of sound, ρ is the density of the propagation medium, ζ is the target acoustic resistance, and λ is the wavelength of the incident ultrasonic wave. The polymeric horn's ability to amplify (Pressure might be stated in Equation 7).

$$\begin{cases} G_h = 10 \log\left(\frac{S_M}{S_m}\right) \\ \text{Where} \\ S_M = \frac{\pi M^2}{4}, S_m = \frac{\pi m^2}{4} \end{cases} \quad (7)$$

Here, A_m , A_t are the areas of the mouth and throat of the designed horn, respectively. To obtain an optimized polymeric horn architecture, i.e., moderate flare angle (10° – 30°) for effective acoustic collection, stable throat to concentrate energy, balancing acoustic amplification, bandwidth, polymeric material constraint, and fabrication feasibility, a combined objective fitness function is formulated as shown in Equation 8 and optimized using the genetic algorithm method.

$$\begin{cases} \text{Max: } G_h = 10 \log\left(\frac{S_M}{S_m}\right) \\ \text{Subject to} \\ \left[\begin{array}{l} M_{min} \leq M \leq M_{max}, m_{min} \leq m \leq m_{max} \\ 10^\circ \leq \theta \leq 30^\circ, \zeta_{max} \leq \zeta \leq \zeta_{min} \end{array} \right] \end{cases} \quad (8)$$

Based on the optimization outcomes, a simulation study was conducted to evaluate the acoustic performance of the horn using ANSYS software. A compliant model was created using finite element analysis to verify the acoustic pressure distribution and energy concentration along the horn axis. Different polymeric materials, based on their density and elastic modulus, were incorporated to capture the acoustic transmission behavior. A modal study using the Modal Solver in ANSYS software was conducted to identify the prominent modes in which the polymer structure can vibrate and observe how the horn behaves over time. Later, the transient structural solver was used to examine the horn's time-domain response under sound stimulation. Harmonic response investigation helps determine the relationship between steady-state gain and bandwidth.

The modeling results showed that three polymer materials could be used to fabricate the conical horn, including epoxy-based resin, poly(methyl methacrylate) photopolymer resin, and polycarbonate resin. Thereafter, the conical horns were made in-house using 3D printing with a proper geometrical configuration as shown in Figure 2.

The SMF–Polymer–SMF Architecture

The SMF–polymer–SMF cavity is built with a photoelastic polymer, approximately 5 millimeters in length and 2 millimeters in width, embedded between two aligned single-mode fibers. This polymer-based cavity functions as an acousto-optic transducer when subjected to mechanical stimulation. This polymeric gap enhances acoustic impedance matching relative to air, facilitating the efficient transmission of acoustic energy and thereby improving sensitivity. To develop this design, the terminal sides of two single-mode fibers are precisely aligned coaxially using a holder. Then, the liquid polymer is molded around the space between the faces of the SMF to create a segment of roughly 5 millimeters in length and 2 millimeters in width, followed by curing as shown in Figure 2. Interfacial behavior between matrix and reinforcement plays a critical role in acoustic response. Three distinct polymers with the desired mechanical capabilities and optical configuration were investigated to construct the cavity, such as polydimethylsiloxane (PDMS), polyurethane elastomers, and optical-grade epoxy resins.

The developed SMF–polymer–SMF arrangement is attached to the developed polymeric horn to form the sensor. A total of 9 sensor prototypes were developed in the laboratory, exploiting all possible combinations of the polymeric built material for the conical horn and the SMF–SMF cavity, as stated earlier.

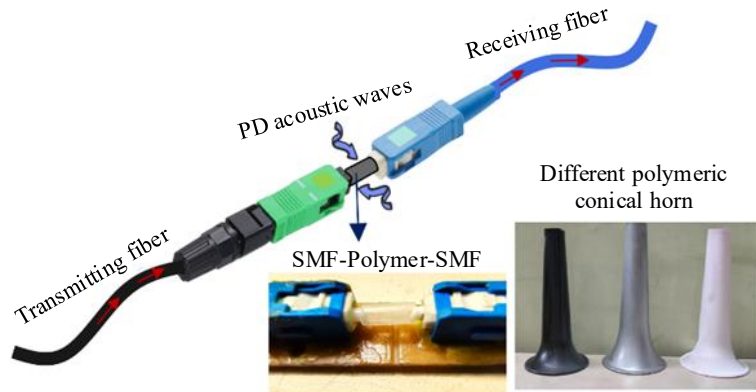


Figure 2. Architecture of the developed SMF-polymer-SMF and different polymeric 3-D printed conical horns.

EXPERIMENTAL SETUP

In this section, primarily, the frequency response characteristics of the developed sensors are explored with respect to sensitivity and signal-to-noise ratio. Thereafter, the sensor giving the best performance is selected for further laboratory-based PD detection experimentation and validation.

Frequency Response Characteristics of the Developed Dual Polymeric Sensors

To explore the frequency response characteristic of the developed polymeric sensor assembly, an experimental platform was developed. Standard ultrasonic transmitters of various frequencies were selected to cover the desired frequency range for acoustic PD detection. These transmitters are excited using an arbitrary function generator with respect to a constant peak-to-peak voltage level of 12 volts. During the experiment, the ultrasonic transmitters are replaced on a test bench at a distance of 500 centimeters from the developed sensor. A calibrated piezoelectric transducer with known sensitivity was placed in near proximity to the developed polymeric sensor, keeping an equivalent distance from the transmitter, to determine the actual value of the incident acoustic pressure, as shown in Figure 3. The responses from both receivers were captured simultaneously and digitized using an oscilloscope. The sensitivity of the proposed polymeric sensor in individual frequency test points was observed using Equation 9.

$$\left\{ \begin{array}{l} \varsigma_0 = 20 \log \frac{V_s}{p} \\ \varsigma(\text{dB re } 1\text{V}/\mu\text{bar}) = 20 \log \frac{\varsigma}{\varsigma_0} \end{array} \right. \quad (9)$$

Where ς denotes the sensor's sensitivity at a specific frequency, ς_0 denotes the reference sensitivity of $1\text{V}/\mu\text{bar}$. V_s represents the output voltage from the sensor at different measurement frequencies, and p signifies the pressure in μbar .

Laboratory Experimentation

Following the real-time development of the dual polymeric sensor, its performance was experimentally verified under laboratory conditions against emulated PD sources. To generate PD, polymeric silicone rubber insulator samples were artificially contaminated using sodium chloride (95% purity) to simulate surface pollution under controlled laboratory conditions. The contamination severity was varied in six incremental steps by adjusting the equivalent salt deposit density (ESDD) from the range $0\text{--}0.25\text{ mg/cm}^2$ at a step of 0.05 mg/cm^2 . The salt solution was prepared with distilled water and uniformly applied to the polymeric insulator surface, then allowed to dry naturally to form a consistent pollution layer. Each differently contaminated polymeric sample was tested separately to measure the change in dielectric strength. During the experiment, the PD data were simultaneously recorded and stored using both the proposed and the electrical detection methods.

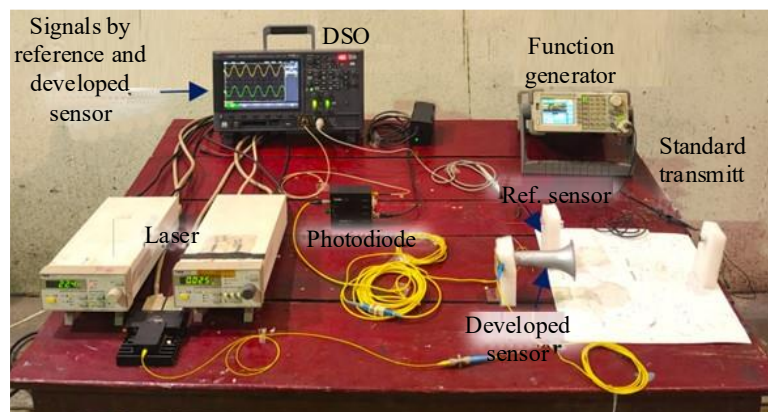


Figure 3. Experimental setup for frequency domain characterization of the dual polymeric sensor.

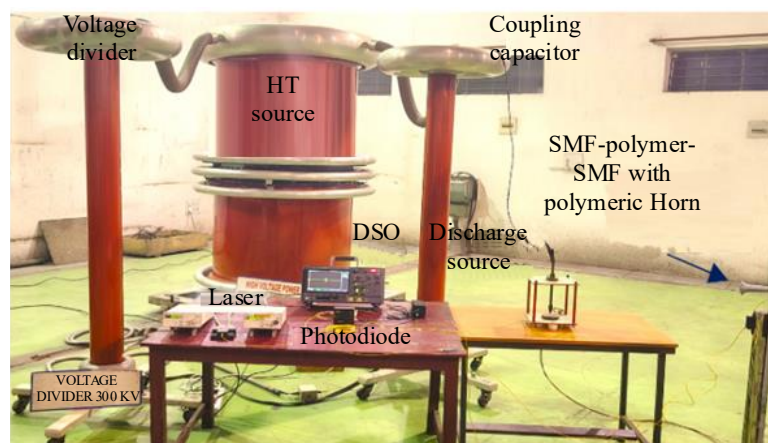


Figure 4. Performance verification and validation of the designed dual polymeric sensor.

The electrical detection method employs a 300 kV, 0.5 A high-voltage transformer along with a 300 kV, 100 pF coupling capacitor to excite polymeric silicone rubber insulator samples placed in parallel to the transformer-capacitor setup. The voltage is gradually increased, and the capacitor links to a data recording unit via an impedance matching device and filtering circuit. High-frequency current pulses produced during dielectric breakdown in the test object are transmitted through the coupling capacitor, amplified, filtered, and subsequently stored.

During detection by the developed dual polymeric sensor, the polymeric horn is kept at a distance of 500 cm from the discharge source. The polymeric cavity between two single-mode fibers was excited by a laser source with a central wavelength of 1550 nm. The coupled light is directed to a photodiode and a transimpedance amplifier unit, where the intensity modulation caused by the interaction of the acoustic wave with the polymeric cavity is detected. The output of the photodiode is connected to an oscilloscope for observing and storing data, as shown in Figure 4.

During this experiment, the supply voltage cycles are also recorded, along with the responses of the proposed and standard methods for syncing PD activities with the supply and generating PRPD plots.

When the voltage across the polymeric silicone rubber insulator samples was gradually increased, partial discharge phenomena initiated at a particular voltage, called partial discharge inception voltage (PDIV). The PDIV values for all six differently contaminated polymeric silicone rubber insulator samples, as detected by both methods, have been stored for further analysis. To verify the frequency content detected by the developed dual polymeric sensor, PD pulses from the recorded signals are extracted and analyzed using the fast Fourier transform by the MATLAB software.

RESULTS AND DISCUSSION

In this section, the results of all experiments are systematically presented, along with relevant discussions.

Primarily, the results shown in Table 1 summarize the sensitivity and SNR obtained for different horn–cavity polymeric material combinations. The differences observed in sensitivity, bandwidth, and noise level for the various horn–cavity material combinations are mainly related to the mechanical behavior of the polymeric materials. Polyurethane is relatively soft, and therefore, it undergoes larger deformation when acoustic pressure waves produced by partial discharge interact with the cavity. This improves acoustic coupling and increases sensitivity, but it also makes the structure more prone to external and structural vibrations, which raises the noise level and lowers the overall signal-to-noise ratio. Epoxy, on the other hand, is physically stronger and prevents too much bending, which makes the structure more stable. On the contrary, this stiffness means that sound energy cannot move through the material as easily at higher frequencies, reducing the bandwidth. PDMS has moderate rigidity, hence it has a good amount of toughness and superior damping qualities. PDMS easily allows ultrasonic waves while lowering the effects of resonance. The combination makes the frequency response smoother and the time-domain data more stable. Thus, the epoxy resin horn and PDMS hollow work together to create balanced mechanical characteristics.

Table 1. Comparative analysis of detection sensitivity.

S.N.	Horn material	Cavity polymer	Sensitivity (dB re 1 V/ μ bar)	SNR (dB)	Comments
1	Epoxy-based resin	Polyurethane	−68.3	22.2	High signal, higher noise
2	Polycarbonate	Polyurethane	−72.4	20.5	Slightly lower pressure gain
3	Epoxy-based resin	PDMS	−75.7	24.6	Lower noise dominates
4	PMMA	Polyurethane	−78.7	18.4	Horn damping adds noise
5	Polycarbonate	PDMS	−80.3	22.3	Stable, lower sensitivity
6	Epoxy-based resin	Optical epoxy	−82.6	21.4	Low noise, stiff cavity
7	PMMA	PDMS	−84.4	20.3	Moderate, well-behaved
8	Polycarbonate	Optical epoxy	−85.5	19.1	Noise floor is very low
9	PMMA	Optical epoxy	−88.9	17.7	The lowest signal dominates

From the perspective of bandwidth, samples made of optical epoxy polymeric cavities respond poorly, showcasing a rapid decrement in amplitude at higher frequencies, whereas samples made of polyurethane exhibit resonance but function best within a narrow frequency range. The PDMS-based samples are more suited for broadband detection of ultrasonic partial discharge signals because they exhibit a smoother, broader frequency response with less resonance, as shown in Figure 5.

For all six polymeric silicone rubber insulator samples with varying contamination levels, the developed sensor detected PD-generated acoustic ultrasonic waves with a sufficient signal-to-noise ratio, establishing the sensor's suitability for non-destructive dielectric testing purposes. The time-domain pulses from a moderately contaminated (0.15 mg/cm²) polymeric silicone rubber insulator sample, at an applied voltage of 18.6 kV, as recorded by the developed dual polymeric sensor and the standard method, are shown in Figure 6. During testing, it was observed that the proposed method achieved an SNR of 23.9 dB, which is similar to the values obtained during the frequency response experiment. During the testing of all polymeric samples with varying contamination levels, the developed dual polymeric sensor responded similarly to the standard method in terms of phase timing, repetition rate, and phase synchronization, thereby establishing the reliability of the dual polymer-based sensor.

For differently contaminated samples, the clustering pattern changes, but the PRPD pattern remains similar between the developed polymeric sensor and the standard method. The PRPD pattern recorded

by the dual polymeric developed sensor for a moderately contaminated insulator sample at 18.6 KV is depicted in Figure 6, where a similar phase distribution can be observed between the proposed and standard methods, which further validates the reliability of the dual polymer-based non-destructive evolution technique.

The increasing contamination of polymeric silicone rubber insulators leads to reduction in dielectric strength, thereby higher partial discharge activity can be observed in lower voltages. A similar trend in PDIV can also be observed in Figure 7, which shows the similar PDIV recorded by the standard and dual polymeric sensor for different contamination levels.

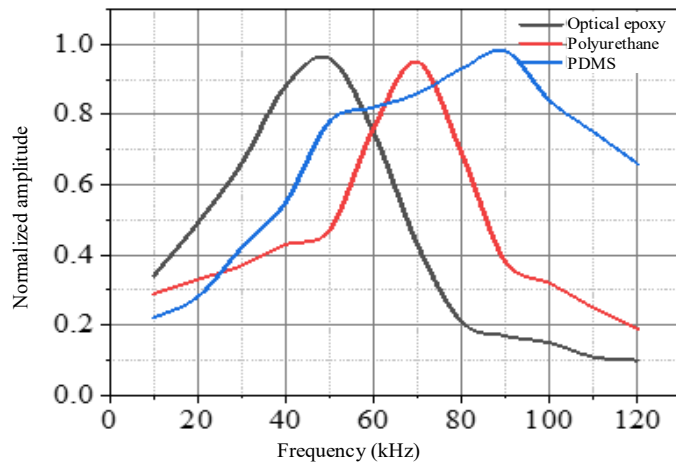


Figure 5. Frequency response of the three cavity materials, i.e., optical epoxy, polyurethane, and PDMS.

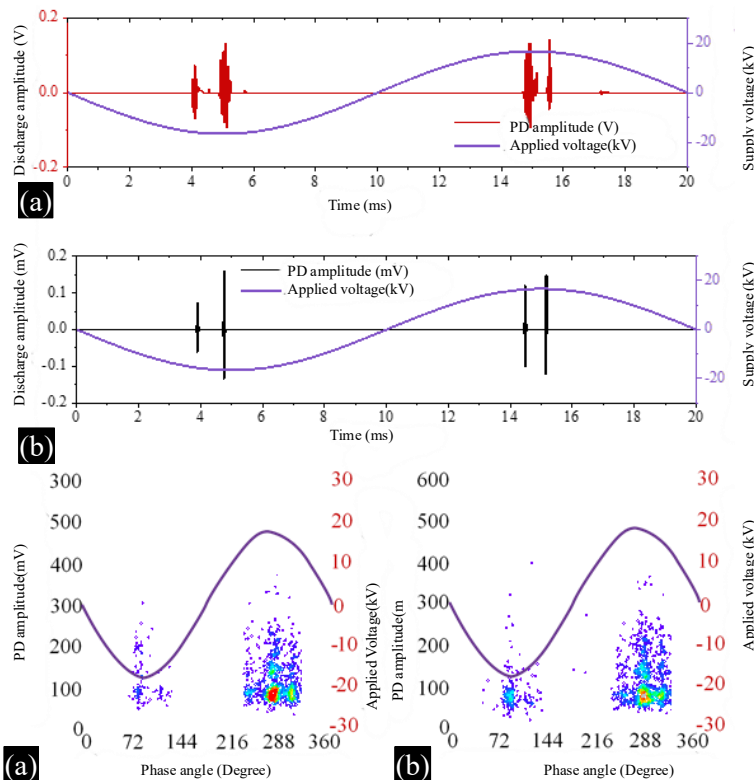


Figure 6. Time domain response and corresponding PRPD as recorded by the (a) epoxy resin horn–PDMS cavity-based sensor, and (b) standard method during testing on moderately contaminated (0.15 mg/cm^2) polymeric silicone rubber sample.

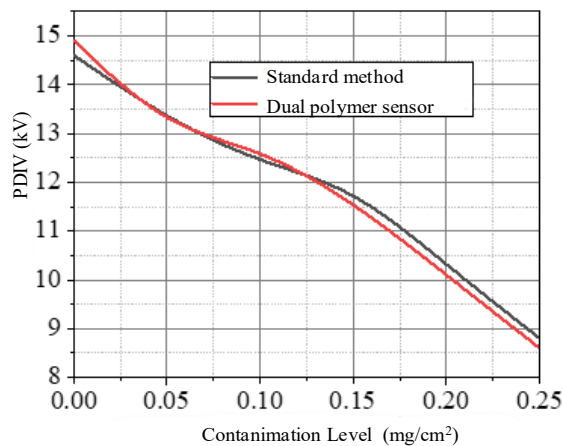


Figure 7. PDIV as recorded by the standard and the dual polymeric sensor-based method for different contamination levels of the polymeric silicone rubber insulator samples.

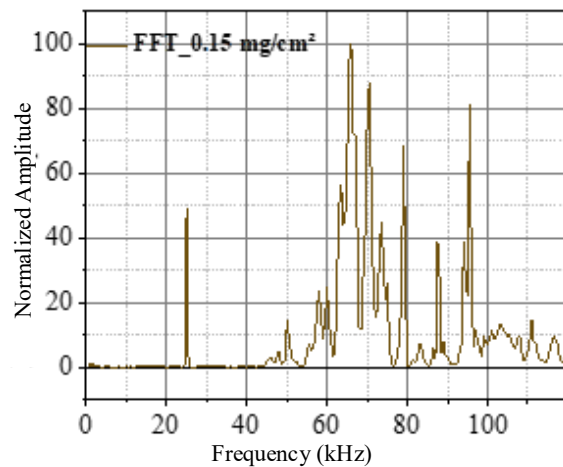


Figure 8. Frequency domain signature of the detected PD pulse by the dual polymeric, epoxy resin horn and PDMS cavity-based sensor during testing on moderately contaminated (0.15 mg/cm^2) polymeric silicone rubber sample.

Hence, for laboratory-based experimentation and validation against the standard method, the epoxy resin horn and PDMS cavity-based dual polymeric sensor is found to be most suitable. Later, in laboratory-based testing, the time domain signature, as recorded by the developed epoxy resin horn and PDMS cavity-based sensor, along with the response obtained by the standard method, is analyzed and compared for polymeric silicone rubber insulator samples of varying contamination levels.

In addition to the time-domain analysis, phase-resolved partial discharge patterns (PRPDs) are recorded for polymeric silicone rubber insulator samples under varying contamination levels to better understand the dielectric condition monitoring capacity of the apt dual polymeric sensor. The PRPD patterns generated by the proposed sensor exhibit similar phase clustering characteristics to those of the standard method.

To further confirm the broadband nature of the epoxy resin horn–PDMS cavity-based sensor, the detected pulses are identified and processed through fast Fourier transformation. It is observed that the pulse content has several distinct high-amplitude peaks distributed across a broad frequency spectrum, establishing its broadband nature, as shown in Figure 8. Finally, from the above experiments and results, it can be concluded that the sensor has significant sensitivity within the desired frequency band of acoustic PD.

CONCLUSIONS

In this work, the first part focused on optimizing the polymeric conical horn structure to efficiently collect and concentrate the acoustic signals generated by partial discharge (PD) events. The horn geometry was optimized using a genetic algorithm, after which three different polymer materials were selected to fabricate the horn and study the effect of material properties on acoustic performance.

In the intermediate cavity of an SMF–polymer–SMF sensing structure, three different types of polymer materials are used. A detailed comparative test was conducted on all horn–cavity polymeric combinations to examine how their frequency bandwidth, sensitivity, and signal-to-noise ratio change. This comparison showed that the epoxy-resin horn and the PDMS-based cavity worked well together, detecting signals with a sufficient SNR, enough sensitivity, and a broader frequency response, ideal for PD detection.

Thereafter, the optimized epoxy horn–PDMS cavity sensor was chosen for the laboratory testing. The sensor's performance was experimentally compared with the conventional electrical PD detection method for discharge activity in six polymeric silicone rubber insulator samples with varying levels of contamination. The developed sensor reliably captured both time-domain signals within a broadband frequency spectrum and phase-resolved PD characteristics for the increasing contamination of polymeric silicone rubber insulators.

Overall, the work demonstrates that the proposed horn-assisted optical fiber polymeric sensor is a simple, compact, and electrically safe solution with strong potential for practical partial discharge monitoring in high-voltage equipment, such as polymeric silicone rubber insulation.

The proposed sensor has been evaluated under laboratory conditions under controlled operating conditions. Its performance under field conditions, the influence of temperature variation on its performance, complications during long-term operation, and problems associated with external disturbances have not been examined in the present work. In addition, the aging behavior of the polymeric materials may influence sensor response over time. The extension of the present study will focus on field testing and extending the approach to other high-voltage equipment.

The future scope of the study involves the investigation of other horn structures and cavity architectures, utilizing different polymer blends or polymers mixed with nanoparticles to enhance sensitivity without compromising bandwidth. The aging of such polymeric sensors, especially under thermal stress, humidity, and high-voltage operating conditions, is to be investigated to ensure the reliable functioning of these sensors during real-life applications.

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