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A Comprehensive Review of Optical Fiber Sensors: Principles, Technologies and Applications

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Abstract—**Optical fiber sensors (OFSs) have emerged as one of the most promising sensing technologies owing to their high sensitivity, compact size, immunity to electromagnetic interference, corrosion resistance, and capability for distributed and remote sensing. These unique characteristics have enabled their widespread adoption in structural health monitoring, biomedical diagnostics, aerospace engineering, industrial automation, environmental monitoring, telecommunications, and electrical power systems. The rapid development of advanced optical materials, fiber fabrication techniques, photonic integrated circuits, and artificial intelligence-assisted signal processing has further expanded the capabilities and application domains of optical fiber sensing technologies.**

This review presents a comprehensive analysis of the operating principles, classifications, mathematical foundations, and recent technological advancements in optical fiber sensors. The major sensing mechanisms, including intensity modulation, wavelength modulation, phase modulation, and polarization modulation, are systematically discussed together with representative sensor configurations such as Fiber Bragg Grating (FBG), Fabry–Perot, Michelson, Mach–Zehnder, Sagnac interferometric, fluorescence-based, and evanescent-wave sensors. The fundamental mathematical relationships governing light propagation, total internal reflection, Bragg resonance, interferometric phase modulation, and evanescent-field sensing are also reviewed to provide a rigorous theoretical understanding of sensor operation. The paper critically compares recent review articles published between 2020 and 2026 and highlights the distinctive contributions, advantages, limitations, and emerging research trends of different optical sensing technologies. Furthermore, representative applications in transformer condition monitoring, structural health monitoring, biomedical instrumentation, aerospace systems, oil and gas industries, environmental sensing, and smart-grid monitoring are comprehensively summarized.

The review reveals that Fiber Bragg Grating and distributed optical fiber sensors presently dominate structural monitoring applications because of their high multiplexing capability, while interferometric sensors continue to provide superior sensitivity for precision measurements. Recent integration of machine learning, Internet of Things (IoT), photonic integrated circuits, and distributed optical sensing is transforming conventional optical sensing into intelligent sensing systems capable of real-time monitoring and predictive diagnostics. Finally, the paper identifies current research challenges and discusses future directions toward miniaturized, multifunctional, AI-enabled, and quantum-enhanced optical fiber sensing technologies.

Keywords—Optical Fiber Sensors, Fiber Bragg Grating, Transformer Condition Monitoring, Structural Health Monitoring, Smart Sensors, Internet of Things, Machine Learning, Mathematical Modeling.

I. INTRODUCTION

Optical fiber sensing technology has undergone remarkable evolution over the past five decades and has become one of the most influential sensing technologies for scientific, industrial, biomedical, and electrical engineering applications[1]-[3]. Initially developed as a medium for optical communication, optical fibers have progressively evolved into highly accurate sensing elements capable of measuring numerous physical, chemical, and biological parameters. Their unique combination of lightweight construction, electrical insulation, high sensitivity, immunity to electromagnetic interference, corrosion resistance, and capability for long-distance distributed sensing has made optical fiber sensors indispensable in environments where conventional electrical sensors exhibit limited performance[4],[5]. These advantages have led to widespread deployment in structural health monitoring, aerospace engineering, biomedical diagnostics, civil infrastructure, energy systems, environmental monitoring, and intelligent manufacturing[6]-[8].

Unlike conventional electrical sensors, optical fiber sensors transmit information using light rather than electrical signals. Consequently, they are inherently immune to electromagnetic and radio-frequency interference, making them particularly suitable for high-voltage substations, power transformers, nuclear facilities, aircraft, and industrial environments characterized by strong electromagnetic fields[9],[10]. Furthermore, optical fibers provide excellent chemical stability, corrosion resistance, small dimensions, flexibility, and low transmission loss, enabling reliable sensing over distances extending to several tens of kilometers without significant signal degradation. These characteristics have significantly expanded their application in modern smart infrastructure and industrial automation.

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The operating principle of optical fiber sensors is based on the interaction between guided optical waves and external perturbations. Variations in temperature, strain, pressure, displacement, vibration, magnetic field, electric field, humidity, chemical concentration, or refractive index alter one or more optical parameters including intensity, wavelength, phase, polarization, or propagation time[11]-[13]. These changes are subsequently detected by optical interrogation systems and converted into measurable physical quantities. Depending on the sensing mechanism, optical fiber sensors may operate using intensity modulation, phase modulation, wavelength modulation, or polarization modulation. Each sensing principle offers distinct advantages in terms of sensitivity, multiplexing capability, dynamic range, response speed, and implementation complexity[14],[15].

Recent advances in optical materials, micro- and nano-fabrication techniques, photonic integrated circuits, specialty optical fibers, and artificial intelligence have considerably enhanced the performance of optical fiber sensing systems [16]. Novel sensing platforms based on photonic crystal fibers, tilted fiber Bragg gratings, long-period gratings, surface plasmon resonance, microstructured optical fibers, distributed acoustic sensing, distributed temperature sensing, and distributed strain sensing have substantially improved measurement accuracy, reliability, and operational flexibility. Simultaneously, the integration of optical sensing with wireless communication, cloud computing, edge intelligence, and Internet of Things (IoT) architectures has enabled the development of intelligent monitoring systems capable of real-time diagnosis and predictive maintenance [17].

Among the numerous application domains, electrical power systems represent one of the most important areas for optical fiber sensing technologies. Reliable monitoring of transformer oil temperature, winding hot-spot temperature, partial discharge activity, moisture content, dissolved gases, vibration, current, voltage, and structural integrity plays a crucial role in improving transformer reliability and extending equipment service life. Optical fiber sensors provide an attractive alternative to conventional electrical sensors because they offer complete electrical isolation, immunity to electromagnetic interference, and high measurement accuracy under harsh operating conditions. These characteristics have resulted in increasing adoption of fiber Bragg grating sensors, interferometric sensors, Raman-based distributed temperature sensors, and optical current sensors in modern smart substations and digital power grids [18].

Although numerous review papers have been published on optical fiber sensing technologies, most focus on specific sensor types or application domains. Many reviews emphasize Fiber Bragg Grating sensors, distributed sensing, biomedical applications, or structural health monitoring, while relatively few provide a unified treatment covering sensing principles, mathematical foundations, sensor classifications, recent technological advances, and transformer condition monitoring within a single comprehensive framework [19]. Furthermore, recent developments involving artificial intelligence, machine learning, photonic integrated circuits, and quantum sensing have not yet been comprehensively integrated into many existing reviews.

The present review aims to bridge these gaps by providing a systematic and comprehensive overview of optical fiber sensing technologies. The paper reviews the physical principles governing optical fiber sensors, discusses the mathematical foundations underlying different sensing mechanisms, critically analyses recent developments reported up to 2026, compares major sensing technologies and review articles, and summarizes representative applications across electrical power systems, civil infrastructure, aerospace engineering, biomedical instrumentation, environmental monitoring, and industrial automation. Particular emphasis is placed on transformer condition monitoring, reflecting the authors' research experience in this field. Finally, emerging research challenges and future directions toward intelligent, distributed, AI-assisted, and multifunctional optical fiber sensing systems are highlighted.

II. Classification of Optical Fiber Sensors

Optical fiber sensors (OFSs) have become indispensable sensing devices owing to their high sensitivity, immunity to electromagnetic interference, compact dimensions, corrosion resistance, and capability for remote and distributed measurements. Their versatility has enabled applications ranging from industrial process monitoring and structural health monitoring to biomedical diagnostics, aerospace engineering, environmental sensing, and electrical power systems. Since different sensing applications require different operating mechanisms, optical fiber sensors have been classified according to several criteria including sensing location, sensing mechanism, modulation technique, structural configuration, and application domain[20]. A systematic classification provides a clear understanding of the operating principles, performance characteristics, advantages, and limitations of each sensor type.

The most fundamental classification divides optical fiber sensors into intrinsic and extrinsic sensors depending on the location of the sensing interaction. Additional classifications are based on modulation mechanisms such as intensity, phase, wavelength, and polarization modulation. More recently, distributed optical sensing techniques based on Raman, Brillouin, and Rayleigh scattering have emerged as a separate class because of their capability to measure parameters continuously along several kilometers of optical fiber [21].

In *intrinsic fiber-optic sensors*, the measurand directly influences the properties of the light as it propagates through the optical fiber. The sensing region is located within the fiber itself, and the light never leaves the fiber core during the sensing process. These sensors utilize changes in physical parameters such as *intensity*, *phase*, *polarization*, or *wavelength* to detect the desired effect [22], [23]. In contrast, *extrinsic fiber-optic sensors* rely on the modulation of light occurring outside the fiber [24][25]. In this case, the optical fiber merely acts as a conduit for transmitting light to an external sensing element and then back to the detector. Although the light temporarily leaves the fiber, this configuration allows specialized sensing elements to be used in environments where direct fiber integration is not feasible [26].

Apart from this fundamental classification, fiberoptic sensors can also be grouped based on three additional criteria [27]:

- **Operating principle:** the physical mechanism involved in sensing,

Table 1. Classification of Fiber Optic Sensors

Classification Criterion	Categories
By Sensing Location	• Point sensors • Distributed sensors • Quasi-distributed sensors
By Operating Principle	• Intensity-modulated sensors • Phase-modulated sensors • Frequency-modulated sensors • Polarization-modulated sensors
By Application Domain	• Physical sensors (e.g., temperature, pressure, strain) • Chemical sensors (e.g., gas detection, pH monitoring) • Biomedical sensors (e.g., glucose monitoring, heart rate) • Environmental sensors (e.g., humidity, water quality) • Industrial process sensors
By Sensor Structure	• Intrinsic sensors • Extrinsic sensors
By Modulation Technique	• Amplitude modulation • Phase modulation • Wavelength modulation • Polarization modulation

- **Sensing location** whether the sensor operates at a point, over a distributed length, or quasi-distributed [28],
- **Application domain** including physical, chemical, or biomedical sensing [29].

These classification criteria are summarized in Table I. Furthermore, fiber-optic sensors operate based on four core principles: intensity modulation, phase modulation, polarization modulation, and wavelength modulation, as detailed in Table II [30][31].

Among these, *intensity-based* and *phase-based* sensors are the most widely implemented in practical applications [32]. Intensity-based sensors are relatively simple in design, cost-effective, and well suited for use with multimode fibers. They detect changes in signal strength due to absorption, scattering, or bending losses. On the other hand, phase-based sensors require *interferometric configurations* such as MachZehnder or Michelson interferometers to detect minute changes in phase caused by external perturbations. Although more complex, these sensors offer high sensitivity and precision, making them ideal for advanced applications such as acoustic and vibration monitoring, gyroscopy, and high-resolution strain measurements [33].

A. Intensity-based Fiber Optic Sensors

Intensity-based fiber optic sensors are among the most widely used and simplest types of optical sensors. These sensors operate by modulating the intensity of guided light,

Table 2. Working Principles of Fiber-Optic Sensors

Principle	Physical Mechanism	Applications
Intensity Based	Light modulation through absorption, emission, scattering, or refractive index changes	Temperature, pressure, displacement, liquid level, etc.
Phase-Based	Phase shift due to interference between a transmitted signal and a reference signal	Gyroscope, hydrophone, magnetometer, acoustic sensing
Polarization-Based	Changes in the state of polarization due to optical anisotropy or external perturbations (e.g., stress or magnetic field)	Electric current and magnetic field sensing in power transmission lines
Wavelength-Based	Spectral shifts in emission or absorption wavelength, typically using Fiber Bragg Gratings (FBGs) or interferometric filters	Temperature, strain, structural health monitoring

which is affected by the measurand either internally within the optical fiber or externally, where the modulated light is reflected back through the same fiber for detection [34].

The modulation of light intensity can be accomplished through various mechanisms [35]. These include coupling misalignment between two aligned fiber segments, reflection of light from an object exposed to the measurand, and attenuation of light due to macro- or microbending of the fiber. Other mechanisms involve evanescent wave coupling to an external medium or another optical fiber, as well as light scattering or absorption caused by the target material [36].

Due to the higher light requirements of intensity-modulated sensors, multimode fibers with large core diameters are typically employed. These fibers support greater light throughput, which is crucial for maintaining signal integrity over the sensor path [37].

The primary advantages of intensity-based fiber optic sensors include their straightforward implementation, cost-effectiveness, potential for multiplexing, and the capability to be configured as distributed sensors, making them suitable for a wide range of industrial and structural health monitoring applications [38].

1) Intensity Modulation Through Light Interruption: Intensity modulation in fiber optic sensors can be achieved through the interruption of light propagation caused by misalignment between optical fibers. This misalignment may occur due to displacement of one fiber relative to another, resulting in changes in the transmitted light intensity [39].

There are generally three types of misalignments that affect light coupling in optical fibers: longitudinal (axial) misalignment, transverse (slanting) misalignment, and angular misalignment. Among these, transverse or slanting misalignment is considered to be the most sensitive and impactful in modulating light intensity [40].

To enhance the sensitivity of such fiber optic sensors, the fiber ends can be cleaved and polished at a specific slant angle.

By keeping the slanted faces of the two fibers sufficiently close to each other, efficient modulation of light intensity can be achieved, as illustrated in Figure 1 [41].

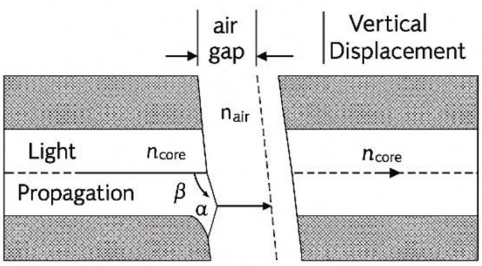

Fig. 1. Frustrated total internal reflection

1) Microbend Optical Fiber Sensor: Microbend optical fiber sensors operate on the principle that small-scale, periodic bends referred to as microbends induce excess transmission loss in an optical fiber. These microbends cause the coupling of energy from the guided modes into radiation modes, which leads to attenuation of the transmitted light signal [42].

When a section of the optical fiber is subjected to a periodic mechanical deformation by a microbend transducer or deformer, the light confinement within the core is disrupted. This disruption results in a measurable loss of signal power, which is dependent on the amplitude and frequency of the microbending pattern [43]. The sensitivity of such sensors can be tuned by designing specific spatial frequencies of the imposed bends and by controlling the pressure applied on the fiber [44].

As shown in figure 2, the fiber may be sandwiched between a pair of toothed or serrated plates to induce microbending. Such regular or random meandering of fiber axis results in redistribution of guided power between modes of the fiber and also the coupling of power from one mode to another mode.

2) Evanescent-Wave Fiber Optic Sensors: The transmission of light through an optical fiber is governed by the principle of total internal reflection. Although the majority of light remains confined within the core of the fiber, a portion of the light penetrates slightly into the cladding at the core-cladding interface as illustrated in Figure 3. This penetrating field, known as the evanescent wave, decays exponentially perpendicular to the interface and does not carry energy away but can interact with the surrounding medium [45].

The strength of the evanescent field is influenced by the refractive index of the cladding medium. A higher refractive index results in a weaker evanescent field and consequently lower light loss. Evanescent-wave sensors leverage this leaked field for sensing applications. By removing a portion of the cladding, the evanescent field is exposed, allowing interaction with external media, which modulates the light intensity in the core [46].

These sensors have found significant application in chemical sensing, especially for detecting the presence of specific analytes that absorb light at the wavelength emitted by the source. In such cases, a light source tuned to the analyte's absorption wavelength is used, and the reduction in output intensity corresponds to the concentration of the chemical [47]. Furthermore, cladding can be replaced with chemically sensitive materials, enabling the sensor to respond to changes in the surrounding environment, such as temperature or pH [48].

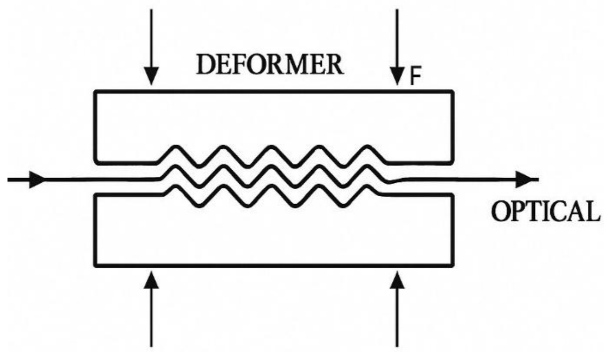

Fig. 2. Microbending in an optical fiber

1) Shutter Multimode Fiber Optic Sensors: Shutter multimode fiber optic sensors are a category of intensity-based sensors that utilize a mechanical shutter to intermittently obstruct the optical beam transmitted between two opposed multimode optical fibers, as illustrated in Figure 4. The position and movement of the shutter are typically influenced by a physical measurand, allowing the system to function as an optical microswitch [49].

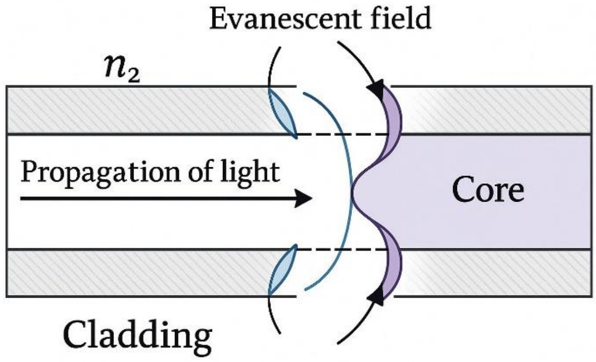

Fig. 3. Evanescent waves in the lower index region

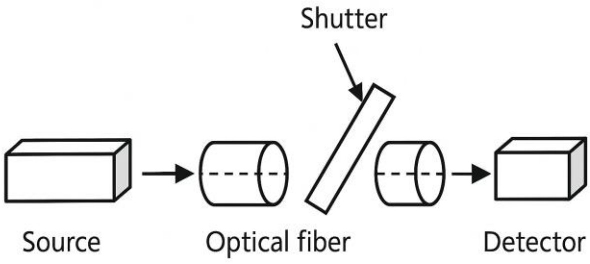

Fig. 4. Shutter Multimode Fiber Optic Sensors

One of the common implementations of this sensor type is in pressure sensing applications. In such cases, the shutter is coupled with a diaphragm, and any pressure-induced displacement of the diaphragm causes modulation in the transmitted light intensity by altering the degree of optical interruption between the two fibers [50]. This principle provides a simple yet effective method for converting mechanical displacements into optical signals.

2) Reflective Fiber Optic Sensors: Reflective fiber optic sensors are a category of intensity-modulated sensors in which the optical signal is reflected back from a surface influenced by the measurand. The returned light, after being modulated, is collected by a receiving fiber for analysis. Typically, a Y-coupler configuration is employed, comprising two multimode optical fibers fused along a certain length. This structure functions as both a power splitter and a sensing probe. An alternative configuration includes two fiber bundles bonded together over a short segment, forming a probe capable of both transmitting and receiving optical signals. As illustrated in Figure 5, the sensor operates by directing light through Port 1 toward a reflective diaphragm positioned in front of the cemented Y-coupler end. The reflected light intensity, which exits through Port 3, is modulated by the physical displacement of the diaphragm or reflecting target from the probe tip [51]. Such reflective intensity-based fiber sensors are well-suited for measuring parameters like pressure and displacement. Their compact and flexible design makes them ideal for applications in biomedical fields, such as intracardiac pressure monitoring using fiber-optic catheters [52]. Moreover, these sensors are employed in industrial settings, including fiber laser Doppler anemometry and texture analysis of surfaces or fluid flow assessments in pipelines [53].

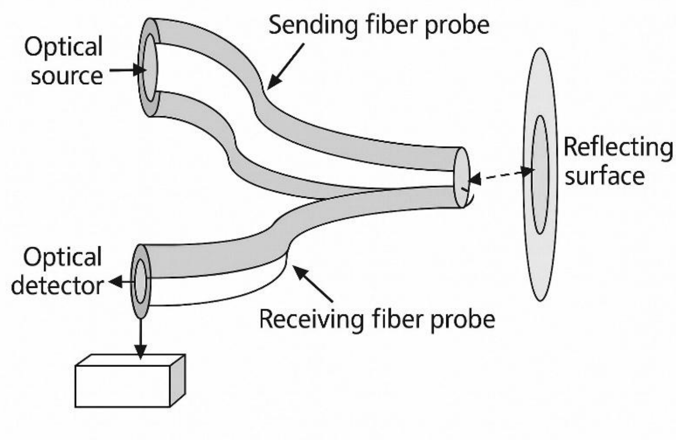

Fig. 5. Reflective fiber optic sensors

B. Wavelength Modulated Fiber Optic Sensors

Wavelength modulated fiber optic sensors operate on the principle that certain physical parameters can induce a shift in the wavelength of the optical signal propagating through the fiber. The magnitude of the measurand is inferred from the spectral shift between the emitted and received wavelengths of light [54]. These sensors are particularly valued for their high sensitivity and resistance to intensity-based noise.

There are three primary categories of wavelength-modulated fiber-optic sensors: Fiber Bragg Grating (FBG) sensors, fluorescence-based sensors, and black-body radiation sensors. Among these, FBG sensors are the most extensively researched and utilized due to their precision and multiplexing capabilities.

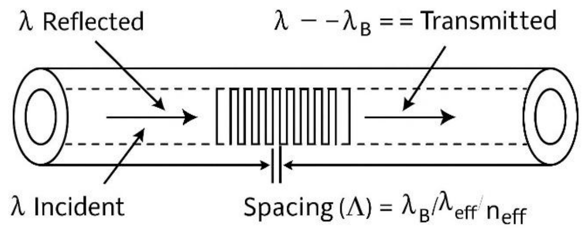

Fig. 6. Fiber Bragg Grating sensors

1) Fiber Bragg Grating (FBG) Sensors: Fiber Bragg Grating sensors exploit the principle of Bragg reflection. They incorporate a periodic modulation of the refractive index within the fiber core, forming a grating that reflects specific

wavelengths of light while transmitting others. This configuration is illustrated in Figure 6. The reflected Bragg wavelength, λ_B, is determined by the grating period and the effective refractive index of the fiber core [55].

Any variation in external parameters such as temperature, strain, or pressure can induce changes in the grating period or the refractive index. As a result, the Bragg wavelength shifts, providing a direct correlation with the applied measurand [56]. The ability to detect minute changes in physical conditions with high accuracy makes FBGs highly suitable for structural health monitoring, aerospace engineering, and medical diagnostics [57].

FBG sensors are also inherently compatible with wavelength division multiplexing (WDM) systems, enabling multiple sensors to be embedded along a single fiber line and monitored independently by analyzing their unique reflected wavelengths [58].

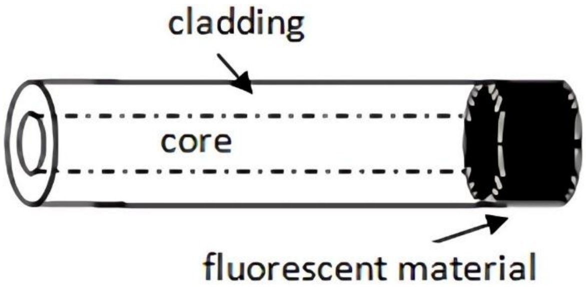

Fig. 7. Fluorescence fiber optic sensors

1) *Fluorescence Fiber Optic Sensors:* Fluorescence-based fiber optic sensors are widely employed in the fields of chemical analysis, biomedical diagnostics, and environmental monitoring. These sensors are capable of detecting various physical parameters such as temperature, humidity, and viscosity with high sensitivity and specificity [59].

A common configuration for fluorescence sensing involves coating the fiber tip with a fluorescent material that emits light upon excitation by an incident optical signal. This design, often referred to as an end-tip configuration, is depicted in Figure 7. In this arrangement, the excitation light travels through the optical fiber to the fluorescent probe. The emitted fluorescent light, which typically has a longer wavelength than the excitation source due to the Stokes shift, is partially collected by the same fiber and transmitted back to a photodetector [60].

The fluorescence intensity or spectral shift can be used to quantify the concentration of analytes or changes in environmental conditions. These sensors offer the advantages of remote detection, immunity to electromagnetic interference, and high selectivity through the use of specific fluorescent dyes or indicators.

Black Body Fiber Optic Sensors: Black body fiber optic sensors represent a simple yet robust class of wavelength-modulated optical sensors, primarily utilized for temperature measurements in electromagnetically harsh environments, such as strong radio frequency (RF) fields [61].

The sensing principle is based on black body radiation, where a blackbody cavity is placed at the tip of a multimode optical fiber, as illustrated in Figure 8. When the cavity is heated, it emits broadband thermal radiation proportional to its temperature. This thermally induced emission is transmitted back through the optical fiber and analyzed at the detector side [62].

The detector is typically paired with a narrow-band optical filter to extract spectral information corresponding to the blackbody radiation. By analyzing the intensity or spectral distribution of the emitted radiation, the temperature of the blackbody cavity can be precisely estimated [63].

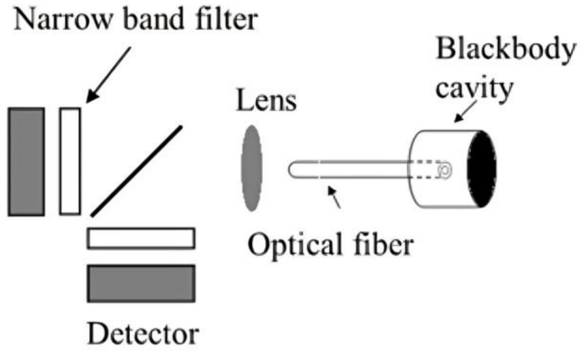

Fig. 8. Blackbody fiber optic sensors

These sensors are inherently immune to electromagnetic interference and are suitable for high-temperature applications, including aerospace engine monitoring, nuclear reactor environments, and industrial furnaces [64].

C. Phase Modulated Fiber Optic Sensors

Phase-modulated fiber optic sensors operate on the principle that an optical signal acquires a phase shift when influenced by a physical parameter known as the measurand. These sensors are particularly valued for their high sensitivity and precision in detecting changes in the optical path length of a fiber [65]. The phase shift of light propagating through an optical fiber can be influenced by multiple factors, including the fiber's structural geometry, its physical length, and the refractive index profile [66]. Perturbations such as longitudinal strain, hydrostatic pressure, and temperature variations can alter the fiber length or refractive index, resulting in a measurable phase change in the guided light signal.

For instance, mechanical strain may stretch the fiber, changing its effective length, while temperature may cause both expansion of the fiber and modulation of its refractive index via the thermo-optic effect. Pressure can similarly induce variations through the photoblastic effect. These physical interactions collectively cause a phase modulation of the optical wave.

To extract useful information from this phase shift, various interferometric configurations are employed to convert phase variations into detectable intensity changes. Common interferometric setups used in fiber optic sensing include the Michelson, Mach-Zehnder, Fabry-Perot, and Sagnac interferometers [67]. Each configuration is suited for specific applications such as acoustic sensing, seismic monitoring, temperature measurement, and biomedical diagnostics [68].

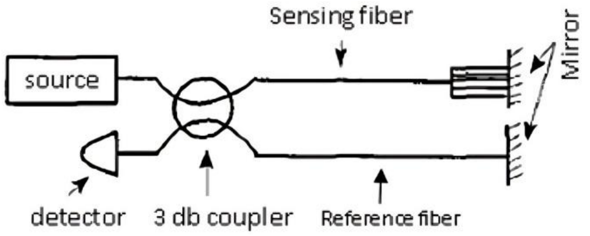

Fig. 9. Michelson phase-modulated fiber optic sensor.

1) Michelson Phase Modulated Fiber Optic Sensor: The Michelson phase-modulated fiber optic sensor operates on a similar principle to the Mach-Zehnder interferometric sensor, with the key distinction that the Michelson configuration is effectively a folded version of the Mach-Zehnder setup [69]. This folded structure enables a more compact design while maintaining high sensitivity.

In the Michelson configuration, an incoming light signal is split into two arms: a sensing arm and a reference arm. Both arms reflect light back toward the beam splitter and detector after interacting with respective reflectors, as illustrated in Figure 9. Due to the double pass of light through each arm (forward and reflected), any phase shift introduced by the measurand is effectively doubled. This dual-pass effect enhances the sensitivity of the Michelson configuration compared to its Mach-Zehnder counterpart [70].

An additional advantage of the Michelson sensor lies in its ability to operate using a single optical fiber link between the sensing head and the source-detector unit, which simplifies the system architecture and reduces cost [71]. However, the setup demands high-quality reflective components to ensure efficient signal return and interference visibility. The use of fiber Bragg gratings or dielectric mirrors at the fiber ends is common in such implementations [72].

Michelson interferometers are widely used in vibration detection, acoustic sensing, and structural health monitoring applications due to their superior sensitivity and robustness in harsh environments [73].

2) Mach-Zehnder Phase Modulated Fiber Optic Sensor:

The Mach-Zehnder phase-modulated fiber optic sensor is a well-established interferometric configuration used for highly sensitive detection of external perturbations. It operates on the principle of phase interference, where the optical signal is split into two separate arms: a sensing arm and a reference arm [74]. These arms independently propagate the light signals before recombining to generate an interference pattern at the detector. Although the Mach-Zehnder interferometer shares a fundamental working concept with the Michelson configuration, it is distinct in that each arm operates independently without folding back the light, as is the case with Michelson sensors. This allows for a wider separation between the sensing and reference paths, which is beneficial in distributed or long-range sensing applications [75].

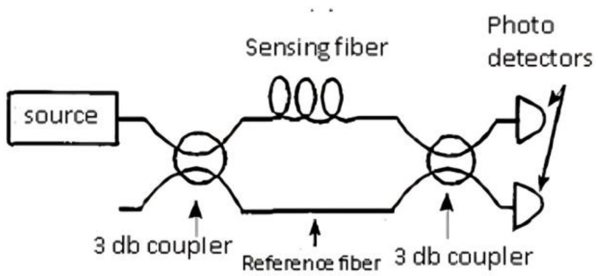

Fig. 10. Mach-Zehnder phase-modulated fiber optic sensor

The schematic of the Mach-Zehnder fiber optic sensor is shown in Figure 10. Variations in phase between the two optical paths caused by measurands such as temperature, strain, or pressure-result in changes in the interference pattern, which can be accurately measured. The Mach-Zehnder configuration offers high stability, linear response, and suitability for multiplexing [76].

Modern advancements in integrated photonics and fiber components have made it possible to realize compact and robust Mach-Zehnder sensors for use in biomedical diagnostics, geophysical monitoring, and aerospace systems [77].

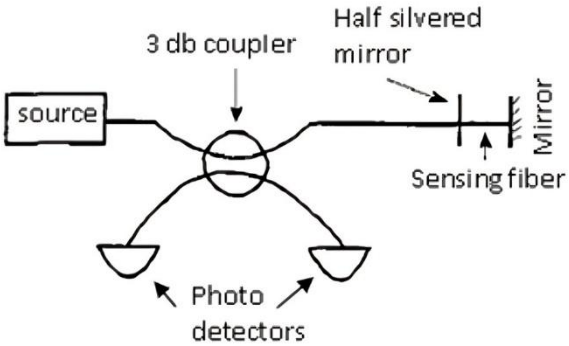

Fig. 11. Fabry-Perot phase-modulated fiber optic sensor.

3) Fabry-Perot Phase-Modulated Fiber Optic Sensor: The Fabry-Perot interferometric fiber optic sensor is a highly sensitive phase-based sensing configuration used for the detection of various physical parameters such as strain, pressure, and temperature. A typical Fabry-Perot interferometer (FPI) consists of two parallel reflective surfaces forming a resonant cavity, where multiple reflections occur. This configuration creates interference patterns that vary in response to changes in cavity length or refractive index, thereby allowing precise sensing [78].

Fabry-Perot sensors can be broadly categorized into two types: Extrinsic Fabry-Perot Interferometer (EFPI) and Intrinsic Fabry-Perot Interferometer (IFPI). In EFPI sensors, the cavity is formed outside the fiber tip, and the optical fiber serves as a conduit for both light delivery and collection. These are especially advantageous in high-pressure and biomedical applications due to their compact and easily fabricated structure [79].

In contrast, IFPI sensors incorporate the interferometric cavity directly within the fiber itself. The cavity region, situated between two partially reflective surfaces fabricated inside the core or cladding, acts as both the waveguide and sensing medium. This design ensures that light remains confined within the fiber, resulting in greater stability and robustness against environmental noise [80].

Figure 11 illustrates a typical configuration of both EFPI and IFPI sensors. Modern fabrication techniques, such as femtosecond laser inscription and thin-film deposition, have enabled the development of highly miniaturized and multiplexed Fabry-Perot sensors suitable for industrial and structural health monitoring [81].

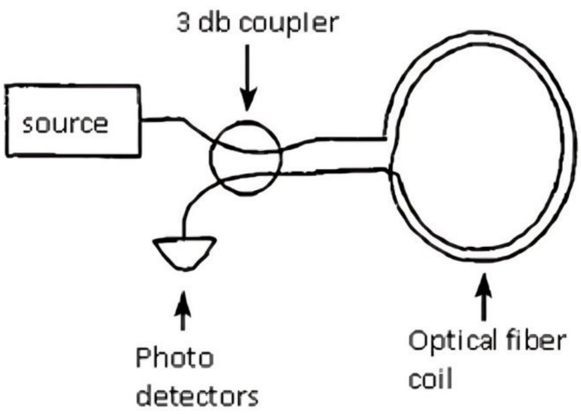

Fig. 12. Signac phase-modulated fiber optic sensor

4) Sagnac Phase Modulated Fiber Optic Sensor: The Sagnac phase-modulated fiber optic sensor is primarily utilized in the form of a fiber optic gyroscope (FOG) to measure angu-lar velocity with high precision. These sensors operate based on the Sagnac effect, where the phase difference between two counter-propagating light beams in a fiber coil is proportional to the rotational rate of the system. This phase difference arises due to the non-reciprocal path difference introduced when the coil experiences rotation [82].

A typical Sagnac-based sensor consists of a single-mode fiber wound into a coil, through which coherent light from a laser is split into two beams traveling in opposite directions. When the system is subjected to rotation, the beams accumu-late different phases, which are interferometrically measured to infer angular velocity. The design is illustrated schematically in Figure 12 [83].

Beyond gyroscopic measurements, Sagnac interferometers have also been adapted for other sensing applications such as detecting acoustic waves, vibrations, and temperature variations. The interferometric nature of the system enhances sensitivity to time-varying perturbations while maintaining immunity to common-mode noise, making them valuable for geophysical and structural monitoring [84].

Recent advancements have focused on integrating photonic circuits and polarization-maintaining fibers to further improve the accuracy and compactness of Sagnac interferometric sensors. These developments have enabled high-precision inertial navigation and real-time structural health diagnostics in aerospace and defense sectors [85].

D. Polarization Modulated Fiber Optic Sensors

Polarization-modulated fiber optic sensors exploit the changes in the polarization state of light to detect various physical parameters. Light, being an electromagnetic wave, possesses electric (**E**) and magnetic (**H**) field components that are perpendicular to each other and to the direction of propagation. The polarization state of light refers to the orientation of the electric field vector and can be categorized into linear, circular, and elliptical polarizations.

In linear polarization, the electric field vector maintains a constant orientation in the plane perpendicular to the direction of propagation. Circular polarization involves the electric field vector rotating in a circular motion, forming a helix along the propagation direction. Elliptical polarization is a general case where the tip of the electric field vector traces an ellipse in the transverse plane.

Polarization-modulated fiber optic sensors utilize special fibers whose refractive indices change under external perturbations such as stress or strain. These changes induce a phase difference between orthogonal polarization modes, which can be detected and analyzed to measure the perturbation [86].

Various physical phenomena influence the polarization state of light, including the Faraday effect, optical activity, electro-optic effect, electrogyration, photo elastic effect, and the Kerr effect. By exploiting these effects, polarization-modulated sensors can detect and measure parameters like magnetic fields, electric fields, pressure, and temperature [87].

A typical setup for a polarization-based fiber optic sensor involves polarizing light from a source using a polarizer, which could be a segment of polarization-maintaining fiber as illustrated in Figure 13. The polarized light is then launched at a 45-degree angle into a birefringent polarization-maintaining fiber segment that serves as the sensing element. External perturbations cause changes in the phase difference between the two polarization modes, altering the output polarization state. By analyzing this output, the external perturbation can be quantified [88]. Recent advancements in this field have led to the development of sensors with enhanced sensitivity and specificity. For instance, sensors based on magneto-optical modulation have been proposed for transverse stress measurements, utilizing polarized light as the stress information carrier. Additionally, reflective optical fiber sensors based on polarization modulation have been demonstrated for hydrogen sensing applications, where changes in the birefringence coefficient of the fiber indicate the presence of hydrogen [89].

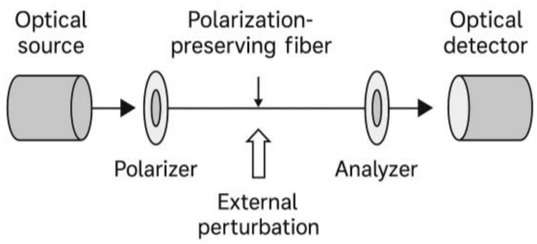

Fig. 13. Polarization Modulated Fiber Optic Sensors

Moreover, novel structures of optical fiber pressure sensors based on polarization modulation have been introduced, employing high-birefringence fibers as sensing units to measure pressure in fluid mediums [90]. These innovations highlight the versatility and adaptability of polarization-modulated fiber optic sensors in various sensing applications.

III. Mathematical Modelling

A. Intensity-Based Fiber Optic Sensor

The working principle of intensity-based fiber optic sensors lies in the modulation of the optical power due to interaction with an external measurand [91], [92]. The general form of the sensor response is:

$$I_{\text{out}} = I_{\text{in}} \cdot T(x) \tag{1}$$

where:

- I_{in} is the input optical intensity,
- I_{out} is the output optical intensity,

$T(x)$ is the transmission or reflection coefficient as a function of the measurand x

1. Light Interruption Due to Misalignment

- *Transverse Misalignment:*

$$T(d) = \begin{cases} \left(1 - \frac{d^2}{a^2}\right)^2 & , d \le a \\ 0 & , d > a \end{cases} \tag{2}$$

where d is the lateral displacement and a is the core radius [93].

- *Longitudinal Misalignment*

$$\mathrm{T}(z) = \frac{1}{1 + \left(\frac{z}{z_0}\right)^2} \tag{3}$$

Where $z_0 = \frac{\pi {\omega_0}^2}{\lambda}$ is the Rayleigh range [94]

- ***Angular Misalignment***

$$T(\theta) = exp\left(-\frac{\pi^2 a^2 \theta^2}{\lambda^2}\right) \tag{4}$$

2. Microbend Sensor Model

Microbending induces coupling of guided modes to radiation modes, resulting in loss. The power loss ΔP due to microbending can be approximated as:

$$\Delta P \propto \alpha(\Lambda, A).P_{in} \tag{5}$$

where:

- Λ is the spatial period of microbending,
- A is the amplitude of deformation,
- α is a coupling coefficient depending on fiber geometry and pressure [95], [96].

3. Evanescent-Wave Sensor Model

The evanescent field intensity at the interface decays exponentially:

$$I_{\text{ev}}(y) = I_0 \cdot e^{-y/\delta} \tag{6}$$

where:

- y is the distance from the core-cladding interface,
- δ is the penetration depth of the evanescent field,
- $$\delta = \frac{\lambda}{2\pi}\left({n_1}^2 \; sin^2\theta - {n_2}^2\right)^{-\frac{1}{2}}$$

This principle is fundamental in chemical and biomedical sensing applications [97], [98].

The transmitted power after interaction with an absorbing medium becomes:

$$I_{\text{out}} = I_{\text{in}} \cdot e^{-\kappa(x) \cdot L} \tag{7}$$

where $\kappa(x)$ is the absorption coefficient dependent on the analyte concentration, and L is the interaction length.

4. Shutter-Type Sensor Model

When a shutter periodically blocks light between two fibers:

$$I_{\text{out}}(t) = I_{\text{in}} \cdot [1 - \sigma(t)] \tag{8}$$

where:

- $\sigma(t)$ is a time-varying function (0 for open, 1 for fully blocked),
- Can be related to pressure or displacement $x(t)$ that controls the shutter [99], [100].

5. Reflective Fiber Optic Sensor Model

For reflective sensors:

$$I_{out} = \rho(x) \cdot I_{in} \cdot e^{-2\alpha L} \quad (9)$$

Where

- $\rho(x)$ is the reflectivity of the target as a function of measurand x (e.g., displacement or pressure),
- α is the attenuation coefficient,
- L is the round-trip fiber length [4].

F. Sensor Sensitivity

The sensitivity of any intensity-based fiber optic sensor is given by:

$$S = \frac{dI_{out}}{dx} = I_{in} \cdot \frac{dT(x)}{dx} \quad (10)$$

This general modeling framework aids in optimizing fiber sensor designs for a variety of applications depending on the target measurand and system configuration [101], [102].

B. Wavelength Modulated Fiber Optic Sensors

1. General Principle

The general wavelength shift due to a measurand is:

$$\Delta\lambda = f(x) \quad (11)$$

where $\Delta\lambda$ is the change in wavelength and x is the physical parameter.

2. Fiber Bragg Grating (FBG) Sensors

FBG sensors reflect light at the Bragg wavelength:

$$\lambda_B = 2n_{eff}\Lambda \quad (12)$$

where n_{eff} is the effective refractive index, and Λ is the grating period [103].

Changes in strain ε and temperature ΔT affect λ_B:

$$\Delta\lambda_B = \lambda_B\,[(1 - p_e)\varepsilon + \alpha\Delta T] \quad (13)$$

where p_e is the photoblastic coefficient and α combines thermo-optic and thermal expansion effects [104].

3. Fluorescence-Based Fiber Optic Sensors

Fluorescence sensors emit light at a longer wavelength after excitation:

$$I_f = \Phi \cdot \epsilon \cdot c \cdot I_{exc} \cdot e^{-\alpha x} \quad (14)$$

where Φ is the quantum yield, ϵ the molar absorptivity, c the dye concentration, and I_{exc} the excitation intensity [105].

The wavelength shift due to the Stokes shift is:

$$\Delta\lambda = \lambda_{em} - \lambda_{exc} \quad (15)$$

4. Blackbody Fiber Optic Sensors

These sensors use Planck's law to determine temperature:

$$L(\lambda, T) = \frac{2hc^2}{\lambda^2} \cdot \frac{1}{e^{\frac{hc}{\lambda k_B}} - 1} \quad (16)$$

where L is the spectral radiance, h Planck's constant, c speed of light, k_B Boltzmann's constant.

Wien's law gives the peak wavelength:

$$\lambda_{max} = \frac{b}{T} \quad (17)$$

with $b \approx 2.898 \times 10^{-3}$ m · K

Wavelength modulated fiber optic sensors provide high sensitivity and noise immunity. Their modeling helps in designing efficient systems for diverse applications.

C. Phase Modulated Fiber Optic Sensors

Phase-modulated fiber optic sensors operate on the principle that an optical signal acquires a phase shift when influenced by a physical parameter known as the measurand. These sensors are particularly valued for their high sensitivity and precision in detecting changes in the optical path length of a fiber [106].

The phase shift $\Delta\phi$ is given by:

$$\Delta\phi = \frac{2\pi}{\lambda} . n_{eff} . \Delta L \quad (18)$$

where λ is the wavelength of the optical signal, n_{eff} is the effective refractive index, and ΔL is the change in optical path length due to the measurand [107].

Perturbations such as longitudinal strain ϵ, hydrostatic pressure P, and temperature T variations influence n_{eff} and ΔL. These effects can be modeled as:

$$\Delta L = L(1 + \epsilon + \alpha_T \Delta T) \quad (19)$$

$$\Delta n = n_0(1 + p_e P + \beta_T \Delta T) \quad (20)$$

where α_T and β_T are the thermal expansion and thermo-optic coefficients, p_e is the photoblastic constant [108].

1. Michelson Phase Modulated Fiber Optic Sensor

The Michelson configuration splits the light into a sensing and reference arm. The phase shift due to double-pass propagation enhances sensitivity:

$$\Delta\Phi = \frac{4\pi}{\lambda} . n_{eff} . \Delta L \quad (21)$$

This configuration is compact and supports single-fiber operation [109].

2. Mach-Zehnder Phase Modulated Fiber Optic Sensor

In the Mach-Zehnder interferometer, the light is split and

travels through independent sensing and reference arms:

$$I = I_0 [1 + \cos(\Delta\phi)] \quad (22)$$

The interference intensity varies with the phase difference

$\Delta\phi$, enabling accurate measurement [110].

3. Fabry-Perot Phase Modulated Fiber Optic Sensor

The Fabry-Perot interferometer uses multiple internal reflections to create high-resolution interference fringes:

$$I = I_{max} \left[\frac{1}{1+F sin^2(\delta/2)}\right] \quad (23)$$

where F is the finesse of the cavity and

$\delta = \frac{4\pi n_{eff} L}{\lambda}$ is the round-trip phase [111]

4. Sagnac Phase Modulated Fiber Optic Sensor

Sagnac sensors utilize counter-propagating light beams affected by rotation Ω:

$$\Delta\Phi = \frac{8\pi A\Omega}{\lambda c} \quad (24)$$

where A is the area enclosed by the fiber loop and c is the speed of light [112].

IV. Optical Sensor Application

Optical sensors have become indispensable in monitoring various parameters within power transformers. The following points highlight their applications:

- **Oil Level Measurement:** Optical sensors using the principle of evanescent effect are employed to measure transformer oil levels in tanks.
- **Microprocessor-Based Temperature Monitoring:** A system based on optical phase modulation and interferometric optical sensors is used for temperature monitoring in transformers, as described in [113].
- **Hot-Spot Temperature Detection:** Fiber optic sensors are used to measure the hot-spot temperature of transformer oil with a microcontroller-based signal processing system, tested experimentally on a 25 kVA transformer [114].
- **Temperature Measurement Principles:** Three common principles, fiber Bragg gratings, Raman scattering, and interferometric point sensors, are employed for temperature measurement using fiber optic sensors, as presented in [115].
- **Partial Discharge Behavior Investigation:** Studies on partial discharge behavior using fiber optic cables for testing transformer boards and plastics in air or oil setups are reported in [116].
- **Moisture Level Monitoring:** A fiber optic sensor-based instrumentation system using a bent multimode fiber measures the moisture level in transformer oil, with output light intensity changes due to refractive index variations described in [117].
- **Combined Optical and Gas Sensing Technology:** The use of optical and gas sensing technologies for transformer oil testing, focusing on absorption properties, is presented in [118].
- **Vibration and Thermal Monitoring:** An interferometric intrinsic sensor is used to measure vibration and thermal magnitude in power transformer magnetic cores, as discussed in [119].
-
- **Ultrasound Detection in Power Apparatus:** Interferometric fiber optic sensors with intrinsic transducers are used to measure ultrasound emissions from partial discharge in power equipment [120].
- **Partial Discharge Measurement:** Intensity-based methods using optical sensors are employed for measuring partial discharge, as presented in [121].
- **Transformer Oil Condition Analysis:** Optical sensors are used to monitor transformer oil condition by analyzing light changes at the output due to gas absorption, as detailed in [122].
- **Asset Management Using Health Index:** A health index-based approach to transformer asset management, relying on condition monitoring and diagnostic standards, is proposed in [123].

Table III presents the major application areas of optical Fiber sensors, whereas Table IV provides a comparative analysis of recent review papers, emphasizing their scope, key contributions, limitations, and the novelty of the present review.

Table 3. Major Applications of Optical Fiber Sensors

Application Area	**Typical Sensor Type**	**Measured Parameters**	**Major Advantages**
Power Transformers	FBG, Raman, Interferometric	Temperature, moisture, partial discharge	EMI immunity, electrical isolation
Structural Health Monitoring	FBG, Brillouin	Strain, displacement, vibration	Multiplexing, long-distance sensing

Application Area	Typical Sensor Type	Measured Parameters	Major Advantages
Biomedical Engineering	Fabry–Perot, Fluorescence	Pressure, glucose, heart rate	Miniaturization, biocompatibility
Aerospace	FBG, Sagnac	Strain, temperature, navigation	Lightweight, high reliability
Oil and Gas	Raman, Brillouin	Temperature, strain, leakage	Distributed monitoring
Environmental Monitoring	SPR, Evanescent-wave	Water quality, gases, pollutants	High chemical sensitivity
Industrial Automation	Intensity, FBG	Pressure, vibration, flow	Real-time monitoring
Defence and Security	Distributed Acoustic Sensing	Intrusion, vibration, underwater acoustics	Long-range surveillance
Smart Cities	Distributed Optical Fiber Sensors	Infrastructure health, utilities	Continuous monitoring

V. CONCLUSION

This paper presents a comprehensive review of recent advancements and applications of optical sensors in various domains. particularly focuses on the monitoring and diagnostics of power transformers. The study emphasizes the evolution of optical sensing technologies, including interferometric, evanescent wave, fiber Bragg grating, Raman scattering, and intensity-modulated sensors, and their integration in electrical systems for temperature, moisture, vibration, partial discharge, and oil quality analysis.

The inclusion of optical sensors in transformer condition monitoring offers significant advantages such as immunity to electromagnetic interference, real-time monitoring, high sensitivity, and the capability for remote sensing. These attributes make them highly suitable for intelligent grid infrastructures and predictive maintenance strategies.

Furthermore, the emerging trend of integrating optical sensors with microcontrollers and IoT platforms opens new frontiers in automation, smart diagnostics, and digital substations. The review also sheds light on current research gaps and highlights opportunities for future innovations in miniaturization, multiplexing, and multi-parameter sensing using optical technologies.

It is evident from the reviewed literature that optical sensors will continue to play a pivotal role in enhancing reliability, efficiency, and safety in power systems. Future work should focus on standardization, cost-effectiveness, and field deployment challenges to accelerate widespread adoption of these technologies in industrial settings.

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