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Fibre-Optic Sensors for Strain and Temperature Measurements

Abstract:
The relevance of this study is determined by the growing demand for reliable and high-precision strain and temperature monitoring in engineering, industrial, and scientific applications operating under harsh environmental conditions. Fibre-optic sensors offer unique advantages over conventional electrical sensors due to their electromagnetic immunity, high thermal tolerance, and suitability for long-range and distributed measurements. The study problem addressed in this article lies in the diversity and complexity of fibre-optic sensing techniques, which complicates their systematic comparison, performance evaluation, and informed selection for specific applications. Despite extensive prior study, a unified analytical overview that consistently integrates physical principles, technological configurations, and application constraints remains necessary. The scientific novelty of this study consists in a comprehensive and methodologically structured analysis of fibre-optic sensors for strain and temperature measurements, combining classical and contemporary approaches within a single analytical framework. The study consistently examines wavelength-based, phase-based, interferometric, and scattering-based sensing techniques with explicit attention to their operational advantages and limitations. The subject of the study is the set of physical principles, technological approaches, and sensing mechanisms underlying fibre-optic sensor systems designed for strain and temperature measurements. The object of the study is fibre-optic sensing systems, including their structural components, operational configurations, and functional characteristics, as implemented in practical monitoring applications. The study aims to provide a systematic analytical review of the operating principles, performance characteristics, advantages, and limitations of modern fibre-optic sensors for strain and temperature measurements and to assess their applicability across different fields of use. The research methods include general scientific methods of analysis, synthesis, induction, deduction, comparison, and systematisation, as well as specialised methods of theoretical optical modelling, spectral analysis, interferometric analysis, scattering-based reflectometric analysis, material property analysis, and structured technical literature review. The study examines major categories of fibre-optic sensors, including fibre Bragg grating sensors, time-of-flight polymer fibre sensors, interferometric sensors, and distributed sensing systems based on Rayleigh, Raman, and Brillouin scattering. Their sensing principles, sensitivity, spatial resolution, operational range, and application-specific constraints are analysed in detail, with particular attention to strain–temperature cross-sensitivity and system complexity. The results of the study demonstrate that fibre-optic sensors constitute a versatile and technologically mature solution for strain and temperature monitoring in civil engineering, aerospace, energy systems, industrial processes, and medical applications. Among the analysed technologies, fibre Bragg grating sensors currently exhibit the highest level of practical maturity, while distributed scattering-based systems show strong potential for future large-scale sensing applications.

Keywords: optical fibre, sensor, temperature, strain, Bragg, scattering, interferometry, reflectometry.

Introduction

In the recent years fibre-optic sensing has become thriving technology in numerous areas such as transportation, safety, medicine, precision engineering, etc. due to significant advances in telecommunications field and availability of optoelectronic components. Fiber-optic sensors allow the measurement of a wide range of physical parameters—including displacement, acceleration, pressure, temperature, intensity of electric, magnetic, and radiation fields, as well as spectral parameters. Their high accuracy, fast response times and ability to provide multiparameter measurements significantly expand their application across numerous domains (*Del Villar & Matias, 2020*).

Fibre-optic sensing has numerous advantages compared to other techniques. Optical fibre acts as both sensor and communication channel, which eliminates the need for power wiring, significantly reducing complexity of the sensing system. Inherent immunity to electromagnetic interference and chemical resistance allows effective use in hazardous environments unsuitable for other types of sensors. Furthermore, low optical attenuation enables sensing over long distances. Many fibre-optic sensor systems support multiplexing techniques that allow distributed sensing.

In general, the main advantages of fiber-optic sensors are:

- suitability for in-situ measurements;
- immunity to electromagnetic interference and chemical inertness;
- capability to operate at high temperatures;
- small diameter and mechanical flexibility (typically 250–500 μm);
- ability to provide remote and multiplexed measurements.

Fibre-optic sensing techniques rely on detecting changes in optical intensity, frequency, phase, or polarisation (*Fang et al., 2012*). From an operational standpoint, fiber sensors are generally classified into two categories: extrinsic sensors in which the fiber serves as a transmission medium for an external sensing element; and intrinsic sensors in which the fiber itself functions as the sensing element. Their operation is based on internal fiber mechanisms, intensity, frequency modulation, or phase-based detection methods. Among many physical quantities, temperature and strain is of particular importance that require precise measurement. It is vital for construction, health care, transportation and various engineering spheres.

This article investigates number of fiber-optic sensing techniques specifically used strain and temperature sensing, challenges and related advantages of the technology, as well as potential field of application.

The subject of the study is the set of physical principles, technological approaches, and sensing mechanisms underlying fibre-optic sensor systems designed for the measurement of strain and temperature in engineering, industrial, and scientific environments. Particular attention is paid to the interaction between optical radiation and the material properties of optical fibres, as well as to the signal modulation, detection, and interpretation techniques that enable accurate and reliable sensing under diverse operational conditions. Within this subject domain, the research addresses both intrinsic and extrinsic fibre-optic sensing paradigms, encompassing wavelength-based, phase-based, intensity-based, interferometric, and scattering-based methods.

The object of the study is fibre-optic sensing systems employed for strain and temperature measurements, including their structural components (optical fibres, gratings, interferometric cavities, and optoelectronic units), operational configurations, and functional characteristics. This object also includes specific implementations such as fibre Bragg grating sensors, time-of-flight polymer fibre sensors, interferometric fibre sensors, and distributed sensing systems based on Rayleigh, Raman, and Brillouin scattering. The object is examined both as a physical system governed by optical and material laws and as an applied technological solution integrated into real-world monitoring and diagnostic applications.

The study aims to provide a systematic analytical review of the fundamental operating principles, performance characteristics, advantages, and limitations of contemporary fibre-optic sensors for strain and temperature measurements, with a view to identifying their applicability across a wide range of practical domains. The research seeks to clarify how different fibre-optic sensing techniques respond to mechanical and thermal impact, how these responses are quantified and interpreted, and under which conditions specific sensor types demonstrate optimal performance. By consolidating theoretical foundations with applied considerations, the study aims to support informed selection and implementation of fibre-optic sensing technologies in demanding environments.

To achieve the purpose, the study sets out the following objectives.

- analyse the physical mechanisms of light propagation and interaction in optical fibres that form the basis of strain and temperature sensing, including refractive index modulation, optical path variation, and scattering phenomena;
- classify fibre-optic sensors according to their sensing principles and structural configurations, distinguishing between intrinsic and extrinsic sensors, point sensors and distributed sensors, as well as between grating-based, interferometric, and scattering-based techniques;
- evaluate the performance characteristics of major fibre-optic sensing techniques used for strain and temperature measurements, including sensitivity, resolution, accuracy, dynamic range, spatial resolution, multiplexing capability, and operational stability;
- identify technological and practical challenges associated with fibre-optic sensing, such as cross-sensitivity between strain and temperature, susceptibility to bending and microbending effects, signal attenuation, system complexity, and cost factors;
- examine existing and prospective application areas of fibre-optic sensors for strain and temperature monitoring, including civil engineering, aerospace, energy systems, industrial process control, and medical technologies;
- outline future directions in the development of fibre-optic sensing technologies, considering advances in optical fibre materials, photonic crystal fibres, light sources, detection methods, and signal processing techniques;

The intended use of the study results lies in their applicability for researchers, engineers, and system designers involved in the development, selection, and deployment of fibre-optic sensing systems. The structured overview of sensing principles and technologies is intended to support academic research in optical sensing and applied photonics, providing a consolidated reference for further experimental and theoretical studies. For engineering practitioners, the results offer a basis for informed decision-making when choosing sensing solutions for specific operational requirements, particularly in applications where conventional electrical sensors are unsuitable or insufficient.

In addition, the materials and conclusion of the study may be utilised in educational contexts, including university-level courses on optical engineering, sensor technology, and applied physics, as well as in professional training programmes for specialists working in monitoring and diagnostic systems. By articulating both the theoretical foundations and practical implications of fibre-optic strain and temperature sensing, the study contributes to the dissemination of knowledge necessary for the effective integration of these technologies into modern engineering and scientific practice.

Methods

The methodological framework of this study was designed to ensure a comprehensive, logically consistent, and scientifically rigorous analysis of fibre-optic sensors for strain and temperature measurements. Given the interdisciplinary nature of the research, situated at the intersection of optical physics, materials science, and applied engineering, the methodology combines general scientific methods with specialised methods specific to fibre-optic sensing technologies. This integrated approach enables both conceptual systematisation of the research field and detailed examination of the physical mechanisms underlying sensor operation.

At the general scientific level, the method of analysis was employed to decompose fibre-optic sensing systems into their fundamental structural and functional components. Complex sensor architectures were examined by isolating individual elements such as optical fibres, sensing regions, modulation mechanisms, and interrogation units. This analytical approach made it possible to identify how external influences, particularly mechanical strain and temperature variations, affect specific optical parameters including wavelength, phase, frequency, and intensity of transmitted or reflected light.

The method of synthesis was applied to integrate fragmented theoretical, experimental, and applied knowledge into a unified conceptual model of fibre-optic strain and temperature sensing. Information obtained from diverse sensor types—such as fibre Bragg gratings, interferometric sensors, time-of-flight polymer fibre systems, and distributed scattering-based sensors—was combined to reveal common principles and structural regularities. Synthesis enabled the formulation of a coherent overview that reflects both the diversity and internal consistency of fibre-optic sensing technologies.

Inductive reasoning was used to derive general conclusions from specific documented implementations and performance data of fibre-optic sensors. Observations of sensor behaviour in particular configurations were generalised to identify broader trends in sensitivity, accuracy, spatial resolution, and operational reliability. This method supported the formulation of generalised assessments of technological maturity and applicability across different sensing approaches.

Conversely, deductive reasoning was applied by starting from established physical laws of optics and material science and applying them to specific fibre-optic sensing configurations. Known relationships between refractive index, optical path length, wavelength, temperature, and mechanical strain were used to predict sensor responses. These theoretically derived expectations were then correlated with reported experimental data to validate the logical consistency of sensor performance characteristics.

The method of comparison played a central role in evaluating alternative fibre-optic sensing techniques. Different sensor classes were systematically compared with respect to measurement principle, sensitivity, dynamic range, spatial resolution, multiplexing capability, resistance to environmental disturbances, and practical implementation complexity. Comparative analysis facilitated the identification of advantages and limitations inherent to point sensors versus distributed sensors, as well as intrinsic versus extrinsic sensing configurations.

Systematisation was used to organise the analysed sensing technologies into a structured classification framework. Fibre-optic sensors were grouped according to sensing principle, fibre type, interrogation method, and application domain. This method ensured terminological clarity and methodological coherence throughout the study, supporting consistent interpretation of results and conclusions.

Alongside general scientific methods, the research employed a set of specialised scientific methods specific to fibre-optic sensing and optical measurement technologies. Theoretical modelling of optical fibre behaviour was used to describe light propagation and its interaction with mechanical and thermal perturbations. Mathematical models governing Bragg wavelength shifts, phase variations in interferometric systems, and frequency shifts in scattering-based sensing were analysed to explain sensor sensitivity and response mechanisms.

Spectral analysis was applied to wavelength-selective sensing techniques, particularly fibre Bragg grating sensors. This method focused on analysing shifts in reflected Bragg wavelengths caused by temperature and strain changes, as well as on evaluating spectral parameters such as bandwidth, reflectivity, and wavelength resolution. Spectral analysis enabled quantitative interpretation of sensor output signals and assessment of measurement accuracy.

Phase and interferometric analysis was used to investigate fibre-optic sensors based on interference phenomena, including Fabry–Perot, Sagnac, and Michelson interferometers. This method examined the relationship between optical phase differences and external influences, allowing evaluation of sensor sensitivity, stability, and susceptibility to noise and environmental disturbances.

Scattering-based reflectometric analysis was employed for distributed sensing techniques utilising Rayleigh, Raman, and Brillouin scattering. This method involved analysing backscattered optical signals as functions of distance and frequency shift to achieve spatially resolved measurements of temperature and strain along the entire fibre length. Reflectometric analysis provided insight into the capabilities and limitations of distributed fibre-optic sensing systems.

Material property analysis was used to assess the influence of fibre composition and structure on sensor performance. Differences between silica fibres, polymer optical fibres, and photonic crystal fibres were analysed in terms of thermal stability, strain tolerance, optical attenuation, and operational wavelength range. This method supported evaluation of material suitability for specific sensing environments and applications.

A structured technical literature review was employed as a specialised method to contextualise the analysed sensing technologies within the current state of research. Peer-reviewed articles, monographs, and technical standards were systematically examined to identify established practices, validated performance metrics, and unresolved challenges in fibre-optic strain and temperature sensing.

Finally, an application-oriented evaluation method was applied to assess the practical relevance of different fibre-optic sensing techniques. Sensor characteristics were analysed in relation to operational conditions, measurement requirements, and integration constraints in application domains such as civil engineering, aerospace, energy systems, and medical technologies. This method enabled translation of theoretical and technical findings into applied engineering contexts.

In summary, the methodological approach of this study integrates general scientific reasoning with specialised analytical techniques specific to fibre-optic sensing. This combination ensures methodological completeness, supports rigorous interpretation of sensor behaviour, and provides a reliable foundation for the subsequent presentation and discussion of research results.

Literature Review

The scientific foundations of fibre-optic sensing for strain and temperature measurements are formed at the intersection of optical physics, materials science, and sensor engineering. The literature used in this study reflects both the classical theoretical background of fibre-optic sensors and contemporary advances that define current technological capabilities and application domains. The reviewed sources collectively provide a comprehensive framework for understanding sensing principles, performance characteristics, and practical implementation issues relevant to the present research.

A fundamental conceptual basis for fibre-optic sensing technologies is provided by the monograph edited by Rajan (*2017*), which offers an extensive overview of optical fibre sensors, including their physical principles, fabrication techniques, and application areas. This source is particularly relevant to the present study as it systematically outlines the main categories of fibre-optic sensors—grating-based, interferometric, and scattering-based—which constitute the core analytical structure of the article. Rajan's work supports the classification logic adopted in this research and serves as a reference point for evaluating sensor maturity and technological readiness.

Complementing this broad overview, Del Villar and Matias (*2020*) focus on the fundamental principles underlying the development of optimised optical fibre sensors. Their work is especially relevant to the present research due to its emphasis on sensitivity optimisation, signal processing, and design considerations. The authors' analysis of how fibre geometry, material composition, and interrogation techniques influence sensor performance directly informs the evaluation of strain and temperature sensitivity discussed in this article.

The overview presented by Engelbrecht (*2017*) provides a concise yet technically rigorous introduction to fibre-optic strain and temperature sensing principles. This source is particularly valuable for its structured explanation of sensing mechanisms and its focus on industrial and engineering contexts. Engelbrecht's contribution supports the present study's emphasis on practical applicability and reinforces the relevance of fibre-optic sensors as reliable tools for monitoring mechanical and thermal parameters in real-world systems.

The monograph by Fang et al. (*2012*) represents one of the key classical references in optical fibre sensors. Its detailed treatment of intensity-based, phase-based, and wavelength-based sensing mechanisms provides essential theoretical grounding for the present research. The fundamental optical relationships discussed by Fang and co-authors underpin the analytical models used to explain Bragg wavelength shifts, interferometric phase changes, and scattering phenomena examined in this article.

Another authoritative contribution to the field is the edited volume by Yin, Ruffin, and Yu (*2010*), which addresses fibre-optic sensors from both theoretical and applied perspectives. This work is relevant to the study due to its detailed discussion of sensor architectures and interrogation methods. The authors' analysis of system-level design challenges aligns with the present article's consideration of implementation complexity and cost factors associated with different sensing techniques.

The study by Foaleng et al. (*2010*) focuses on high-resolution Brillouin-based distributed sensing and is directly relevant to the discussion of scattering-based fibre-optic sensors. Their work demonstrates the feasibility of long-range, high-precision strain and temperature measurements using Brillouin echoes, thereby supporting the present study's assessment of distributed sensing as a promising yet technically demanding approach.

Gangwar et al. (*2023*) provide a recent and comprehensive review of optical fibre-based temperature sensors. This source is particularly important for establishing the current state of research and identifying recent technological advances. Its relevance to the study lies in its systematic comparison of temperature sensing techniques and its critical evaluation of sensor sensitivity, stability, and application constraints, which directly inform the results and discussion sections of this article.

The comparative experimental study by Gomez et al. (*2009*) examines polymer optical fibre sensors, fibre Bragg gratings, and conventional strain gauges in the context of aircraft structural health monitoring. This source is highly relevant for the present research as it provides empirical evidence of the advantages and limitations of different sensing technologies under realistic operational conditions. The findings reported by Gomez et al. support the article's evaluation of polymer fibre sensors as cost-effective solutions for large-strain measurements, albeit with limitations in attenuation and spatial resolution.

Hecht's monograph *Understanding Fiber Optics* (*2015*) remains a foundational educational resource in the field. Its relevance to the present study lies in its clear exposition of fibre types, light propagation mechanisms, and attenuation phenomena. This work supports the material property analysis conducted in the article and provides a reliable theoretical reference for discussing differences between single-mode, multimode, polymer, and photonic crystal fibres.

The recent study by Kukhtin and Hnatenko (*2023*) is directly related to the subject of the study, as it addresses fibre-optic temperature sensing using Bragg structures. This source is particularly valuable for its focus on practical sensor implementation and performance evaluation. Its findings reinforce the article's conclusions regarding the maturity and applicability of Bragg-based sensing technologies.

Leal-Junior et al. (*2024*) examine the role of optical fibre sensors in modern healthcare devices. This work expands the application perspective of fibre-optic sensing and is relevant to this study's discussion of medical applications. The authors' analysis of biocompatibility, miniaturisation, and electromagnetic immunity supports the argument that fibre-optic sensors are uniquely suited for certain medical and biomedical contexts.

The comprehensive review by Lee et al. (*2012*) focuses on interferometric fibre-optic sensors and provides detailed theoretical and experimental insights into Fabry–Perot, Michelson, and Sagnac configurations. This source is essential for this study's analysis of phase-based sensing methods and their sensitivity to strain and temperature variations.

Li and Zhang (*2022*) provide an in-depth analysis of Raman distributed optical fibre sensing, highlighting its physical principles and practical applications. This source is particularly relevant to the discussion of temperature-only distributed sensing and supports this study's evaluation of Raman-based systems as strain-insensitive yet technically complex solutions.

The classical work by Othonos et al. (*2006*) on fibre Bragg gratings remains a cornerstone reference in the field. Its detailed discussion of grating fabrication, spectral characteristics, and sensing mechanisms underpins the theoretical framework used in the present article to explain Bragg wavelength shifts and sensor sensitivity.

Finally, the edited volume by Venghaus (*2006*) provides an authoritative treatment of wavelength filters in fibre optics. Its relevance to the present study lies in its detailed explanation of wavelength-selective components and spectral filtering techniques, which are essential for understanding the operation of Bragg-based sensing systems and their interrogation methods.

Thus, the reviewed literature demonstrates that fibre-optic sensors for strain and temperature measurements constitute a well-established yet dynamically evolving research field. The analysed sources provide both the theoretical foundation and applied context necessary for the present study, supporting its methodological approach, analytical framework, and interpretation of results. The integration of classical references with recent review articles and application-oriented studies ensures that the research is grounded in established knowledge while remaining responsive to current technological developments.

Results

Optical Fibre

Majority of fibre-optic sensing systems utilize optical fibres originally developed for telecommunications or other general-purpose applications. These include multimode optical fibers, single-mode fibers and gradient fibres. In certain cases, particularly for strain measurements, polymer optical fibers have found implementation, though their applicability is limited due to their high attenuation, which can exceed 100 dB/km.

Multimode fibers have relatively large core diameters, which greatly simplifies coupling from broadband light sources such as LEDs. However, this type optical fibre exhibits modal dispersion and high attenuation ≈1 dB/km, which limits their use to relatively short distances of few hundred meters.

Single-mode optical fibre characterized by much smaller core diameter ~10 μm compared to multimode fibres. Its use is advantageous for high-spatial-resolution techniques. Also, single-mode optical fibres exhibit very low attenuation, typically below 0.2 dB/km at 1550 nm, making them ideal for long-range distributed sensing applications. However, they require the use of coherent light sources and precise coupling.

Most optical fibers and fiber-optic sensors are fabricated from fused silica (amorphous SiO_2), which makes them capable of operating at temperatures up to 1000 °C. The refractive index of the core or cladding can be altered by adding dopants such as germania (GeO_2) or fluorine (F). The allowable mechanical strain is typically limited to about 1%. Polymer optical fibers, typically fabricated from PMMA, are available as large-core multi-mode fibres with diameters up to 1 mm. This type optical fibre is cheap alternative to silica multimode fibers, which can tolerate very small bending radii, and can sustain strains up to roughly 10%. However, this type of fibres exhibits high attenuation ~100 dB/km, with minimum loss occurring in the visible spectral range, restricting their use to short-range applications. Graded-index POFs made from cyclic fluoropolymers offer reduced attenuation and lower modal dispersion, albeit at a higher cost.

A Photonic Crystal Fiber is an advanced optical fiber with a microstructure of tiny air holes running along its length, allowing it to guide light in unique ways not possible with conventional fibers, offering properties like endlessly single-mode guidance, hollow-core guidance, and highly nonlinear characteristics for applications in lasers and sensing. Such fibers difficult to produce have very high cost and used mainly as sensor parts of fiber-optic systems. More on optical fibre types and their characteristics could be found in (*Hecht, 2015*).

Time of Flight Polymer Sensors

Polymer optical fibers are well suited for the real-time measurement of relatively large strains in long extended structures, as they can tolerate high elongations without mechanical failure. Figure 2 illustrates an example of such sensor designed to measure the strain or elongation relative to a reference fiber (*Figure 1*) (*Gomez et al., 2009*).

In this approach, the optical light emitted by an LED or laser diode is harmonically modulated by an RF oscillator at a frequency f. The modulated light is detected by photodiodes, and an RF phase comparator determines the phase shift between the transmitted and received signals. The path-integrated strain or elongation ΔL of the fiber is proportional to the phase shift $\Delta\varphi$:

$$\Delta L = \frac{c_0}{n_{co} f_m} \cdot \frac{\Delta\varphi}{360} \quad (1)$$

where

c_0 is speed of light in vacuum,

n_{c0} is index of refraction of the fiber core,

f_m is modulation frequency.

With fast data acquisition, dynamic strain or vibrations in the low-Hz range can be recorded. This technique does not inherently provide spatial resolution of the strain distribution along the sensing fiber. However, spatially resolved measurements can be achieved by integrating interferometric optical frequency-domain reflectometry.

One of the primary challenges arises from disturbances in the optical path caused by accidental or unavoidable bends and microbends in optical fibers. These imperfections introduce random variations in fiber attenuation, as well as fluctuations in the polarization state and phase of the transmitted light, thereby degrading overall performance of such.

Bragg Fiber Sensors

A fiber Bragg grating (FBG) is a single-mode optical fiber with a periodic modulation of the refractive index in its core, acting as wavelength selective mirror or filter. When Bragg condition is satisfied, incident light experiences strong reflection due to the coherent superposition of many weak reflections at the grating periods.

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

where

Λ is a grating period,

n_{eff} is the effective refractive index of the fiber core.

To provide good spectral response, usually only single-mode optical fibres used for fiber Bragg fibre manufacture. In these structures both temperature and strain affect the refractive index and the grating period, thereby shifting the Bragg wavelength.

The sensing principle of FBG-based sensors usually involves wavelength shift measurements of a Bragg peak due to strain or temperature change. Bragg grating-based sensors provide good linearity and high accuracy compared to other fiber-optic types. Generally, FBG sensors are capable of operation at high temperatures with some examples such as Sapphire-FBG up to 1800°C. Bragg structures of types I (mainly germanium doped and germanosilicates, $\Delta n < 10^{-3}$, <300°C) and II ($\Delta n \sim 10^{-2}$,<800°C) are mostly used (*Rajan, 2017*; *Yin et al., 2010*). Bragg structures can be produced for a wide range of wavelengths λ=450–2000nm. Reflectivity indexes from 1% to 99% can be achieved with FWHM of around 0.2–2 nm. Additional information on sensitivity of optic fiber sensors and operational range, including FBG, can be found in work (*Gangwar et al., 2023*). Typical Fiber Bragg sensors schematics for strain and temperature measurements are presented in Appendix (*Figure 2*).

Bragg resonance, which is the peak center wavelength of back-reflected light from a grating, depends on the effective index of refraction of the core and the grating period. A change in temperature or strain will directly affect these two indicators (*Othonos, et al., 2006*).

$$\Delta\lambda_B = 2\left[\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right]\Delta l + 2\left[\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right]\Delta T \quad (3)$$

Also, this indicator can be presented in the form:

$$\Delta\lambda_B = \lambda_B\left[1 - \frac{n^2}{2}[p_{12} - v(p_{11} - p_{12})]\right]\varepsilon_z \quad (4)$$

where:

p_{11} and p_{12} are components of the strain optic tensor,

ν is the Poisson's ratio,

$\varepsilon_z = \partial l/l$.

A typical germanosilicate fibre exhibits a 1.2 pm shift in the centre wavelength of the grating as a result of applying 1 µε to the Bragg grating. The second term in (3) represents the effect of temperature on an optical fibre. A shift in the Bragg wavelength due to thermal expansion changes the grating spacing and the index of refraction. This fractional wavelength shift for a temperature change ΔT may be written as

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \quad (4)$$

where α_Λ represents temperature coefficient of expansion for silica and its value is approximately $0.55 \cdot 10^{-6}$.

The second term α_n is far more dominant thermo-optic coefficient α_n is approximately $8.6 \cdot 10^{-6}$ for silica fibers. In general, the shift at 1550 nm is 14 pm/C° for silica fibers doped with germanium (*Venghaus, 2006*). Furthermore, temperature response is strongly wavelength dependent, at 830 nm and 1300 nm shifts correspond to 6,8 pm/C° and 10 pm/C° respectively.

FBG allows distributed sensing of multiple gratings along a fiber, each with a distinct Bragg wavelength with appropriate multiplexing. The main disadvantage of this approach is a necessity of spectrometer and broadband radiation sources, such as super luminescent LEDs. Nevertheless, modern compact spectrometers allow measurements with a precision of ~10 pm, which translates to temperature and strain measurement precisions of approximately 1 K and 10 με. Alternatively, methods that involve tunable lasers and simple photodetectors to scan the reflection spectrum (*Kukhtin & Hnatenko, 2023*).

Scattering Based Sensors

During light propagation in optical fibers, intrinsic scattering mechanisms such as Rayleigh, Brillouin, and Raman scattering occur due temperature and strain. Each scattering process offers distinct spectral and temporal characteristics. Scattering measurements typically done via regular unmodified optical fibres and does not allow wavelength multiplexing technique with multiple sensing points. Instead, it relies on a time-of-flight principle that enables continuous, spatially resolved sensing along the entire fiber length, and referred to as distributed fiber-optic sensing (*Engelbrecht, 2017*).

Unlike Bragg grating sensors, distributed sensing via scattering does not require any special inscription or modification of the fiber. Backscatter information can be measured using multiple reflectometry methods, such as optical time-domain reflectometry, optical frequency-domain reflectometry, coherent optical frequency-domain reflectometry or code division optical reflectometry.

Among all scattering mechanisms Rayleigh scattering is the strongest effect with typical power of approximately −73 dB/m at 1550 nm. Such extremely weak reflections require highly sensitive detection techniques, which allow measurements of Releigh fingerprints changes due to temperature and strain change. Generally, Rayleigh-based c-OFDR systems provide good spatial resolution and fast measurement speeds, but are typically limited to a few hundred meters of sensing range and require a highly stable, precisely tuneable laser.

Raman scattering arises from the interaction of light with the vibrational modes of molecular bonds. In fused silica, these vibrational modes spread for ~10 THz, producing two distinct spectral components in the scattered light (*Figure 3*). These components are shifted to lower and higher frequencies and referred as Stocks and Anti-Stockes components. Temperature sensing relies on evaluating the power ratio between the Stokes and Anti-Stokes components which is temperature-dependent due to fundamental thermodynamic and quantum-electronic effects (*Li & Zhang, 2022*).

$$\frac{P_{AS}}{P_S} \sim exp\left(-\frac{hf_v}{kT}\right) \tag{5}$$

where

h is Planck's constant,

k is Boltzmann's constant.

Spontaneous Raman scattering is the weakest of the scattering mechanisms. As with other distributed fiber-optic sensing techniques, spatial resolution in Raman-based systems is achieved via high sensitivity refractometry methods. Multimode or graded-index fibers are typically used for distances of several hundred meters, whereas single-mode fibers can be operated at ranges of several kilometres due to their lower attenuation and reduced pulse dispersion. A key advantage of Raman distributed temperature sensing is its insensitivity to strain.

Brillouin scattering in the optical fiber occurs due to interaction of light with acoustic waves that modulates refraction index. When light of wavelength λ is scattered from this modulated area that travels with a speed v_a, it experiences a Doppler shift in optical frequency:

$$\Delta f_B = 2n_{eff}v_a/\lambda_0 \quad (6)$$

For a wavelength of 1550 nm, the Brillouin frequency shift in standard fused-silica single core fiber is approximately 11 GHz (*Foaleng et al., 2010*) (*Figure 3*). This microvawe shift can be measured via heterodyne techniques. Brillion frequency is affected by both temperature and strain and can be effectively measured in single-mode silica fibres due to their constant and well-defined effective index.

Interferometric Sensors

Interferometric fiber sensors can also be for strain and temperature measurements. The most commonly used configurations include Fabry–Perot, Sagnac, Michelson interferometers.

A Fabry–Perot interferometer consists of two parallel mirrors separated by a cavity with a length L. An example of such sensor is shown in fig 4.a. In this sensor, interference occurs from the multiple superposition of the reflected and transmitted beams at the two reflective surfaces. The reflection or transmission spectrum of this sensor exhibits wavelength-dependent intensity modulation, originating from the optical phase difference between the reflected and transmitted beams. The optical phase difference between the interfering beams at a given wavelength is generally expressed as (*Lee et al., 2012*):

$$\delta = (2\pi/\lambda)2nL \quad (7)$$

where

λ is the wavelength of incident light,

n is the refractive index of cavity material,

L is the length of the cavity.

Fiber-optic Sagnac interferometers is another approach for temperature and strain sensing. In this sensor, the input light is divided by a 3-dB fiber coupler into two beams that propagate in opposite directions and are subsequently recombined at the same coupler, as shown in the Appendix (*Figure 4.b*) (*Othonos et al., 2006*). The interferometer can be fabricated simply by splicing together the two output arms of a standard 3-dB coupler. Typically, high-birefringence (HB) fibers or polarisation-maintaining fibers (PMFs) are commonly used as the sensing element. A polarisation controller is typically placed before the sensing fiber to adjust the input polarisation state.

The output signal of the Sagnac interferometer results from the interference between the counter-propagating beams polarized along the fast and slow axes of the birefringent fiber. The phase difference of the interference is given by:

$$\delta_{SL} = \frac{2\pi}{\lambda} BL \tag{8}$$

where

$B = |n_f - n_S|$ is the birefringence coefficient of the sensing fiber,

L is the fiber length,

n_f and n_s are the effective refractive indices of the fast and slow polarisation modes, respectively.

Michelson fiber interferometer (as Fabry-Perot and Zehnder) using classical, well-known schemes is easy to implement. In the Michelson arrangements, light is reflected at the fiber ends, propagates back, and subsequently interferes with another wave from the second arm. Interferometric operation requires coherent laser source. These architectures can be implemented quite simply with optical fibers, requiring only basic optoelectronic components. It worth mentioning that, despite simple arrangement and low price, such systems found limited use.

Discussion

As been shown in previous paragraphs fiber-optic sensors for temperature and strain measurements represent a huge milestone in sensing. The main advantage of fibre-optic sensing is wide availability of telecommunication optical components that allows creation of long-range distributed sensing systems at appropriate price. In the future prices for such systems are expected to be even lower. Currently fiber Bragg systems proved to be very versatile and widely used for various applications, including multiparameter distributed sensing. The main limitation factor for Bragg systems is complexity related to spectrometric measurements and high spectrometer cost. However, resent appearance of low-cost spectrometers based on diffraction grade with linear CCD array can potentially significantly expand their application. On the other hand, time of flight sensors, despite their inferior characteristics can be effectively utilized for tasks that require relatively high strain/extension measurements. Also, it should be noted that their price is currently quite low. Scattering sensing techniques are very promising, but due to complexity and high requirements for reflectometry equipment, they found very limited use. Their wide implementation is yet to be seen. Another direction that shows great prospects is sensors based on photonic–crystal fiber. Currently, use of such fiber is limited due to high cost and limited availability.

It is also worth mentioning application areas of fibre-optic sensors for strain and temperature measurements. Civil engineering showing high demand for such fiber optic systems. These systems are the most effective means for mechanical load and strain measurements and maintenance of bridges, tunnel, dams, high-rise buildings. The aerospace industry is a potentially another important user of fibre-optic sensors due to radiation an EMI immunity and ability to operate in harsh conditions. The inert nature of optical fibre and ability to withstand high temperatures, makes this technology, particularly suitable for nuclear energy systems and certain medical procedures (*Leal-Junior et al., 2024*). In medical contexts, optoelectronic temperature sensors are especially advantageous for monitoring tissue temperature during radiotherapy and related treatments. The miniature dimensions of silica based optical fibers further enhance their suitability for such applications.

Conclusion

The technology of fiber optic sensors is very promising for numerous applications in the field of civil engineering, industry, aerospace, medicine and many other. Moreover, their inherent advantages, such as ability to withstand high temperatures up to 1000º C, miniature dimensions, ability to work in harsh conditions, immunity to electric and magnetic fields and radiation make them a perfect solution to certain applications, for which no other sensing techniques could be applied.

This article provided a brief review of basic types of these sensors, as well as description of their operation principle and main advantages. Fiber-optic sensors can be based on various techniques and physical principles, including amplitude and phase detection, spectral measurements, interferometry etc. All that shows their inherent versatility and potential wide application. Among various types of fiber-optic sensors, Bragg sensors for strain and temperature sensing exhibit maternity and current wide implementation. Another major benefit of Bragg sensors use is their ability to provide distributed long sensing networks with multiple sensors along optical fibre.

This offers opportunities for applications like monitoring composites at high temperatures or to provide detailed map of strain field of complex structures. Scattering based systems, despite their complexity, can be even more advantageous in this regard. Future advances in fibre-optics, light sources, novel detection methods open bright future and prospects to fiber-optic sensing technology and its spread to new application fields.

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Appendix

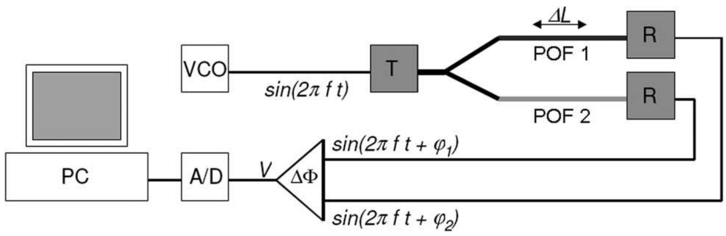

Figure 1. Time of flight strain sensor

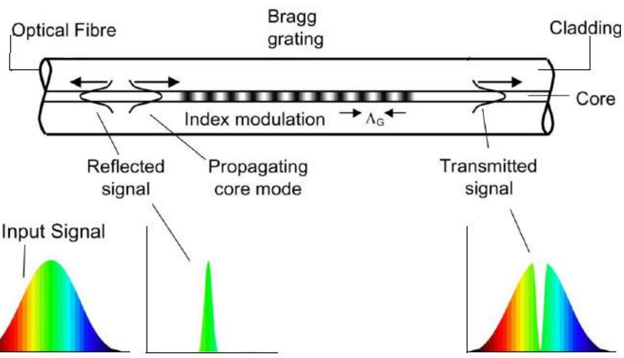

Figure 2. Schematics of fibre Bragg grating

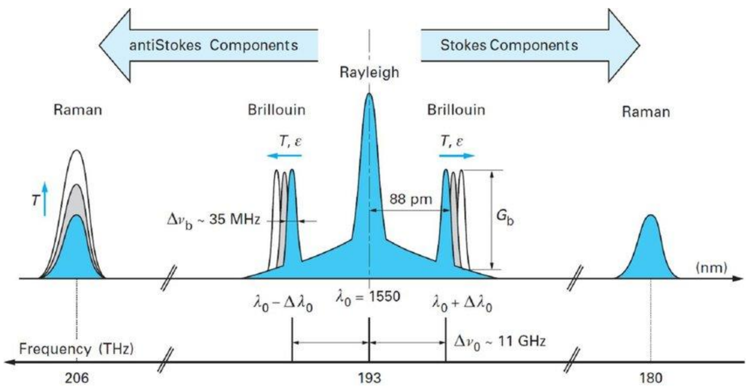

Figure 3. Scattering effects in silica fibre

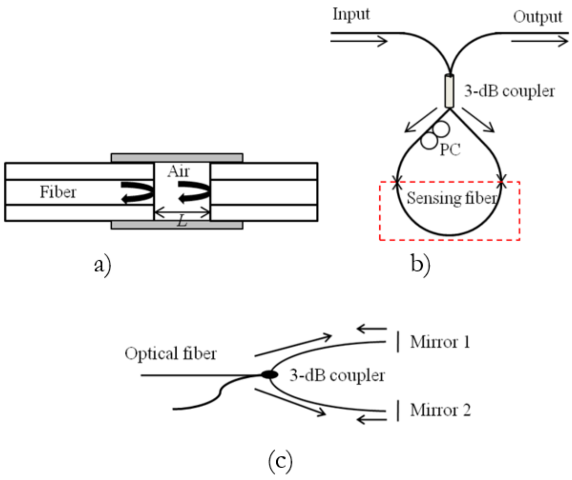

Figure 4. Basic schematic for fibre-optic interferometers (a) Fabry-Perot, (b) Sagnac, (c) Michelson