Application of Optical Fibers in Temperature Monitoring

Subjects: Engineering, Electrical & Electronic | Engineering, Environmental | Instruments & Instrumentation
Contributor: Rahul Kumar Gangwar, Sneha Kumari, akhilesh Kumar pathak, Sai dheeraj Gutlapalli, Mahesh Chand Meena

The current generation is witnessing a huge interest in optical waveguides due to their salient features: they are of low cost, immune to electromagnetic interference, easy to multiplex, have a compact size, etc. These features of optical fibers make them a useful tool for various sensing applications including in medicine, automotives, biotechnology, food quality control, aerospace, physical and chemical monitoring. Among all the reported applications, optical wave guides have been widely exploited to measure the physical and chemical variations in the surrounding environment. Optical fiber-based temperature sensors have played a crucial role in this decade to detect high fever and tackle COVID-19-like pandemics. Recognizing the major developments in the field of optical fibers, this entry provides recent progress in temperature sensors utilizing several sensing configurations including conventional fiber, photonic crystal fiber, and Bragg grating fibers. Additionally, this entry also highlights the advantages, limitations, and future possibilities in this area.

Keywords: waveguide ; photonic crystal ; optical fiber ; Bragg gratings ; temperature ; sensor ; COVID-19

1. Introduction

Reliable temperature monitoring plays a key role in the metallurgical industry, the aerospace field, nuclear energy production, and medical applications [1][2]. In the metallurgical industry, real-time monitoring of the internal temperature of high-temperature boilers is key to measuring combustion efficiency and safety prevention [3][4]. On the other hand, temperature monitoring inside the turbines and combustion chambers of an aero-engine or aircraft can help extend its service life [5][6][7]. Recently, the appearance of COVID-19 gained huge interest in terms of the need for temperature-monitoring instruments in the medical sector for continuous monitoring of the temperature of individuals in public places [8][9]. According to the accuracy, detection, and installation techniques, high- temperature-monitoring technology can be categorized as (i) contact measurement [10], and (ii) non-contact measurement [11]. Thermocouple sensors made of expensive metals are generally utilized for the former type of temperature sensing due to their ease of operation, mature preparation approach, and wide operating range [12]. However, thermocouple sensors suffer several limitations—they have a short life, poor corrosion resistance, low accuracy, are susceptible to electromagnetic interferences, etc. The main concerns when using thermocouple devices are that their metal or alloys used during fabrication which can be easily oxidized and damaged at high temperatures, leading to a shorter service life and poor sensing accuracy [13]. Infrared thermography is a type of non-contact temperature-sensing technology, designed to avoid direct contact between the sensing equipment and high-temperature environments to provide a non-destructive sensing performance [14]. Unfortunately, the radiation temperature-monitoring technology is only suitable for surface measurements, i.e., explosion flame, and cannot detect the temperature of the internal structure of the closure device. Extremely harsh environments with high pressures, high temperatures, and strong electromagnetic radiation present a challenge to these conventional detection techniques.

Compared to conventional sensing technology, optical fiber-based sensors have gained huge interest owing to their excellent properties: they are of low cost, immune to electromagnetic interference, easy to multiplex, have a compact size, etc. [15]. To date, several approaches have already been implemented for temperature sensing including microstructured optical fibers (MOFs) [16][17], conventional fibers (e.g., single-mode fibers (SMFs), multimode fibers (MMFs), and plastic optical fibers (POF)) [18][19][20][21], and grating-based fibers (e.g., fiber Bragg grating (FBG), long period grating (LPG), and tilted FBG (TFBG)) [22]. The commonly employed high- temperature-sensing optical fibers mainly include silica and MOFs. Theoretically, the maximum temperature that a temperature sensor can detect is based on the fiber materials rather than that of its sensing mechanism. Usually, silica-fiber-based temperature sensors are limited to operating within 1000 °C due to the diffusion of the germanium dopant [1]. Additionally, temperature sensors based on pure silicon fibers such as MOFs can operate at 1300 °C, which is closer to the melting point of silicon, whereas temperature sensors based on single-crystal fibers can operate stably below 1900 °C. The basic priniciple and the corresponding advantages and limitations of each types of optical fibers based temperature sensors are discussed below. **Figure 1** summarizes all types of optical fiber temperature sensors.

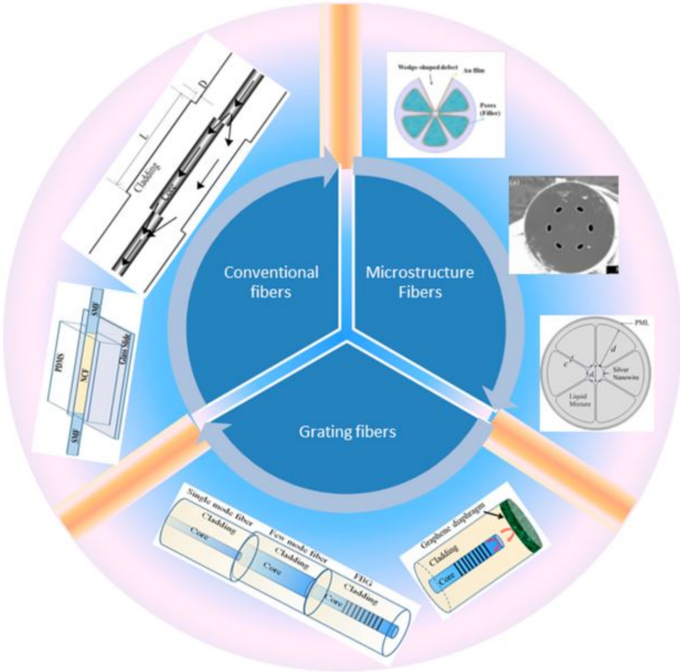

Figure 1. Summary of various optical fiber-based temperature sensors. (Reprinted from 10.3390/opt4010013)

2. Microstructure Optical Fibers (MOFs) Based Temperature Sensors

The last decade has witnessed an enormous interest in optical fibers used for sensing and long-distance operation applications [23][24][25]. The optical fiber in sensors is applied as a sensing element to monitor surrounding parameters such as strain, pressure, vibration, and temperature. Among conventional fibers, MOFs have played a key role in various sensing applications [26][27][28]. MOFs are waveguides made of optical fibers in which the guiding property is acquired by modifying the waveguide structure rather than the waveguide's index of refraction [29]. Light is steered using complete internal reflection in ordinary optical fibers. A core with a refractive index greater than that of the surrounding material is where the guiding takes place (cladding). The cladding and core can be doped differently, or various materials can be used, to produce the index change [30]. The method used in microstructured fibers is fundamentally different. Fibers are made of a single substance (often silica), and light directing is accomplished by the existence of air gaps in the region around the solid core [31]. Unlike conventional optical fibers, photonic crystal fibers (PCFs) are made up of small air holes that are spaced at regular intervals, enabling greater design freedom and unique optical properties [32][33]. A periodic pattern of air holes extending the full length of a PCF, centered on a solid or hollow core, is what gives this geometry its name. The primary distinction between the two types of fibers is based on the fact that PCF waveguide properties derive from an arrangement of extremely small and closely spaced air holes rather than from the spatially varying glass composition of a conventional optical fiber, which runs the entire length of the fiber.Based on post-processing techniques, the micro air holes can also be filled with liquid, gas, or even solid materials, greatly changing the PCF guiding characteristics and enabling the fabrication of a variety of functional fiber devices such as electrically controlled optical switches [34][35][36], all-optical modulators [37], temperature-controlled tunable optical filters [38], photonic bandgap fiber polarimeters [39][40], and PCF sensors [41].

Advantages and Limitations

The thermo-elastic deformation of MOF can be significantly smaller than that of normal fibers under the same heat impact, which is among its advantages. Additionally, the temperature equalization velocity in MOFs is higher than in conventional fibers. The thermal gradients in MOFs are lower than in conventional fibers. The size of the MOF, the number of air rods, how they are arranged, and other variables all affect how much these variations are worth. The fact that the air rods in MOFs may be filled with a variety of materials, such as a particular gas combination or a certain kind of nanomaterial, is another crucial benefit of these fibers. This will make it possible to obtain fiber with special optical and thermal characteristics. For instance, compared to fiber-optic gyros based on ordinary optical fibers, employing MOFs with air rods loaded with thermally conductive nanoparticles, such as carbon nanotubes, can dramatically minimize temperature gradients (up to over 10 fold) in the optical fiber coil.

3. Conventional Silica Fibers Based Temperature Sensors

Single-mode fibers (SMFs), multimode fibers (MMFs), no-core fibers (NCF), multicore fibers (MCFs), etc., are the types of conventional fibers that are made of either fused silica and/or germanium-doped silica. These fibers are named based on their appearance; for example, an SMF contains a germanium core (8 μm) and fused silica cladding (125 μm), whereas the NCF contains only silica cladding of diameter of 125 μm. Optical fiber plays a crucial role in sensing elements to monitor several physical and chemical parameters such as chemical variations, strain, pressure, vibration, and temperature [42][43][44][45]. There are several ways of converting a temperature signal into an optical and then an electrical signal. The most popular used approach is to employ SMFs, MMFs, NCFs, MCFs, etc., as temperature sensors. Other than this, the application of the SMF–MMF–SMF structure was also exploited at a large scale [46][47][48]. The sensing mechanism of conventional fibers uses an amplified emission source to input broadband light into the sensor and the photodetector to detect the response. The measured temperature range relies on the used photodetector's sensitivity and the properties of the fiber which acts as a sensor.

Advantages and Limitations: So far, the application of different kinds of fiber as standard fiber for temperature-sensing application has been presented. However, each variety has its own merits and demerits. The proposed fiber as a sensor offers the advantage of small size, low cost, higher output power, less detection limit, resistance to electromagnetic interference, remote detection and multiplexing. Moreover, a few of these fiber-based sensors suffer from the need for a larger measuring range and a narrower linewidth to measure the minute wavelength shift, fabrication complexity, and the employment of sophisticated equipment. Although plastic optical fibers comprise several advantages such as a large core diameter, a lower cost and are highly flexible, they fail to gain enough attention in temperature sensing because of some major drawbacks, i.e., lower bandwidth, high attenuation, shorter range, etc., compared to silica fibers.

4. Grating Fiber Based Temperature Sensors

Nowadays, fiber Bragg grating (FBG) is considered as among the most popular optical components widely exploited in optical networking, physical and chemical sensing due to their ease of fabrication, small size, multiplexing feature, and low cost. An FBG comprises a periodic variation of the refractive index (RI) within the core of a single-mode fiber, which satisfies the phase matching condition between the fundamental mode and other modes, either the core mode or the cladding modes or radiation (or leaky) modes [49]. In 1978, Hill et al. fabricated and reported the first FBG in a germanium-doped core [50]. The grating was made by using the laser lithography technique to incorporate the permanent periodic variation of the refractive index in the fiber core. The sensing principle of FBG-based fibers can be defined as the grating period, grating length, and the effective refractive index of such fibers that are affected by the variation in the surrounding media [51]. The change in the outer environment leads to the change in its resonance condition; consequently, the variation in resonance wavelength takes place. Based on the property of these gratings, it can be classified into three categories: (1) fiber Bragg grating (FBG), (2) long-period fiber grating (LPFG), and (3) tilted FBG (TFBG). The grating-based optical fibers gain huge attention in physical and chemical sensing due to their unique features of immunity to electromagnetic interferences, compact size, highly sensitive, multiplexing capability, and in situ monitoring. Owing to their design of label-free monitoring of the surrounding environment, grating-based sensors, such as FBG, LPG, etched FBG, and TFBG, have attracted extensive attention in order to develop physical and chemical sensors. In grating-based fibers, the Bragg wavelength is calculated by the refractive index modulation period (L) and the effective refractive index of the fiber (n_{eff}) [52]. A change in the refractive index of the fiber is observed, under the variation of the temperature, leading to a linear drift in the value of the Bragg wavelength. Temperature monitoring using grating fibers can be easily achieved by demodulating the Bragg wavelength variation. Compared to other optical fiber sensors, the grating-based temperature sensors showed several advantages including good linearity, high stability, multiplexing capability, and mass production, which have been used widely in commercialization.

Advantages and Limitations: The grating-based optical fiber gains huge development in temperature sensing due to its salient features such as high sensitivity, a fast response time, excellent stability over a larger time, and ease of multiplexing, enabling simultaneous temperature monitoring at multiple points along the length of the fiber. In addition to these advantages, the grating-based fiber suffers several limitations such as limited temperature range, highly expensive, signal processing complexity, strain sensitivity, and polarization sensitivity. These limitations may cause false or mixed output results, and differentiating the output data are a difficult task itself.

5. Prospects and Challenges:

With the advancement of micro- and nano-technology and the development of fibers with unique optical characteristics, there is little question that designs and fabrications of innovative microstructured fiber-optic sensors will continue to be a thriving research topic. Opportunities and challenges coexist simultaneously in the work to be performed on microstructured fiber-optic sensors in the future. These include the ability to measure multiple parameters simultaneously and with selectivity. Although several microstructured fiber-optic sensors with dual-parameter measuring capabilities have been proposed to date, efforts should be made to reduce measurement error and expand dual-parameter measurement to three-parameter or even more parameter characterizations because the cross-talk effect is typically brought on by more than two parameters in many applications. Even greater sensitivity also requires MOF sensors with exceptionally high accuracies for more exact measurements. Sensing in severe conditions is required including those in high pressure, strong radiation, and extremely low or high temperatures. An intelligent MOF sensor should have functionalities that can be changed and adjusted in response to various target samples and circumstances. A more adaptable and potent sensor architecture is desirable. The robustness of the microscopic structures is the key to the sensing performance and longevity of the device; therefore, better packaging without sacrificing sensitivity will be the future goal. Additionally, there is a need for a simplified and easy fabrication process for the MOF sensor. One main aspect of the MOF-based sensor is to control the attenuation loss which is more important for the practical application.

Real-time monitoring of temperature in patients in the inpatient floor and ICU with small devices that can monitor the fluctuations in real time as with telemetry can be extremely useful in patients with pneumonia and or sepsis and any other infections especially those who are intubated and unable to speak in critical care units. This will enable more efficient detection of hospital-acquired infections and will be helpful for quicker reaction to tackle possible infection in patients. In a normal clinical setting, the patient has to inform the nurse that they have a fever or the nurse has to keep checking the temperature of the patient at regular intervals. With a real-time temperature-monitoring device, it would be easier and faster to detect a new infection and nip it in the bud before it goes on to form a major infection or abscess and may be useful in ultimately reducing a lot of incidences of sepsis.

Temperature monitoring is often overlooked in critical care when compared to other factors such as pulse oximetry and telemetry but it is an important factor, a biological alarm that signals infection or some other abnormality in the patient. So this technology can be extremely useful in not only detecting cases of COVID-19 or flu during pandemics for screening a large number of people easily but it can also providing a means to monitor critically ill patients and give the doctors a head start in treating the infection before it becomes worse. This can revolutionize not just screening but also patient monitoring.

Each fiber comprises unique advantages and certain limitations. Multimode fibers contain a large core diameter, enabling a larger number of modes of propagation. The special feature makes such fibers more sensitive to the variation of temperature compared to the SMF. Additionally, such fibers are also robust in nature and suffer a lower bending loss, making them ideal for any harsh environments. These unique features make them the most suitable candidate for distributed temperature-sensing systems, e.g., Raman and Brillouin scattering-based temperature sensors, whereas multicore fibers contain multiple cores, which are generally used for temperature monitoring in a distributed manner. The temperature-induced changes in the refractive index value of the core cause variation in the transmission of light, which can be monitored to determine the temperature. The advantage of multicore fibers is that they can measure temperature at multiple points simultaneously over long distances, which makes them an ideal candidate for structural health monitoring applications. PCFs are specialized fibers with a unique structure that enables the propagation of light in a photonic bandgap, therefore making them highly sensitive to temperature variation. The bandgap shifts with temperature variation and can be measured to determine the temperature. These fibers also have a very low bending loss and excellent temperature stability, which makes them a superior candidate for high-temperature monitoring. PCFs are suitable for temperature sensing in high-temperature environments, e.g., furnaces, power plants, and engines. In summary, the MMF, multicore fibers, and PCFs offer unique advantages for temperature-monitoring applications along with the feature of distributed temperature sensing, high-temperature stability, and large temperature range**.**

References

1. Ma, S.; Xu, Y.; Pang, Y.; Zhao, X.; Li, Y.; Qin, Z.; Liu, Z.; Lu, P.; Bao, X. Optical Fiber Sensors for High-Temperature Monitoring: A Review. Sensors 2022, 22, 5722, doi:10.3390/s22155722.
2. Childs, P. R. N.; Greenwood, J. R.; Long, C. A. Review of temperature measurement. Rev. Sci. Instrum. 2000, 71, 2959–2978, doi:10.1063/1.1305516.

3. Yang, S.; Homa, D.; Heyl, H.; Theis, L.; Beach, J.; Dudding, B.; Acord, G.; Taylor, D.; Pickrell, G.; Wang, A. Application of Sapphire-Fiber-Bragg-Grating-Based Multi-Point Temperature Sensor in Boilers at a Commercial Power Plant. Sensors 2019, 19, 3211, doi:10.3390/s19143211.
4. Willsch, M.; Bosselmann, T.; Flohr, P.; Kull, R.; Ecke, W.; Latka, I.; Fischer, D.; Thiel, T. Design of fiber optical high temperature sensors for gas turbine monitoring. In; Jones, J. D. C., Ed.; 2009; p. 75037R.
5. Atkins, R. A.; Gardner, J. H.; Gibler, W. N.; Lee, C. E.; Oakland, M. D.; Spears, M. O.; Swenson, V. P.; Taylor, H. F.; McCoy, J. J.; Beshouri, G. Fiber-optic pressure sensors for internal combustion engines. Appl. Opt. 1994, 33, 1315, doi:10.1364/AO.33.001315.
6. Watson, J.; Castro, G. A review of high-temperature electronics technology and applications. J. Mater. Sci. Mater. Electron. 2015, 26, 9226–9235, doi:10.1007/s10854-015-3459-4.
7. Gao, S.; Wang, L.; Feng, C. Multi-spectral pyrometer for gas turbine blade temperature measurement. In; Kazemi, A. A., Kress, B. C., Mendoza, E. A., Eds.; 2014; p. 920217.
8. Zhang, L.; Zhu, Y.; Jiang, M.; Wu, Y.; Deng, K.; Ni, Q. Body Temperature Monitoring for Regular COVID-19 Prevention Based on Human Daily Activity Recognition. Sensors 2021, 21, 7540, doi:10.3390/s21227540.
9. Costanzo, S.; Flores, A. A Non-Contact Integrated Body-Ambient Temperature Sensors Platform to Contrast COVID-19. Electronics 2020, 9, 1658, doi:10.3390/electronics9101658.
10. Bielska, S.; Sibinski, M.; Lukasik, A. Polymer temperature sensor for textronic applications. Mater. Sci. Eng. B 2009, 165, 50–52, doi:10.1016/j.mseb.2009.07.014.
11. Wawrzynczyk, D.; Bednarkiewicz, A.; Nyk, M.; Strek, W.; Samoc, M. Neodymium(iii) doped fluoride nanoparticles as non-contact optical temperature sensors. Nanoscale 2012, 4, 6959, doi:10.1039/c2nr32203j.
12. Kus, A.; Isik, Y.; Cakir, M.; Coşkun, S.; Özdemir, K. Thermocouple and Infrared Sensor-Based Measurement of Temperature Distribution in Metal Cutting. Sensors 2015, 15, 1274–1291, doi:10.3390/s150101274.
13. Jun, S.; Kochan, O. Investigations of Thermocouple Drift Irregularity Impact on Error of their Inhomogeneity Correction. Meas. Sci. Rev. 2014, 14, 29–34, doi:10.2478/msr-2014-0005.
14. Nie, B.; He, X.; Zhang, C.; Li, X.; Li, H. Temperature measurement of gas explosion flame based on the radiation thermometry. Int. J. Therm. Sci. 2014, 78, 132–144, doi:10.1016/j.ijthermalsci.2013.12.010.
15. Pathak, A. K.; Viphavakit, C. A review on all-optical fiber-based VOC sensors: Heading towards the development of promising technology. Sensors Actuators A Phys. 2022, 338, 113455, doi:10.1016/j.sna.2022.113455.
16. Mollah, M. A.; Islam, S. M. R.; Yousufali, M.; Abdulrazak, L. F.; Hossain, M. B.; Amiri, I. S. Plasmonic temperature sensor using D-shaped photonic crystal fiber. Results Phys. 2020, 16, 102966, doi:10.1016/j.rinp.2020.102966.
17. Cheng, T.; Li, X.; Li, S.; Yan, X.; Zhang, X.; Wang, F. Surface plasmon resonance temperature sensor based on a photonic crystal fiber filled with silver nanowires. Appl. Opt. 2020, 59, 5108, doi:10.1364/AO.391226.
18. Wang, Z.; Chen, D.; Yang, X.; Liang, S.; Sun, X. Temperature sensor of single-mode-no-core-single-mode fiber structure coated with PDMS. Opt. Fiber Technol. 2022, 68, 102793, doi:10.1016/j.yofte.2021.102793.
19. Savovic, S.; Kovacevic, M. S.; Bajic, J. S.; Stupar, D. Z.; Djordjevich, A.; Zivanov, M.; Drljaca, B.; Simovic, A.; Oh, K. Temperature Dependence of Mode Coupling in low-NA Plastic Optical Fibers. J. Light. Technol. 2015, 33, 89–94, doi:10.1109/JLT.2014.2375515.
20. Kreger, S. T.; Sang, A. K.; Gifford, D. K.; Froggatt, M. E. Distributed strain and temperature sensing in plastic optical fiber using Rayleigh scatter. In; Udd, E., Du, H. H., Wang, A., Eds.; 2009; p. 73160A.
21. Chu, C.-S.; Lo, Y.-L. A Plastic Optical Fiber Sensor for the Dual Sensing of Temperature and Oxygen. IEEE Photonics Technol. Lett. 2008, 20, 63–65, doi:10.1109/LPT.2007.912568.
22. Liao, C. R.; Wang, D. N. Review of femtosecond laser fabricated fiber Bragg gratings for high temperature sensing. Photonic Sensors 2013, 3, 97–101, doi:10.1007/s13320-012-0060-9.
23. Markos, C.; Travers, J. C.; Abdolvand, A.; Eggleton, B. J.; Bang, O. Hybrid photonic-crystal fiber. Rev. Mod. Phys. 2017, 89, 045003, doi:10.1103/RevModPhys.89.045003.
24. Chaudhary, S.; Amphawan, A. Solid core PCF-based mode selector for MDM-Ro-FSO transmission systems. Photonic Netw. Commun. 2018, 36, 263–271, doi:10.1007/s11107-018-0778-4.
25. Amphawan, A.; Chaudhary, S.; Neo, T.-K.; Kakavand, M.; Dabbagh, M. Radio-over-free space optical space division multiplexing system using 3-core photonic crystal fiber mode group multiplexers. Wirel. Networks 2021, 27, 211–225, doi:10.1007/s11276-020-02447-4.

26. Pathak, A. K.; Ghosh, S.; Gangwar, R. K.; Rahman, B. M. A.; Singh, V. K. Metal Nanowire Assisted Hollow Core Fiber Sensor for an Efficient Detection of Small Refractive Index Change of Measurand Liquid. Plasmonics 2019, 14, doi:10.1007/s11468-019-00969-y.
27. Pathak, A. K.; Rahman, B. M. A.; Viphavakit, C. Nanowire Embedded Micro-Drilled Dual-Channel Approach to Develop Highly Sensitive Biosensor. IEEE Photonics Technol. Lett. 2022, 34, 707–710, doi:10.1109/LPT.2022.3182783.
28. Kumar Vyas, A.; Kumar Gangwar, R.; Kumar, S. Elliptical air hole PCF-based low-cost sensor for refractive index and temperature detection: Design and analysis. Opt. Fiber Technol. 2022, 73, 103060, doi:10.1016/j.yofte.2022.103060.
29. Gangwar, R. K.; Pathak, A. K.; Qin, J.; Wang, X. Physics of photonic crystals and applications. In Modern Luminescence from Fundamental Concepts to Materials and Applications; Elsevier, 2023; pp. 313–327.
30. Gangwar, R. K.; Singh, V. K. Highly Sensitive Surface Plasmon Resonance Based D-Shaped Photonic Crystal Fiber Refractive Index Sensor. Plasmonics 2017, 12, 1367–1372, doi:10.1007/s11468-016-0395-y.
31. De, M.; Gangopadhyay, T. K.; Singh, V. K. Prospects of Photonic Crystal Fiber as Physical Sensor: An Overview. Sensors 2019, 19, 464, doi:10.3390/s19030464.
32. Russell, P. Photonic Crystal Fibers. Science (80-.). 2003, 299, 358–362, doi:10.1126/science.1079280.
33. Knight, J. C. Photonic crystal fibres. Nature 2003, 424, 847–851, doi:10.1038/nature01940.
34. Larsen, T.; Bjarklev, A.; Hermann, D.; Broeng, J. Optical devices based on liquid crystal photonic bandgap fibres. Opt. Express 2003, 11, 2589, doi:10.1364/OE.11.002589.
35. Du, F.; Lu, Y.-Q.; Wu, S.-T. Electrically tunable liquid-crystal photonic crystal fiber. Appl. Phys. Lett. 2004, 85, 2181–2183, doi:10.1063/1.1796533.
36. Haakestad, M. W.; Alkeskjold, T. T.; Nielsen, M. D.; Scolari, L.; Riishede, J.; Engan, H. E.; Bjarklev, A. Electrically tunable photonic bandgap guidance in a liquid-crystal-filled photonic crystal fiber. IEEE Photonics Technol. Lett. 2005, 17, 819–821, doi:10.1109/LPT.2004.842793.
37. Alkeskjold, T. T.; L�gsgaard, J.; Bjarklev, A.; Hermann, D. S.; Anawati, A.; Broeng, J.; Li, J.; Wu, S.-T. All-optical modulation in dye-doped nematic liquid crystal photonic bandgap fibers. Opt. Express 2004, 12, 5857, doi:10.1364/OPEX.12.005857.
38. Steinvurzel, P.; Eggleton, B. J.; de Sterke, C. M.; Steel, M. J. Continuously tunable bandpass filtering using high-index inclusion microstructured optical fibre. Electron. Lett. 2005, 41, 463, doi:10.1049/el:20050037.
39. Alkeskjold, T. T.; Bjarklev, A. Electrically controlled broadband liquid crystal photonic bandgap fiber polarimeter. Opt. Lett. 2007, 32, 1707, doi:10.1364/OL.32.001707.
40. Qian, W.; Zhao, C.-L.; Wang, Y.; Chan, C. C.; Liu, S.; Jin, W. Partially liquid-filled hollow-core photonic crystal fiber polarizer. Opt. Lett. 2011, 36, 3296, doi:10.1364/OL.36.003296.
41. Jha, R.; Villatoro, J.; Badenes, G.; Pruneri, V. Refractometry based on a photonic crystal fiber interferometer. Opt. Lett. 2009, 34, 617, doi:10.1364/OL.34.000617.
42. Wildner, W.; Drummer, D. A Fiber Optic Temperature Sensor Based on the Combination of Two Materials With Different Thermo-Optic Coefficients. IEEE Sens. J. 2016, 16, 688–692, doi:10.1109/JSEN.2015.2488979.
43. Pathak, A. K.; Chaudhary, D. K.; Singh, V. K. Broad range and highly sensitive optical pH sensor based on Hierarchical ZnO microflowers over tapered silica fiber. Sensors Actuators, A Phys. 2018, doi:10.1016/j.sna.2018.08.013.
44. Khanikar, T.; Pathak, A. K.; Singh, V. K. Reflectance-based no core fiber sensor with enhanced Sensitivity for salinity detection. Optik (Stuttg). 2018, 159, doi:10.1016/j.ijleo.2018.01.053.
45. Pathak, A. K.; Singh, V. K. A wide range and highly sensitive optical fiber pH sensor using polyacrylamide hydrogel. Opt. Fiber Technol. 2017, 39, doi:10.1016/j.yofte.2017.09.022.
46. Wang, K.; Mizuno, Y.; Kishizawa, K.; Toyoda, Y.; Lee, H.; Ichige, K.; Kurz, W.; Dong, X.; Jakobi, M.; Koch, A. W. Temperature sensing based on multimode interference in polymer optical fibers: sensitivity enhancement by PC-APC connections. Jpn. J. Appl. Phys. 2022, 61, 118001, doi:10.35848/1347-4065/ac9810.
47. Sun, X.; Zhang, L.; Zeng, L.; Hu, Y.; Duan, J. Micro-bending sensing based on single-mode fiber spliced multimode fiber Bragg grating structure. Opt. Commun. 2022, 505, 127513, doi:10.1016/j.optcom.2021.127513.
48. Pathak, A. K.; Gangwar, R. K.; Priyadarshini, P.; Singh, V. K. A robust optical fiber sensor for the detection of petrol adulteration. Optik (Stuttg). 2017, doi:10.1016/j.ijleo.2017.09.036.
49. Chiavaioli, F.; Gouveia, C.; Jorge, P.; Baldini, F. Towards a Uniform Metrological Assessment of Grating-Based Optical Fiber Sensors: From Refractometers to Biosensors. Biosensors 2017, 7, 23, doi:10.3390/bios7020023.

50. Hill, K. O.; Fujii, Y.; Johnson, D. C.; Kawasaki, B. S. Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication. Appl. Phys. Lett. 1978, 32, 647–649, doi:10.1063/1.89881.
51. Rahman, B. M. A.; Viphavakit, C.; Chitaree, R.; Ghosh, S.; Pathak, A. K.; Verma, S.; Sakda, N. Optical Fiber, Nanomaterial, and THz-Metasurface-Mediated Nano-Biosensors: A Review. Biosensors 2022, 12, 42, doi:10.3390/bios12010042.
52. Chen, J.; Liu, B.; Zhang, H. Review of fiber Bragg grating sensor technology. Front. Optoelectron. China 2011, 4, 204–212, doi:10.1007/s12200-011-0130-4.