



Recent Applications of Fiber Bragg Grating Sensors in Humidity and Water Content Detection in Agriculture: A Comprehensive Review of Development, Challenges, and Future Trends

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Abstract

There has been a growing interest in using Fiber Bragg Grating (FBG) sensors for the detection of humidity and water content due to their high sensitivity, ease of installation, multiplexing capability, reliability, and resistance to electromagnetic interference. Although, several studies and papers have been published on FBG sensors and their applications in various fields such as construction, geophysical, there is a lack of a consolidated review that specifically focuses on recent developments in agriculture with particular reference soil humidity and water content. Therefore, a comprehensive and up-to-date analysis of the advances, detection mechanisms, challenges, and potential future directions in this field is needed. This paper provides an in-depth analysis and summarizes the fundamental principles, advancements, methodologies, and recent research findings, highlighting the potential application in agriculture, development, challenges, and prospects for FBG-based humidity and water content detection. By utilizing the changes in FBG wavelength or amplitude caused by the presence of humidity, they provide an effective means for real-time monitoring and control of water content. However, challenges remain to be addressed, such as the need for accurate calibration and the potential for drift over time. In this review, we further discuss the strategies and techniques proposed to overcome the highlighted challenges, such as sensor packaging, signal processing algorithms, and calibration procedures, and suggest that further studies could be done to investigate the novel materials with enhanced sensitivity and selectivity, development of miniaturized and wireless FBG sensor system, as well as investigating multiplexing techniques for simultaneous measurement of multiple parameters.

Keywords Fiber Bragg Grating · Coating methods · Water contents · Humidity · Calibration processes · Signal processing

1 Introduction

Fiber Bragg Grating (FBG) sensors consist of an optical fiber transformed into a grating structure that reflects a particular type of light, the Bragg wavelength. As light passes

through the fiber, a section of it is reflected at the Bragg wavelength, while the remainder moves forward [1, 2]. The refractive index of the material surrounding the sensor can be affected by humidity and water content, resulting in minor changes in the Bragg wavelength. These changes can be detected and exploited to determine the humidity and water content of the environment [3–5]. On the other hand, humidity and water content are critical parameters that must be accurately monitored in various applications [6, 7]. FBG sensors are an excellent tool for agriculture due to their remarkable sensitivity, robustness, versatility, and remote sensing capabilities [8–10]. These sensors can be used for many purposes, such as monitoring soil and crop health and keeping an eye on structural and livestock conditions [9, 11–13]. Although their cost, limited availability, data interpretation, and expertise requirements may pose a challenge, they provide substantial advantages to farmers

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seeking reliable and precise data to enhance their agricultural methods [11, 14, 15]. However, it should be noted that excessive humidity can lead to the growth of mold and mildew, corrosion of electronic components, and degradation of materials [16–18]. Additionally, insufficient humidity levels can cause discomfort, dryness, and damage to sensitive equipment. Therefore, precise measurement and control of humidity are essential in industries such as agriculture, pharmaceuticals, food processing, HVAC systems, and environmental monitoring. Humidity-sensitive material is often applied to FBG sensors to detect humidity and water content, such as the coating, which interacts with water molecules, altering the refractive index surrounding the FBG sensor and resulting in a shift in the Bragg wavelength as humidity or water content levels vary. By observing the shift in the reflected light wavelength, we can accurately know the environment's humidity or water content level. However, it is essential to note that FBG sensors are primarily used for relative humidity measurements rather than direct absolute humidity or water content measurements in agriculture. The precise relationship of the wavelength shift to humidity or water content depends on the sensor calibration and the specific coating utilized. FBG sensors require calibration to adjust for temperature, strain, wavelength shifts, and manufacturing variations for precise readings [19–22], whereas they are coated to protect them from moisture, chemicals, and other environmental factors while enhancing sensitivity and reducing strain transfer [4, 7, 23]. The advantages of FBG technology to detect humidity and water content in agriculture include its exceptional accuracy and sensitivity, remote sensing abilities, and durability [18, 24]. These benefits make FBG sensors an essential tool for reliable and accurate monitoring in agricultural applications.

Traditional methods such as gravimetric, psychrometric, hygrometry, and dew point measurement have been widely used, but may not provide real-time or highly sensitive measurements. However, FBG has limitations such as variation in sensitivity, slow feedback time, limited accuracy, need for frequent calibrations, and susceptibility to contamination [25, 26]. On the other hand, FBG sensors offer a unique and promising approach to humidity and water content detection and the ability to multiplex measurements that make them well-suited for humidity detection applications in agriculture [27, 28]. During exposure to changes in humidity or water content, the FBG sensor experiences a shift in its Bragg wavelength that is measured using an optical interrogator system, allowing an accurate determination of humidity levels [29, 30]. Bragg wavelength shifts are directly proportional to change in humidity or water content changes, allowing precise measurements with high resolution [30]. In addition, FBG sensors have a quick response time, making it possible to monitor humidity levels in real-time accurately in agriculture. FBG sensors have immunity to electromagnetic

interference unlike capacitive or resistive sensors because FBG sensors do not require electrical connections, making them immune to electromagnetic noise [6, 31, 32]. This makes FBG sensors particularly suitable for use in environments with high levels of electromagnetic interference, such as industrial settings. However, to effectively monitor moisture levels in agriculture, it is essential to understand how the system functions. An important consideration is that different weather conditions can cause the upper layers of the soil to dry quickly. Various factors, such as air circulation, temperature changes, and evaporation rate, affect the drying process because when the top surface is exposed to air and sunlight, evaporation rates increase and can accelerate drying [33, 34]. By strategically placing sensors at various depths in the soil, fluctuations in moisture content can be recorded across multiple layers. This real-time monitoring provides a comprehensive understanding of the moisture levels within the soil profile, allowing farmers to schedule irrigation and manage their crops with knowledge.

Furthermore, FBG sensors can operate in harsh environments, including high temperatures and corrosive conditions where the sensing element of an FBG sensor is encapsulated within a protective coating, which protects it from external factors [21, 35, 36]. This robustness makes FBG sensors ideal for applications where traditional sensors may fail or deteriorate [37]. Over the past few years, there has been notable advancement in the development and application of FBG sensors for detecting humidity and water content. Researchers have experimented with different techniques to enhance the performance of FBG sensors, such as using various fiber types, coatings, and interrogation systems.

These advances have led to improved accuracy, sensitivity, and reliability of FBG sensors in humidity detection applications. Therefore, this review article aims to provide a comprehensive overview of the recent applications and developments of FBG in the detection of moisture and water content. We discuss the principles behind FBG sensing, its advanced sensors for detecting humidity and water contents, and the various techniques used to enhance their performance. Additionally, this paper will highlight the comparison in coating materials, comparison with traditional methods, key challenges and future prospects in the field of FBG-based humidity sensing.

2 FBG Working Principle

FBG sensors have many practical uses in measuring various physical parameters, including strain, temperature, pressure, humidity, and water content [38–40]. These sensors use the fiber's optical properties, which change in response to water content, to make these measurements. The basic principle behind FBG sensors is the Bragg reflection phenomenon

(λ_B), which occurs when a light wave passes through a fiber with a periodic modulation of the refractive and encounters a change in the refractive index of the surrounding medium [13, 22, 39, 41]. Using an FBG sensor to gauge humidity and water content, the fiber is subjected to the observed conditions where the existence of humidity in the surrounding air or on the fiber's surface alters its refractive index, resulting in a distinct spectral pattern generated by the reflection of light waves in the fiber [16, 42]. This adjustment to the Bragg reflection spectrum allows the assessment of humidity and water content which can be determined using the formula $\lambda_B = 2n_{eff}\Lambda$, where n represents the effective refractive index of the fiber core, and Λ is the refractive index modulation period [34]. As illustrated in Fig. 1, the FBG reflects a narrow spectral segment of light at the Bragg wavelength [43]. Studies have verified that an FBG operates on the principle of recurring disturbance of the refractive index along the fiber axis [44]. This disturbance is created by exposing the fiber core to a powerful ultraviolet interference pattern [45]. As a result, when a wide-range light moves within the optical fiber and arrives at the grating, only one wavelength is reflected and the remaining signal is marginally reduced (as depicted in Fig. 1). The reflected wavelength is identified as the Bragg wavelength, which the subsequent equation can represent:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

The Bragg wavelength (λ_B) can detect variations in strain or temperature. This is because any alteration in strain or temperature results in a modification of the fiber refractive index (n_{eff}) or the grating period (Λ). Consequently, a shift in the Bragg wavelength occurs and by observing this shift, one can determine the value of the strain or humidity. Furthermore, changes in strain (Δ_ϵ) or temperature (Δ_T) can also cause a shift in the pitch of the grating, which is detectable by measuring changes in the wavelength of the reflected light. The equation that relates these changes (Eq. 2) is the following:

$$\Delta\lambda_B = K_\epsilon\Delta_\epsilon + K_T\Delta_T \tag{2}$$

where K_ϵ is the strain coefficient and K_T is the temperature coefficient.

FBG sensors have proven to be highly effective in measuring physical parameters and creating magnetic sensors in various fields, as evidenced by various monitoring applications [35, 46–48]. A study [35] detailed the development of the FBG sensor using a phase mask between an ultraviolet laser and a photosensitive fiber to write the grating structure. As light passes through the photomask, its shadow governs the grating's formation inside the fiber. Interference arises from the light's intensity when transmitted and reflected at the grating location. The fiber's core is infused with a spectrum of light, and any fluctuations in temperature or strain will cause a corresponding shift

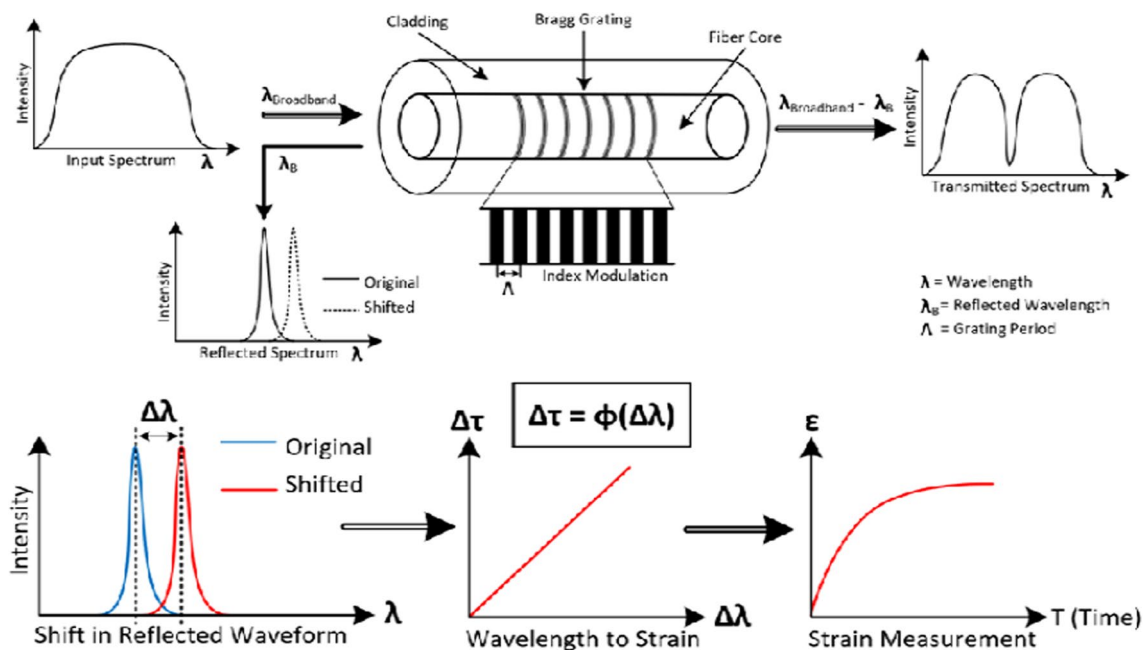


Fig. 1 Sensing principle and operation of FBG-based sensor relationship between wavelength shifts with apply strain for humidity and water content

in the central Bragg wavelength. This correlation is direct and proportional and can be expressed as

$$\frac{\Delta\lambda}{\lambda} = (1 - P_{eff})\Delta\epsilon + (\alpha + \xi)\Delta T \tag{3}$$

where $\Delta\lambda$ represent the shift in the Bragg wavelength, ξ is the thermos-effect of the single mode fiber, α is the coefficients of thermal expansion, ϵ represent the axial stain, ΔT represent the temperature variation and P_{eff} represents the effective elasto-optical coefficient of the fiber.

Using FBG technology to measure relative humidity requires a humidity sensitive material to convert RH into Bragg wavelength measurement [49, 50]. The FBG remains stable, and a humidity-absorbing film causes strain on the fiber, leading to precise RH measurements. Conclusively, FBGs devices leverage the refractive index fluctuations within the optical fiber core to produce reflectors designed for particular wavelengths which allows them to detect temperature and strain accurately while maintaining their reliability and compactness.

3 Coatings on the Surface of the FBG Sensors

Optimizing the sensitivity and selectivity of FBG sensors for the detection of humidity and water content involves considerations such as the choice of fiber material, coating materials, sensor design, and signal processing techniques [43]. A protective coating on their surface can be highly beneficial to improve the accuracy and longevity of FBG sensors in detecting humidity and water content. These sensors are commonly used to measure temperature, strain, and pressure, but their performance may be affected by the properties of the fiber’s surface [31]. Hence, a protective layer is crucial to enhance their dependability and endurance [51]. Each of the coating materials for FBG-based sensors has different parameters in terms of sensitivity, durability, efficiency, effectiveness and chemistry (Table 1). The selection of the coating material should be focused specifically on its water absorption properties, stability, and compatibility with the sensing environment [52–55]. For example, when the FBG sensor is exposed to environmental factors such as moisture, humidity, and temperature fluctuations, its performance can be affected. To avoid degradation, a protective coating can be applied to prevent moisture and other contaminants from entering. Furthermore, the signal reflected by the FBG sensor may weaken due to absorption and scattering of the surrounding materials. However, a coating can help reduce signal attenuation by decreasing the amount of light scattered or absorbed by these materials. To avoid degradation, a protective coating can be applied to prevent moisture and other contaminants from entering. Furthermore, the signal

Table 1 Comparison of various coating materials

Parameters	Polymer coatings	Metal coatings	Thin film coating	References
Chemistry	Synthetic polymers, which are long chains of repeating molecules	Metallic elements	Variety of materials, including metals, dielectrics, and semiconductors	[58]
Binding	Bound to a substrate using an adhesive, such as a polyurethane or epoxy-based adhesive	Bound to a substrate using a process called electroplating	Bound to a substrate using a process called sputtering	[30, 59, 60]
Efficiency	Easier to apply than metal coatings	Highly durable and resistant to corrosion, but more difficult to apply than polymer coatings	Highly efficient and can be deposited using a variety of techniques and difficult to apply	[2, 61]
Ranges	Between 0.5 and 5 dB/cm over the wavelength range of 1500–1600 nm	Between 5 and 10 dB/cm over the wavelength range of 1500–1600 nm	Between 0.1 and 0.5 dB/cm over the wavelength range of 1500–1600 nm	[7]
Cost	Less expensive. Its costs between \$10 and \$50 per meter, depending on the type, thickness, and volume needed	Because of the intricacy of the coating process, metal coatings for FBG sensors are usually more expensive than polymer coatings, costing between \$50 and \$100 per meter of fiber	While more expensive than polymer coatings, thin-film coatings can provide better performance in some applications, ranging from \$100 to \$200 per meter of fiber	[14, 62, 63]
Stability	Less stable than metal coatings	Highly stable and resistant to degradation	Highly stable and resistant to degradation	[45]
Tolerance	Affected by temperature, humidity and other environmental factors, which can cause them to degrade over time	Withstand a wide range of temperatures and environmental conditions without degrading	Withstand a wide range of temperatures and environmental conditions without degrading	[2, 36, 62]
Sensitivity	Less sensitive to chemicals and abrasion than metal coatings	Highly sensitive to chemicals and abrasion	Highly sensitive to chemical	[56]

reflected by the FBG sensor may weaken due to absorption and scattering by surrounding materials [50, 56, 57].

Coating materials applied to the FBG sensor can significantly affect its sensitivity and selectivity due to its high affinity for water molecules to ensure efficient water vapor absorption. Polymer coatings such as polyimide or polyethylene glycol (PEG) are commonly used due to their high water absorption capacity [50]. When exposed to water vapor, specific coatings may expand, exerting pressure on the FBG sensor, resulting in a Bragg wavelength deviation. According to [64], polyimide FBGs (FBGs without coatings) are layered with polyimide on the outer coating after removing the original coating. A calibration experiment shown in (Fig. 2) compared the strain detected by a bare polyimide FBG and an uncoated FBG. The findings indicated that coating with polyimide does not impact the strain measurement and on the substrate surface is typically insignificant [65]. Therefore, when mounted on a substrate surface, a polyimide FBG without a coating can be considered an uncoated FBG.

Furthermore, [66] utilized a hygroscopic material to coat the FBG which involves two steps that are depicted in

(Fig. 3a). First, when there is an increase in environmental humidity, water molecules are absorbed with the pores of agarose or agar, which replace air. This leads to swelling of the agarose or agar layer as a result of the hydrophilic nature of these materials. The degree of swelling increases with higher environmental humidity, and some hypersensitive materials have a quality correlation with silica. Therefore, their swelling cause macrostrain in the FBG, which results in a $\Delta\lambda_B$ that indirectly, measures RH. The authors performed preliminary analysis at two RH values (roughly 15% and 45%) and a consistent temperature of approximately 20 °C to assess the properties of the spectra and their correlation with variations in relative humidity, and obtained spectra from three FBG coated sensors and a reference FBG spectrum (Fig. 3d–g) where the coated are spectra compared to the FBG sensor (Fig. 3f).

Additionally, as the relative humidity increases, the FBG-coated sensors demonstrate a shift in spectra toward a larger wavelength as a result of the coating material enlargement. Conversely, the reference FBG's spectrum shift is almost negligible, indicating minimal sensitivity to RH (as shown

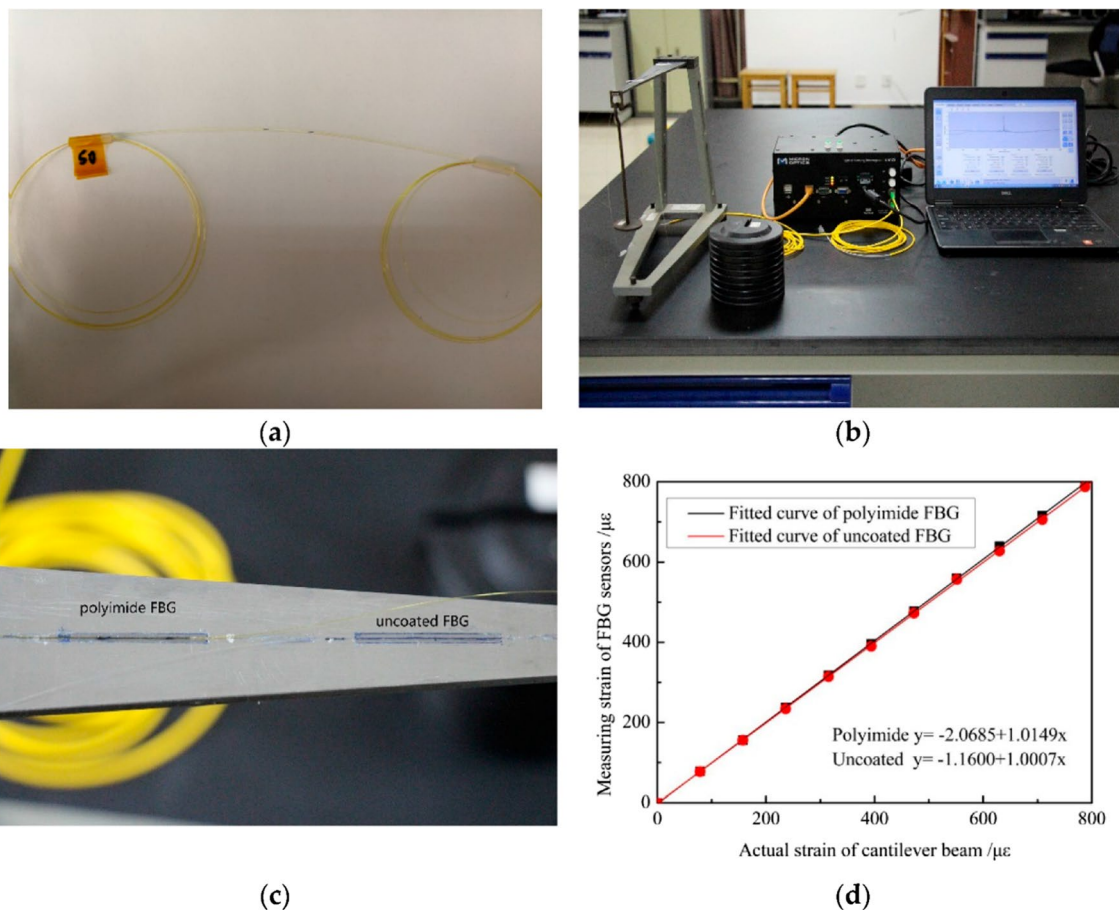


Fig. 2 Polyimide FBG samples **a** bare polyimide, **b** uncoated FBG with strain transfer ratio experiment polyimide, **c** comparison of polyimide bonding types, **d** coated and uncoated FBG results [64]

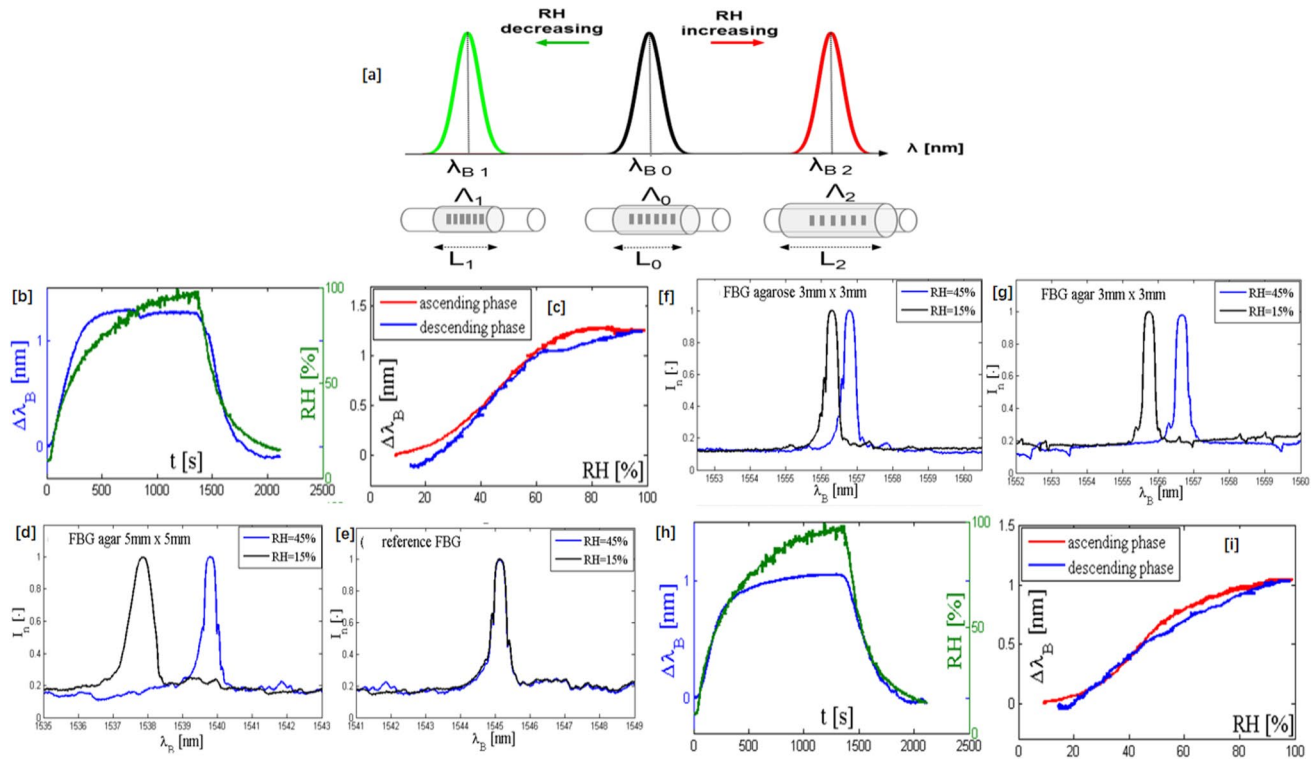


Fig. 3 FBG coating measuring system **a** length & spatial periods of the grating with Bragg wavelength values, **b, c** corresponding RH trending, **d–g** FBG-coated sensor & reference FBG sensor values [66]

in Fig. 3b and h). The coated sensors' response time to RH changes is comparable to or faster than that of the reference sensor. In slow-moving air, the reference sensor response time is 50 s. However, the coated sensor's response must be faster to keep pace with RH changes. On the basis of Fig. 3c and i, it can be observed that the conjunction within the output and input of the two sensors is quite similar. The maximum change in wavelength ($\Delta\lambda_B$) for the agarose-coated sensor is around 1.0 nm, while for the agar-coated sensor, it is around 1.2 nm. These two sensors responded to changes in relative humidity, so we can estimate their average sensitivity by calculating the ratio between the $\Delta\lambda_B$ recorded for the two extreme RH values used during the test and the difference between these two RH values. The sensitivity of the agar and agarose coated sensors is approximately 0.14 nm/% and 0.12 nm/% respectively. The degree of hysteresis for both coated sensors is considered acceptable.

The diameter of etched tilted FBG coated with GO affected its performance (Fig. 4i–iii) and confirmed that there is a variant of highest sensitivity at 20 μm diameter which used a buffered oxide etch to facilitate the etching process [67]. The coating's response to increasing humidity changes the refractive index, affecting interference at recombination. However, [68] found that the resonant wavelength shift moves towards the blue spectrum with increasing humidity. Humidity was measured using a tapered

plastic optical fiber (POF) that is highly sensitive with a 0.0386 mV/%H and a dynamic range from 50 to 75%H. The POF was coated with seeded Al-doped ZnO and prepared using the sol–gel method with a ZnO nanocrystal seed layer, which determined RH through water absorption on the fiber surface. This caused an increase in the refractive index of the coating and more light leakage, making the amount of light transmitted at the fiber output directly proportional to the RH [69]. The data presented in (Fig. 4a–e) show that the wavelength of light varies with humidity and particle diameter. For example, when the diameter was 20 μm and the RH was 20%, the wavelength was 1535.962 nm. However, when the RH increased to 80%, the wavelength shifted to 1535.367 nm, resulting in a shift of 595 pm. The results follow in line with other particles, where the wavelength shifts as the humidity increases. Overall, this information highlights the importance of considering the diameter and humidity when studying the behavior of light.

However, to properly reflect the negative thermal and optical coefficient characteristics of polydimethylsiloxane (PMS), the fiber cladding should be coated with PMS to allow the excitation of evanescent solid waves [7]. This can be achieved through a core offset, tapered, or bend fiber, which is simple to prepare, highly adaptable, and cost-effective and has garnered significant attention in the field [70–73]. Furthermore, ensuring the long-term stability and

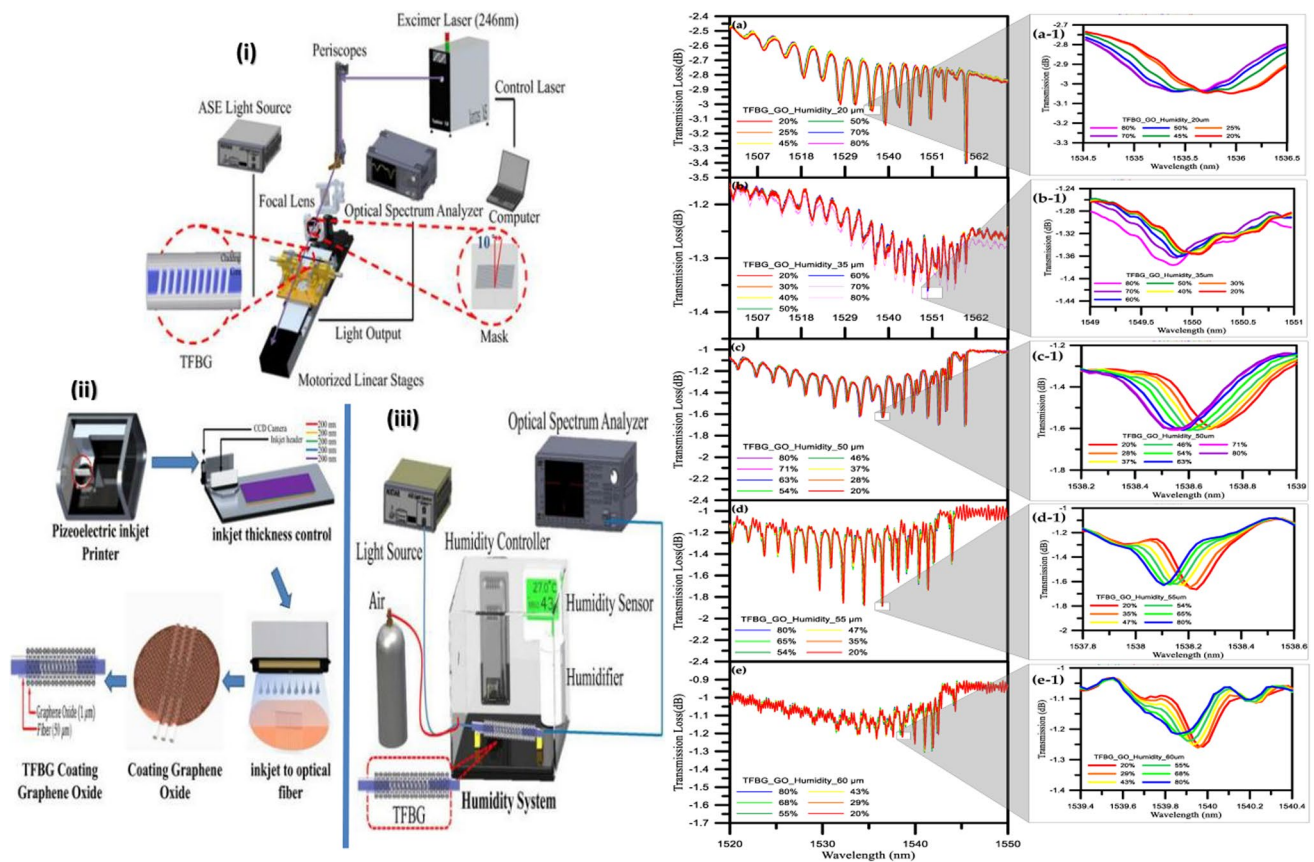


Fig. 4 FBG sensor coating for humidity sensing. (i) Fiber sensing fabrication process (ii) graphene oxide coating process (iii) experimental setup **a–e** FBG humidity sensor spectral with differ-

ent diameters of 20, 35, 50, 55 and 60 μm respectively, **a–l–e–1** 1535.367–1535.962 nm, 1549.815–1550.060 nm, 1538.2–1539 nm, 1537.8–1538.6 nm and 1539.4–1540.4 nm respectively [67]

reliability of FBG sensors for the measurement of humidity and water content is a significant challenge [46]. Humidity and water content can have detrimental effects on the sensor's performance, leading to drift or degradation over time. Moisture-induced swelling or changes in the refractive index of the sensing materials can result in shifts in the Bragg wavelength, affecting the accuracy and reliability of the measurements. Advancement in FBG sensor production for humidity and water content measurements are being made to address these challenges through the development of novel sensing materials with improved stability and sensitivity [24, 74]. For example, researchers have explored the use of nanomaterials, such as graphene oxide or metal–organic frameworks, which exhibit a high surface area and tunable properties. These materials can improve the interaction between the sensor and the surrounding medium, leading to improved sensitivity and stability [34, 75]. Furthermore, the integration of FBG sensors with other technologies to enable real-time monitoring and data analysis help to overcome the challenges. For example, combining FBG sensors with wireless communication systems allows remote monitoring of humidity and water content in various applications,

such as structural health monitoring or environmental sensing [76–78]. Additionally, advances in signal processing algorithms and machine learning techniques enable a more accurate interpretation of sensor data, leading to enhanced measurement capabilities. During the heat-curing process, the film shrinks, causing uneven stress on the moisture-sensitive material and resulting in a fragile FBG region [79]. Additionally, thermal curing can warp the film, leading to a chirp effect that affects the sensor's practical monitoring.

To prepare the FBG sensor for use, the optical fiber coating was removed from 10 mm at either end, simplifying the application of the polyimide coating [34, 41, 49, 80]. Subsequently, the fiber was affixed to a pre-coated glass with the aid of a release agent [7]. Furthermore, a sensitive coating was administered to the FBG sensor surface, which responds to the surrounding environment, such as humidity or water vapor, resulting in the alteration of the reflected wavelength of the FBG sensor. The coating substance can be selected based on its ability to absorb or absorb moisture, ensuring precise measurement of humidity or water content [34, 59]. In summary, FBG sensors offer great potential for measuring humidity and water content due to their unique properties.

However, challenges remain to select appropriate materials, design highly sensitive sensors, and ensure long-term stability and reliability [5]. Ongoing advancements in sensing materials, fabrication techniques, and integration with other technologies are addressing these challenges and driving further improvements in the production of FBG sensors for measurements of humidity and water content.

3.1 Analysis of Typical Responses and Impacts Exhibited by FBG Sensors

FBG sensors are affected by multiple factors when detecting humidity and water content, which include the wavelength of light, coating materials, and environmental conditions. When exposed to humidity or water, sensors change their optical properties, which can be analyzed to determine water content levels [39, 79]. FBG sensors often respond to humidity by exhibiting a shift in their Bragg wavelength. The changes in the refractive index of the medium, causing a shift that can be positive or negative depending on the fiber coating [81, 82]. Variations in humidity levels can lead to a modification in wavelength, which can be positive or negative, depending on the coating material [10, 41]. This occurs when water interacts with the coating material, causing it to swell or expand and, consequently altering the effective refractive index of the fiber, leading to a change in the Bragg wavelength [28, 53]. The degree of deviation is dependent on the amount of moisture present. However, it is crucial to

understand that the influence of humidity and water content on FBG sensors can differ according to factors such as design, calibration and environmental conditions [83–85]. The embedded FBGs were produced and subjected to tension tests to determine the highest strain detection ranges of the embedded FBG, which is based on the varying materials adopted for the coatings (Fig. 5). The optical fiber diameter was 0.25 mm in both cases, while the steel tube's outer and inner diameters varies as depicted in (Fig. 5b, c) which provides an illustration of the FBG embedded on strand in the tension test. The recoated FBG specimens were prepared with polyimide and acrylate, and bonded to the seamless tube using epoxy resin. The authors later suggested that the impact of FBG sensor aid and ensure the reliable sensitivity for detecting the temperature, strain, and water content in a given experiment.

Kim et al. [84] in the study further proposes a technique to increase the detection of embedded FBG strain ranges detection (Fig. 5d). Then a polyimide tube protects the sensor, and epoxy resin is injected to combine them (Fig. 5e). During the conducted research, two types of FBG sensors were created: a standard FBG sensor and a new FBG sensor where the tube has a 1.23 mm outer diameter and a 1.13 mm inner diameter with typical values of 231 MPa for tensile strength and 2.50 GPa for elastic modulus. Their tests found that using the polyimide tube to protect the FBG sensor effectively increases its maximum strain measurement range when embedded in a strand (Fig. 5f). However, due to the

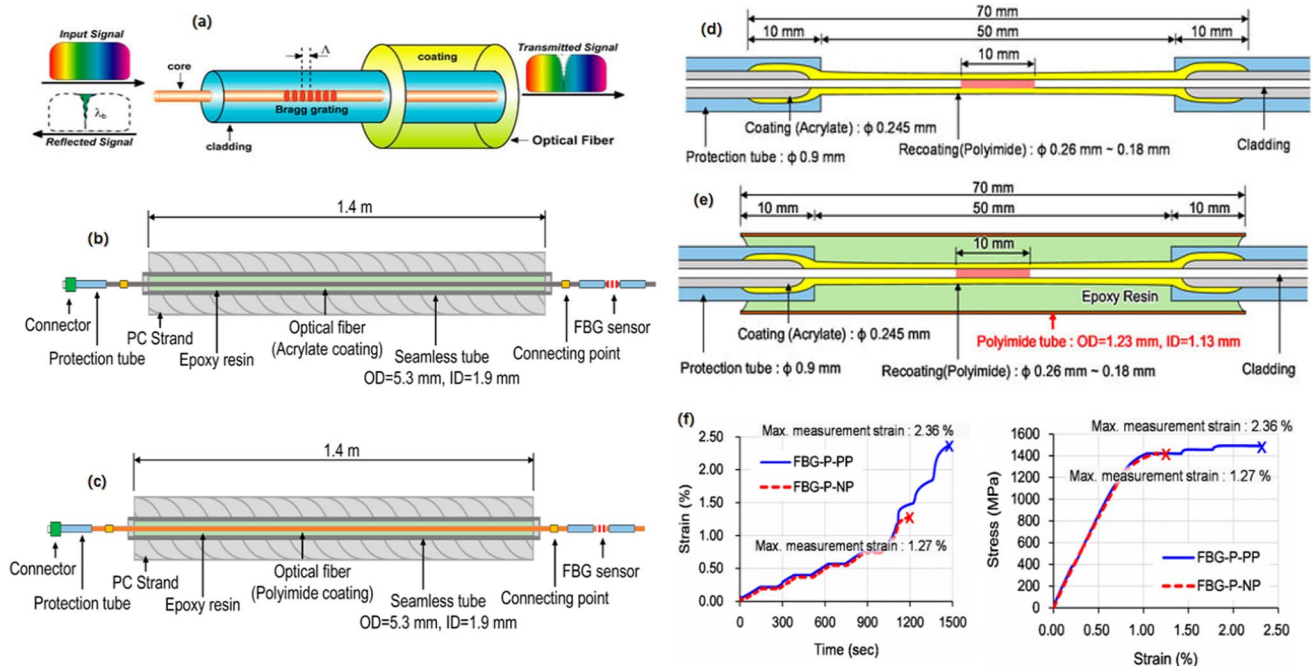


Fig. 5 Fibers strand-embedded recoated with polyimide and acrylate **a** FBG sensor setup, **b** fiber recoated with acrylate, **c** fiber recoated with polyimide, **d** FBG without polyimide tube, **e** FBG with polyimide tube, **f** representative test result of strains and time curves [84]

fragility of the FBG sensor that can easily be damaged, they suggested that the monitoring of the strain using the FBG sensing system should be performed at the optimum yield strain [46, 77, 78]. These effects can lead to measurement inaccuracies, calibration errors, reduced sensitivity, and permanent sensor damage [20, 77]. However, according to [17, 86] study explored the relationship between moisture concentration, hydrophobic materials, and stress in flip chip ball grid array packages during reflow was explored. Their findings revealed that the use of hydrophobic materials can increase Von-Misses stress. Moreover, [31, 87] researches introduced an FBG-Fabry Perot cavity sensor that simultaneously measures temperature and humidity, making it a versatile tool in agriculture. Also, [88] study compared FBG-based humidity sensors with electrical sensors in a harsh waste environment, showing the superiority of the former.

In an attempt by [52] to detect the humidity with FBG, a sensing system was constructed to measure CO₂ and humidity in a testing chamber (Fig. 6a). Multiple FBG sensors were strategically placed along the central axis, showing the highest sensitivity to CO₂ at 0.585 $\mu\epsilon/\text{vol}\%$ CO₂ and to humidity at 4.191 $\mu\epsilon/\%$ RH. During testing, the temperature was maintained at 20.0 ± 0.5 °C with great care [52].

According to the authors, as the humidity levels increased from 2.2% RH to 85.0% RH (as shown in Fig. 6b, c), the sensors displayed wavelength shifts of 463 pm and 282 pm, respectively. Additionally, dynamic sensing response curves of the sensors across the same humidity range were also displayed in (Fig. 6d, e). It is essential to mention that the sensors' response curves matched up precisely with the humidity levels detected by the hygro-thermograph (indicated by the blue dotted line). The response values of the sensors were collected from (Fig. 6d, e), which display the varying humidity conditions, and their corresponding linear fits are depicted in (Fig. 6f, g).

Groundwater salinity can be measured accurately using the PI capillary coating method because the pre-treatment techniques can enhance the salt sensitivity of the coating procedure, and there is no noticeable variation in salinity sensitivity across batches [89]. The wavelength of the P-FBG (polyimide coated FBG) is positively correlated with the temperature, and higher salinity sensitivity leads to greater temperature sensitivity. In gravel aquifers, the enclosed P-FBG salinity sensor provides a high level of accuracy in measuring both salinity and temperature. To validate the applicability of the P-FBG salinity sensor, further practical

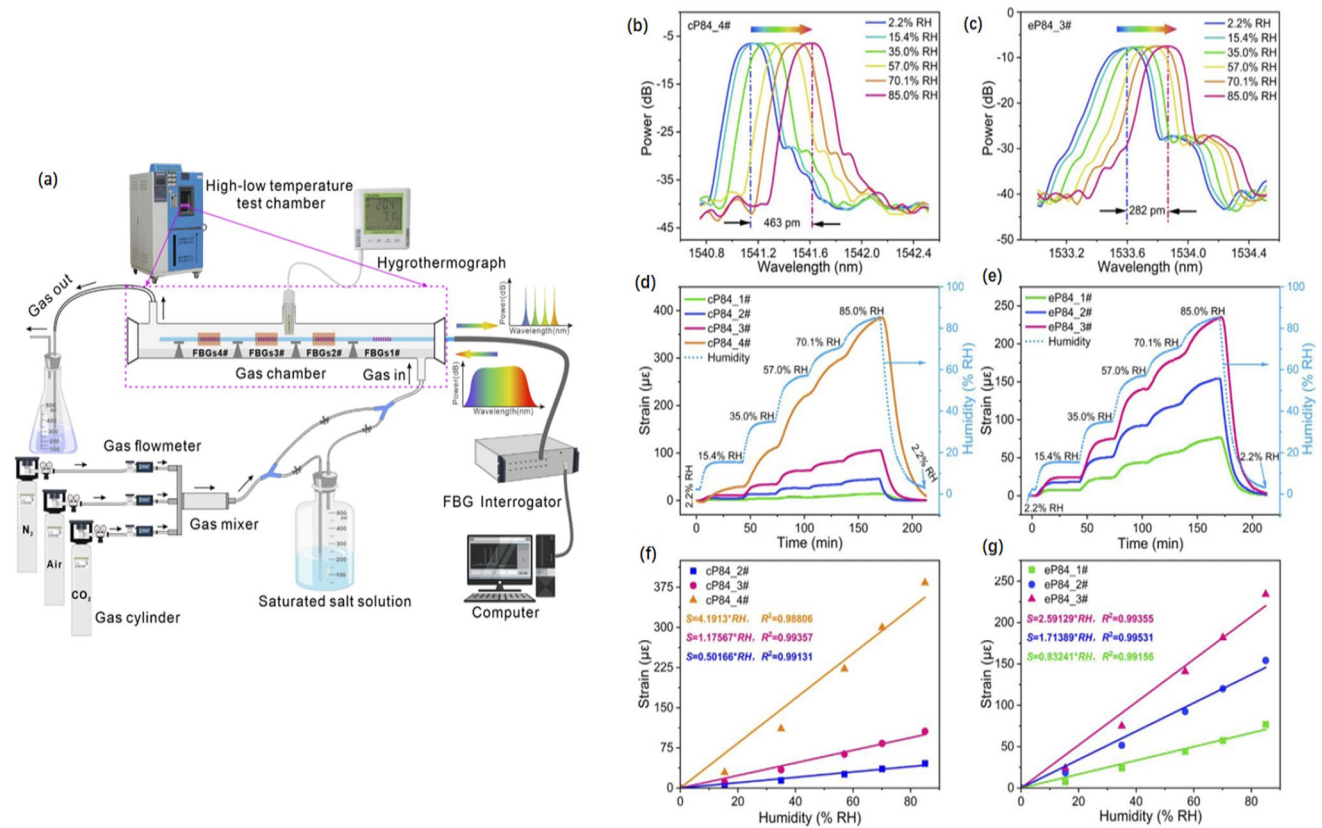


Fig. 6 Comparison of FBG-based sensor **a** experimental sensing setup system with FBG sensor, **b** and **c** show wavelength shifts of sensors; **d** and **e** display dynamic sensing response curves of sensors

with humidity **f** and **g** show response strains and sensors in response to humidity under pure N₂ conditions at room temperature [52]

test should be carried out to investigate reasonable layout methods for long-term monitoring of groundwater salinity in coastal aquifers.

It should be noted that FBG sensors are often coated with materials specifically designed for humidity sensing applications. These coatings are typically hydrophilic and have a high affinity for water molecules [20]. They are designed to enhance the responses and sensitivity of the sensor to changes in humidity. The response of FBG sensors to water content is similar to that of humidity, as water content is essentially a measure of the moisture volume available in a material [90, 91]. However, the response can be more complex due to factors such as water absorption and desorption kinetics, as well as the presence of other substances in the material [92]. In some cases, FBG sensors can exhibit hysteresis in their response to changes in humidity or water content. Hysteresis refers to the phenomenon in which the sensors output does not follow the same path during increasing and decreasing levels of humidity or water content. This behavior can be attributed to the time-dependent nature of moisture absorption and desorption processes.

4 Recent Applications of FBG in Humidity Detection

4.1 Review of Studies Utilizing FBG Sensors for Humidity Monitoring

FBG sensors are an attractive option in various fields including agriculture, due to their ability to measure and monitor different environmental parameters with high accuracy, reliability, and immunity to electromagnetic interference, making them promising for agricultural field [46, 93]. These sensors can be effectively embedded in the soil to track soil moisture levels and temperature fluctuations, thus helping farmers in optimize irrigation practices and ensuring optimal crop growth [74]. In addition, they can be conveniently attached to animals to monitor their health and identify any abnormal behaviors. In the realm of agricultural structures, FBG sensors play a crucial role in monitoring structural integrity to prevent costly repairs, as well as measuring air quality, water quality, and pesticide levels to ensure sustainable practices. However, it is essential to recognize that the initial costs associated with sensor installation and maintenance can be substantial. Despite this, the long-term benefits of improved efficiency and productivity often outweigh the initial investment. Another parameter measured by FBG sensors is the humidity, which is very important in agricultural practices as it directly affects plant growth, enhanced soil performance and overall productivity. However, there are still limitations and challenges associated with the use of FBG sensors, such as a limited range of measurable humidity levels and the

potential for signal attenuation over long distances. When FBG sensors are embedded in concrete to measure humidity in real-time, the results indicate that they provide precise and reliable measurements and the data can be utilized for quality control and optimizing the curing process [2]. To meet food demand while ensuring environmental preservation, efforts are underway to improve and refine agricultural practices. A key component of effective environmental monitoring is the use of reliable sensing techniques, such as FBG sensor technology, which has proven to be invaluable in this regard, particularly for critical applications [10]. By employing a tilted polyimide-covered FBG, the gradient-boosting regression approach enables the simultaneous monitoring of important environmental parameters, such as temperature and humidity [10, 94]. This technique is particularly well suited for predicting both temperature and humidity in real-time, as it offers enhanced performance metrics. Thus, it is highly useful for tracking these variables simultaneously.

Studies by [95, 96] on using FBG sensors to monitor real-time temperature and relative humidity in greenhouses with a sensor network that embedded FBG sensors at various locations within the greenhouse structure found that FBG sensors provide accurate and reliable measurements, facilitating precise greenhouse climate control. [97] Devised a sensor system that utilized FBG sensors implanted at different levels within the soil to effectively monitor soil moisture levels in agricultural settings. Their findings indicated that the data collected from the FBG sensors resulted in more efficient irrigation practices, improving water management, and higher crop yields. Another study created a sensor system that merged FBG sensors with an automated irrigation control system by [81], proving that precision irrigation with FBG sensors considerably reduced water consumption while ensuring ideal soil moisture levels for plant growth. FBG sensors have been widely incorporated into agricultural production for a range of purposes, encompassing crop monitoring, livestock management, structural health monitoring, and environmental surveillance. Farmers may find it beneficial to seek assistance from data analysts or agricultural experts to interpret the extensive amount of data collected by these sensors. Regarding future prospects, the application of FBG technology in agriculture holds promise in the development of wireless sensor networks and the enhancement of data analysis algorithms, thus allowing more precise decision making.

In their research, [98] has produced a updates fiber optic sensor that accurately measures temperature and humidity levels. This sensor can detect humidity levels between 30 and 60% humidity and temperatures between 15 and 65 °C. The humidity sensitivity of the sensor is 22.07 pm/%RH, and its temperature sensitivity is 9.98 pm/°C. To further enhance its functionality, researchers are exploring the possibility of coating the grating area or adjusting the sensor layer's

positioning on the FBG. Another suggestion [49] is to utilize a humidity fiber sensor on both ends of an FBG coated with polyimide. This sensor can measure humidity levels from 25% RH to 95% RH and has significantly improved long-term stability at an environmental temperature of 25 °C. Despite the sensors' good linearity and sensitivity, they remain susceptible to environmental temperature changes. A hygroscopic substance can be applied to the grating to create an FBG-based relative humidity sensor; the swelling impact of the moisture-sensitive polymer's volume expansion results in a change in the Bragg wavelength (Fig. 7a). Because of the inherent temperature dependency of Bragg wavelength, this shift occurs in the presence of temperature changes. A polymer coated FBG responds by superimposing the effects of temperature and relative humidity in a linear way [99, 100]. Thus, the Bragg wavelength shift can be represented as a linear equation when temperature and relative humidity levels fluctuate.

$$\frac{\Delta\lambda_{Brag}}{\lambda_{Brag}} = S_T\Delta T + S_{RH} \times \Delta RH \quad (4)$$

where S_{RH} is the relative humidity and S_T is the temperature sensitivities of the coated FBG.

It is crucial to acknowledge that coated FBGs possess an innate sensitivity to variations in temperature and humidity. As a result, obtaining precise relative humidity measurements requires the use of suitable techniques that can distinguish the enhancement of humidity and temperature within the sensor readings. This technique, commonly known to as temperature compensation, usually involves obtaining a temperature reading as close to the humidity sensor location

as possible [101, 102]. The mechanism of this sensor shows that a hygroscopic substance can be applied to the grating to create a relative humidity sensor where the swelling impact of the moisture-sensitive polymer's volume expansion shifts the Bragg wavelength. Temperature changes cause this shift, which puts the FBG under longitudinal strain. Another option is the thermal effect, which combines the thermal-optic effect and the thermal expansion of the material.

According to (Fig. 7b), the humidity deviation is within $\pm 3\%$ RH, the declared accuracy of the capacitive sensors. This meets the requirements established by the compact muon solenoid experiment [101]. Minor variations in relative humidity readings between FBG and standard hygrometers can impact dew point calculations. This is especially noticeable in (Fig. 7c) when the volume contains dry air. In such cases, both sensors function outside of the recommended operating range. During shallow humidity conditions, it is challenging to determine which dew point temperature measurement is the most precise. Therefore, it can only be concluded from the experiment that both sensors detect dry air within the volume.

Furthermore, FBG is thermally sensitive, so a thermal compensation scheme is necessary, as an uncoated Bragg grating can be used as it is insensitive to humidity variations [33, 58]. Liu et al. [103] placed the sensor in a testing chamber for humidity testing, where the chamber humidity control was accurate to within $\pm 1\%$ RH, and set the humidity range from 40 to 90%RH, with the temperature maintained at 25 ± 0.1 °C. During the test, they monitored the reflection spectra as the humidity increased in increments of 10%RH, and kept each humidity level constant for at least

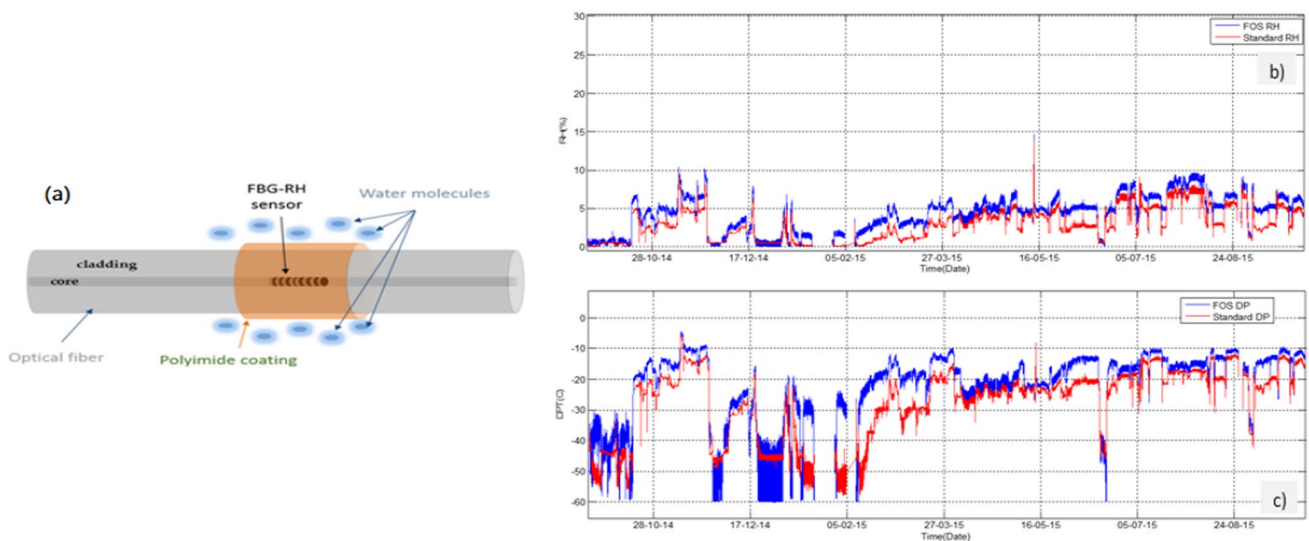


Fig. 7 Coating FBG sensor for humidity detection **a** FBG-coated relative humidity sensor, **b** RH results, **c** dew point construction from FBG based thermos-hygrometer [101]

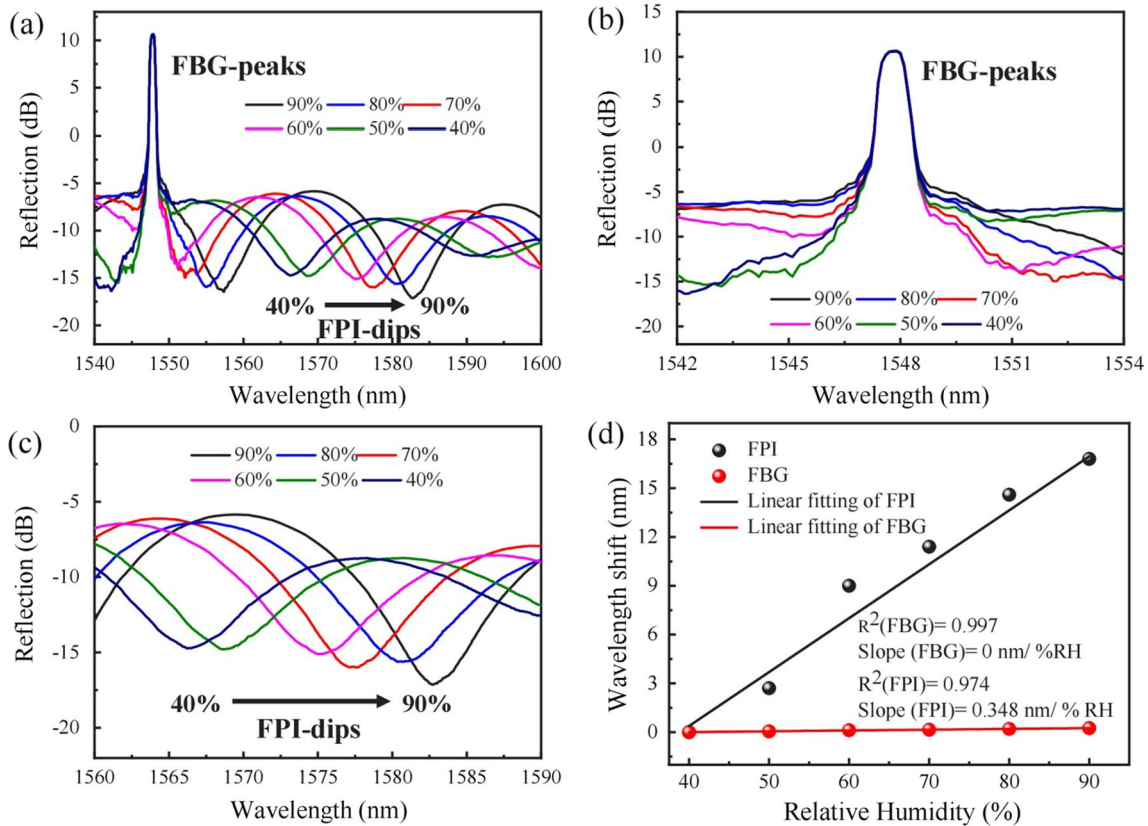


Fig. 8 Humidity responses of the FBG-FPI sensor: **a** reflection spectra increased from 40 to 90%RH, **b** FBG peaked zoomed in **c** zoomed-in FPI-dip, **d** linear fitting of humidity testing results [103]

15 min to ensure the sensor's output had stabilized. Figure 8a shows two Fabry–Perot interferometer (FPI) dips and an FBG peak on interference spectra in the 1540–1600 nm wavelength range. As humidity increased, the FPI-dip wavelength (approximately 1575 nm) shifted by 8.78 nm toward the red, while the FBG-peak wavelength remained almost unchanged. Figure 8b shows that the FBG peak remained steady regardless of humidity changes.

In contrast, in (Fig. 8c), the FPI-dip wavelength shifted by 8.78 nm due to micro-cantilever expansion caused by increased humidity which led to differences within optical path of the reflected light and a shift in the reflected spectrum through the resonant wavelength. Based on the parallel measurements ($N = 5$) of the corresponding FPI-dip wavelength shift, the error was less than 10% for each humidity level. The results of the humidity test were linearly fitted and are depicted in (Fig. 8d). The FPI sensing part exhibited a remarkable humidity sensitivity of 0.348 nm/%RH ($R^2 = 0.974$), while the FBG part demonstrated a negligible humidity sensitivity. These test results are indicative of the high humidity sensitivity of the FPI sensing part [103].

Additionally, a proposed method by [41] involves the establishment of an online procedure for deploy a large-scale distributed humidity sensor using a P-FBG (polyimide

coated FBG) array based on an optical fiber drawing tower. The data indicates that the PI-FBG array exhibits a humidity sensitivity ranging mostly between 1.3 and 1.5 pm/%RH, with an average sensitivity of 1.4 pm/%RH and a linearity of 99% or higher. The P-FBG array humidity sensor demonstrates consistent and reliable short-term stability fluctuations as a coating material for the optical fiber humidity sensor. Each humidity sensor within the P-FBG array exhibits an accuracy deviation of less than 2%RH, which indicate excellent humidity measurement accuracy. Further advancements in the drawing and coating processes can potentially enhance the sensitivity and consistency of the P-FBG array humidity sensor. Hygroscopic materials have a strong affinity for water molecules and readily absorb or release moisture depending on the ambient humidity level [13]. When the hygroscopic coating absorbs moisture, it swells and causes a strain on the FBG sensor. This strain changes the reflected wavelength, which can be measured and correlated with the humidity level. In an experiment by [40], the FBG was tested at a temperature of 25 °C. Figure 9a shows a limited portion of single-mode optical fiber that has a regularly modulated refractive index, known as the FBG structure. Figure 9b shows that the sensitivity of all materials increases with thickness. To optimize the absorption properties of the

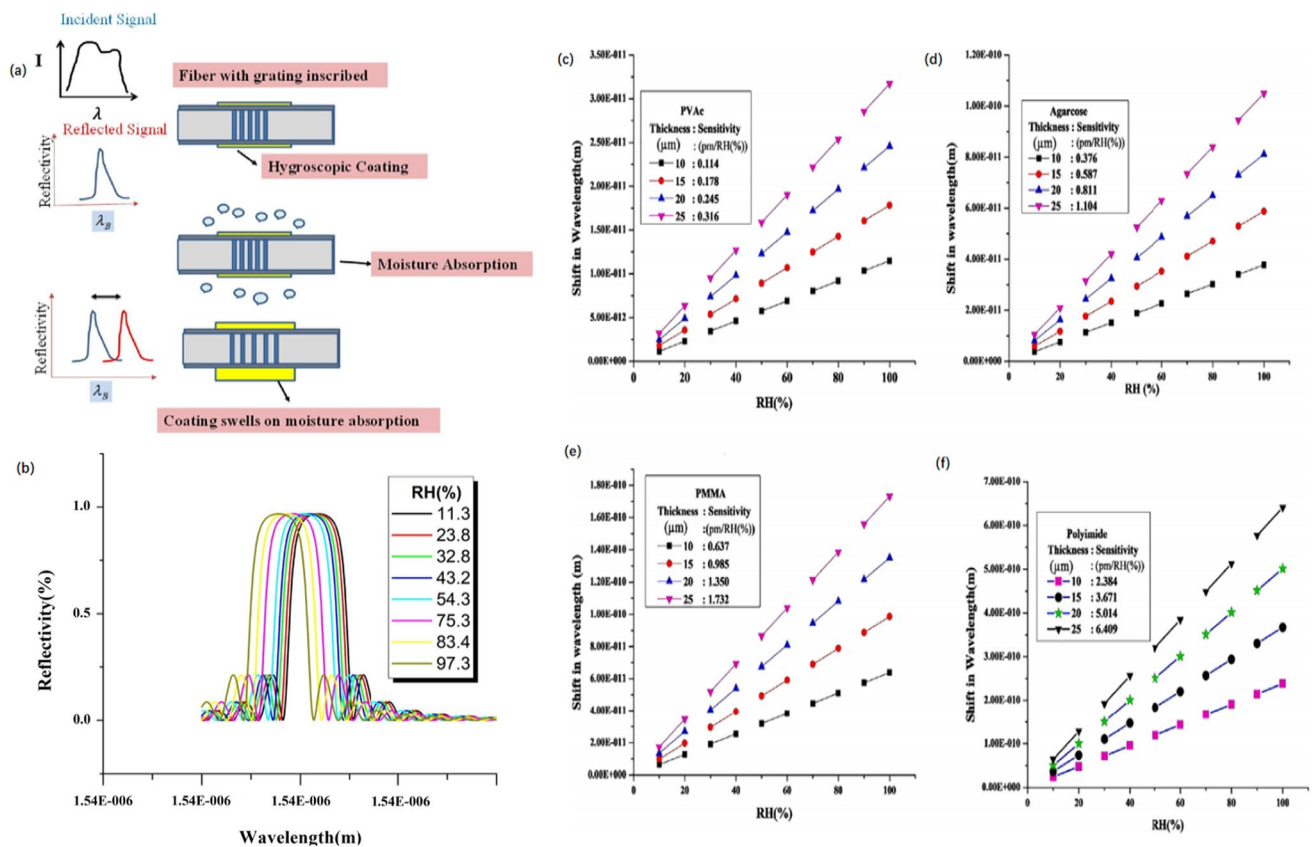


Fig. 9 FBG Humidity-based sensor **a** hygroscopic polyimide coating setup, **b** FBG shift, **c** wavelength shift for the tested materials [40].

materials, the thickness of the coating is carefully adjusted. The FBG was coated with different materials of varying thicknesses and then subjected to fluctuations in humidity levels ranging from 11.3 to 97.3% humidity. The study's authors [40] analyzed the FBG response time and discovered that the FBG used experienced a red shift in wavelength response as humidity levels increased. (Fig. 9c–f) shows the reflected properties of the proposed FBG for different humidity levels.

According to research by [104], a film composed of porous silica xerogel applied to an MMF using the sol–gel technique can gauge humidity levels. The film sensitivity ranges from 0.079 a.u./nm/%RH to 0.088 a.u./nm/% humidity, with a limit of detection of 4% humidity, a response time of 10 s, and a dynamic range of 4–100% humidity. The film's sensing mechanism relies on the multi-mode fiber's alteration in reflectivity as the silica xerogel film absorbs water molecules. In a separate study [105], an examination was carried out on the impact of the size of silver nanoparticle in polyaniline composite for humidity sensing. The configuration that proved to be the most efficient had a response time of 30 s, a sensitivity of up to 28.78 millivolts per percentage of relative humidity, and a dynamic range of 5–95% relative humidity [69]. Hence, it is recommended to use a dual FBG

structure to improve resistance to changes in temperature and humidity that will involve separating the reference FBG from the one used for measurement [106, 107]. According to research, humidity can affect the wavelength shift of a grating that is under strain differently than a strain-free FBG [108]. To ensure that FBG use humidity sensors are effective, it is essential to assess several factors, including sensitivity, response time, linearity, hysteresis, repeatability, stability, and temperature dependence. These sensors are vulnerable, but offer quick response times and are very stable; making them ideal for situations that requires accurate and dependable humidity measurements.

Polymer humidity-sensitive materials such as chitosan [109], agarose [59], Nafion [110], polyvinyl alcohol [111], and polyimide [98] can be used to create films that expand as they absorb water molecules, making them ideal for high-humidity environments. When the FBG is coated with a polyimide section, it becomes susceptible to changes in humidity in its surroundings. As the moisture level increases, the polyimide expand and as it decreases, the polyimide contracts. This expansion and contraction strains the FBG, leading to a change in its wavelength. The relationship involving the central wavelength shift of FBG and the change in humidity levels may be expressed [3].

In their comparative experiments, it was discovered that incorporating graphene film into FBG humidity sensors based on polyimide films can significantly enhance their sensitivity [93]. In addition, the sensors boast a compact structure, good repeatability, and promise for potential humidity measurement applications. Adding moisture-sensitive dopants to the fiber core or cladding allows for measuring humidity or water content with great accuracy [57]. Alternatively, nanostructured coatings can be customized to have a high sensitivity to moisture or water vapor by adjusting their surface properties and composition [57, 112]. Applying these coatings to the FBG sensor results in wavelength changes when exposed to humidity or water vapor, making it possible to precisely measure humidity or water content precisely [113].

An experiment was carried out using an electron microscope to determine the thickness of the polyimide coating, and their findings show that the thickness of the coating is directly related to the number of repetitions [98]. Achieving a smooth and uniform polyimide film is significantly dependent on the dip coating rate. Through experimentation, we have discovered that a consistent film can be achieved with a rise and fall rate of 10 $\mu\text{m/s}$. As demonstrated in (Fig. 10b) with a diagram of the dip-coating process configuration system and their experimental setup, as shown in

(Fig. 10a), includes a light source, FBG wavelength confirmation unit, semiconductor optical amplifier, optical circulator, polyimide-coated FBG sensor array, saturated salt solutions, etc.

The spectrum of the sensor array in (Fig. 10c) is known to change in response to fluctuations in relative humidity. The reflection of signals from the five sensors was expected to produce a wavelength shift that corresponded to the RH change. These five FBGs were created under identical conditions and shared nearly identical optical properties, including a similar center wavelength. Despite overlapping in frequency, the reflected spectrums of the five RH sensors could be distinguished in the time domain. However, the optical spectrum analyzer could not provide complete information on the condition of each RH sensor along the cable, including the wavelength shift. In their experiment, a wavelength demodulation system was used with TDM technology was used to evaluate the changes in wavelength of each RH sensor based on FBG, when exposed to varying levels of humidity. The reflected spectra of all five sensors in the array were analyzed, as illustrated in (Fig. 10d). These sensors were placed inside a container with a humidity level of 83.4%. Using the equation, the peak wavelengths were calculated, resulting in measurements of varying orders. The use of fused deposition modeling with polylactic acid

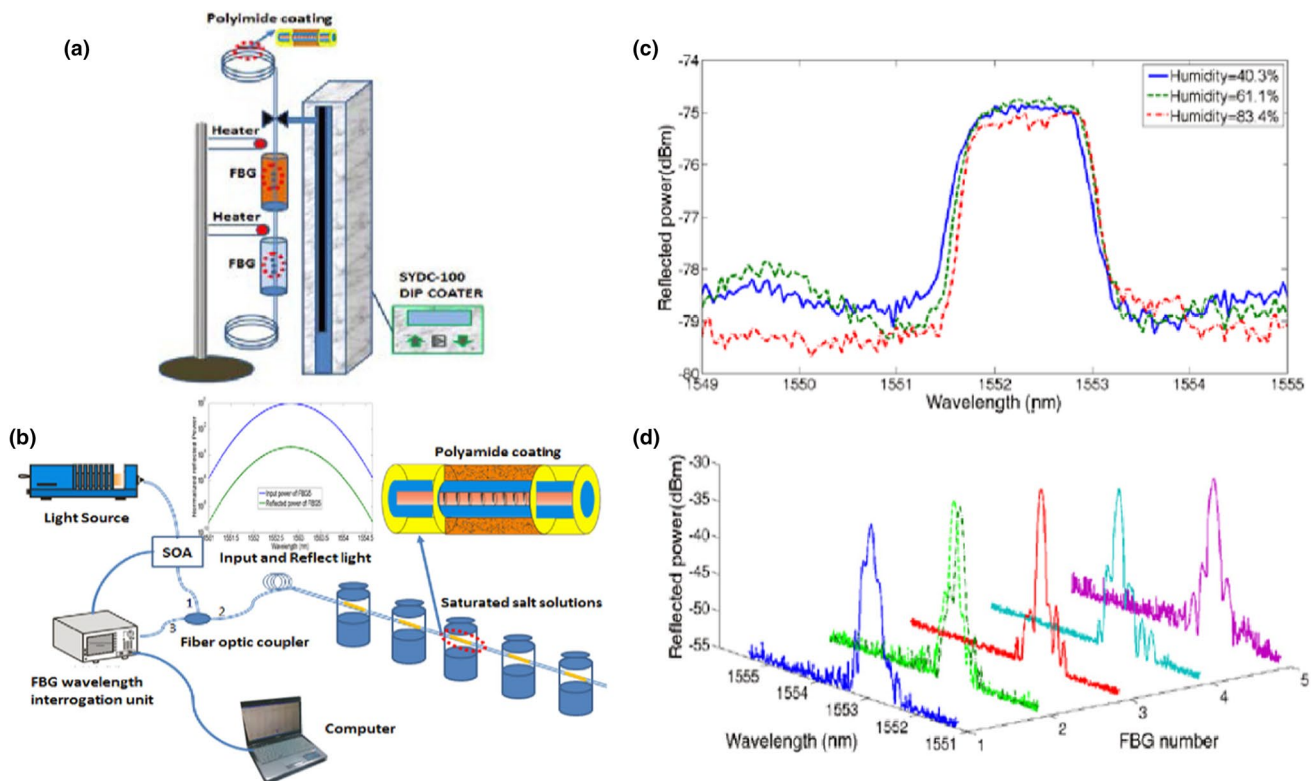


Fig. 10 FBG detection for humidity measurement **a** dip-coated polyimide FBG chain, **b** set-up, **c** spectral overlap of humidity sensors, **d** humidity sensors at level of 83.4%

(PLA) material to construct FBG pressure sensors has been studied by [35] and [114]. Also, [115] discovered that the sensing performance of FBG sensors was not affected by their embedding in melted PLA materials. Another experiment was demonstrated on how to use bare FBG sensors to measure tilt angles using the FDM method where the focus was on fusing FBG sensing technology with 3D printing to produce a tilt sensor.

5 Recent Applications of FBG in Water Content Detection

5.1 Review of Studies Using FBG Sensors for Real-Time Water Content Measurement

Accurately measuring water content is crucial in various fields such as agriculture, environmental monitoring, and civil engineering, and FBG sensors have undergone extensive research regarding their practicality and efficacy in real-time measurement. These investigations have explored various aspects such as sensor design, calibration techniques, and field applications. FBG-based water content sensors offer numerous advantages over traditional methods of water content measurement, including higher accuracy, real-time monitoring capabilities, and the ability to measure water content at multiple depths (Table 2). Phase-shifted FBGs were found to create a sensor with reliable measurements and higher resolution in various temperature and humidity environments [116]. However, a novel humidity optical sensor set-up that uses cascaded and spectrally overlapped FBGs to respond effectively to changes in relative humidity while minimizing temperature sensitivity has also been reported [7]. Another study by [9] involved encapsulating urea granules with EC and coating FBGs with AgNP to monitor the gradual release of urea in soil and water using FBG sensors. AgNP-coated FBGs were specifically used to monitor the slow release of urea in soil and water, while the release rate of EC-coated urea granules was determined through a water test using different operating wavelengths. During the controlled-release process in water, the FBGs exhibited changes in Bragg wavelength, respectively. These findings highlight the effectiveness of FBG sensors as a valuable tool for monitoring urea emissions in soil and water. It was also confirmed that a coating-based FBG humidity sensor with optimized sensitivity and rapid response is efficient for adequate detection of water content, as the investigation also looked at the versatility of the coating in terms of sensing different chemical components [4, 10]. A fiber optic humidity sensor with an excellent linear response to humidity was proposed by [54, 93, 117] which was based on a cascaded chirped FBG Fabry–Perot interferometer coated with a humidity-sensitive film. Furthermore, [118]

utilized taper technology to develop a chirped microstructure FBG for strain-sensing applications, while [119] explored the temperature and strain sensitivities of two different undoped polymer optical fibers and their inscription times. In an attempt to analyze the utilization of FBG sensors for measuring water temperature by [28], study were carried out in the range of 4 to 25 degrees Celsius by using FBG sensor which exhibited exceptional responsiveness, accuracy, and a sensitivity of 0.0101 nm/°C. This characteristic makes it suitable for applications in water engineering, environmental monitoring, and industrial settings, because of its stability and rapid response time. The findings contribute to the advancement of technology for precise and instantaneous measurement of water temperature, enabling meticulous monitoring across diverse applications. However, more research is needed to understand its performance in various climatic conditions and a wider temperature range.

Numerous scientific studies have been carried out to increase sensor precision and reliability of sensors, such as [76, 125] who focused on utilizing long-period gratings (LPGs) in conjunction with FBGs to enhance water content measurements. The resulting hybrid LPG-FBG sensor demonstrated superior performance over conventional FBG sensors, delivering highly accurate and dependable measurements [20]. Achieving precise measurement of water content through FBG sensors necessitates meticulous calibration techniques. Multiple studies have suggested various calibration methods to establish a correlation between the measured wavelength shift and the actual water content. As an illustration, researchers [77, 83, 91] have formulated a calibration model utilizing artificial neural networks (ANNs), which can effectively forecast the water content with the use of FBG sensors [81]. The ANN model exhibits immense potential for real-time monitoring applications through data collection, preprocessing, feature extraction, model training, model validation, and deployment and has yielded results consistent with empirical data [126–128]. ANN has used FBG sensors to improve the accuracy of water content forecasting in soil moisture monitoring, water resource management, land assessment, and infrastructure health monitoring [129–131]. The study of Alshaiqli, et al. [4] revealed that FBG sensors demonstrated enhanced linearity performance under varying humidity conditions where the percentage errors for these conditions were reduced. By incorporating ANN technology, the accuracy and sensitivity of the FBG sensors were significantly improved, making them suitable for a wide range of applications including structural soil monitoring, crop production, and food processing. Their study suggested that the use of ANN-based FBG sensors could effectively enhance the performance of fiber optic sensors, particularly in the realm of environmental monitoring and related fields. However, future research should focus on exploring different coating materials and grating configurations based on

Table 2 Comparative assessment of FBG-based water content sensors with traditional methods

Parameters	FBG-based water content sensor	Traditional methods	Mechanisms	References
Sensitivity	FBGs are made of a single mode fiber that is sensitive to strain, allowing for accurate measurements of water content changes	TDR and capacitive sensors are less sensitive and may not detect small changes in water content	Studies have shown that FBG-based water content sensors can achieve sensitivities as low as 0.01% volumetric water content (VWC), making them suitable for a wide range of applications [8]	[120]
Response time	FBG-based water content sensors have a fast response time, typically within milliseconds, allowing for real-time monitoring of water content changes	Slower response time, typically within seconds or minutes	Studies have reported response times ranging from milliseconds to seconds for FBG-based water content sensors, making them suitable for real-time monitoring applications [90]	[62, 90]
Accuracy	FBG-based water content sensors have shown high accuracy in measuring water content, with errors typically within $\pm 5\%$	Higher errors, typically within $\pm 10\%$	Studies have demonstrated that FBG-based water content sensors can achieve accuracies as high as $\pm 0.5\%$ VWC, making them suitable for precision applications [121]	[51, 121]
Stability	High stability over time, with minimal drift or aging effects	Higher drift or aging effects, particularly in harsh environments	Studies have shown that FBG-based water content sensors can maintain their performance over long periods without significant degradation [88, 90]	[54, 85, 122]
Cost	FBG-based water content sensors are relatively low-cost compared to traditional methods, particularly when considering the long-term cost of ownership	TDR and capacitive sensors, may have higher upfront costs and require more frequent maintenance and replacement	The long-term stability and durability of FBGs can contribute to cost savings by reducing the need for frequent recalibration or replacement [27]	[14, 51, 123]
Durability	Highly durable and can withstand harsh environmental conditions, such as high temperatures, humidity, and vibrations	More susceptible to environmental factors and have shorter lifetimes		[15]
Coverage	FBG-based water content sensors can measure water content over a wide range of applications, including soil, crops, and water resources	Limited coverage and applicability		[124]

ANNs to further enhance the performance of FBG sensors in humidity and temperature applications.

Furthermore, Liu et al. [39] conducted outdoor model experiments and utilized thermodynamic principles to investigate the inaccuracies in water content measurement using the AH-FBG (active heated-FBG) method. The findings suggest that the approach with the maximum temperature increase value [$\Delta T_{\max}(\theta)$] approach exhibits superior accuracy for gas and soil, but significant measurement errors persist for biochar mixed soil. The errors in water content monitoring are due to variations in heat power and longitudinal heat transfer during heating, which are influenced by initial ground temperatures and water content gradients. By successfully implementing four ANN models, the researchers developed the AH-FBG-ANN approach as an enhancement to the conventional data analysis method. The precision of monitoring is highly influenced by the cover conditions, which also impact the gradients of the soil water content and initial ground temperatures. Therefore, considering the cover layer is crucial for field monitoring [132]. Additionally, etching-based methods serve as an alternative means of creating FBG sensors capable of detecting humidity and water content, which involves selective etching of the fiber cladding

surrounding the FBG to unveil the core region [133]. A new sensor configuration has been designed to measure the water content and temperature in tanks with different densities of liquids, including aircraft fuel, biochemicals, and explosives [134]. Throughout an experiment conducted, the water content in the soil was methodically increased from 0 to 4% until a fully saturated state of 24%. As demonstrated in (Fig. 11a), the relationship within the water content of one sensor during calibration and the wavelength shift of FBG sensors [91]. The graph reveals that the wavelength of the FBG sensors gradually altered as the soil absorbed water from the pressure–volume controller. However, the wavelength increased drastically once the water content exceeded 12%, eventually reaching saturation at 24%.

During the monitoring process, it was observed that the FBG sensor exhibited a trend in the variation of water content that was comparable to that of the conventional sensor at a depth of 0.2 m. This indicates the proper functioning of both sensors, as depicted in (Fig. 11b). The pressure sensors displayed changes aligned with the recorded precipitation of the rainfall gauge, but differed from the variation in water content. These discoveries offer substantial proof of the effectiveness of pressure sensors. Based on observations from the

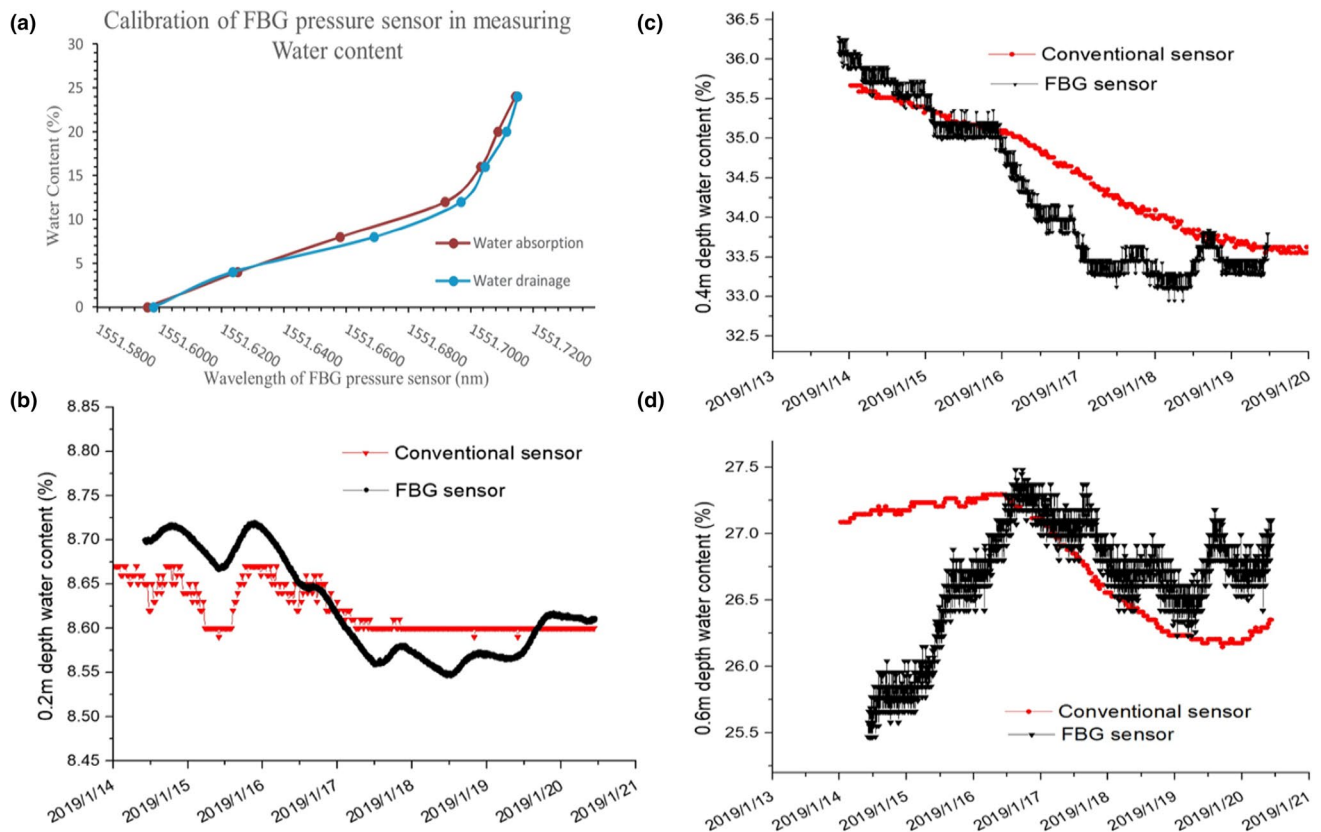


Fig. 11 FBG water content sensor detection **a** measuring water content of soil with calibration of FBG sensor, **b** comparison at depth 0.2 m, **c** comparison at 0.4 m, **d** comparison at 0.6 m [91]

authors [91], it was discovered that the ground tends to dry more rapidly during early morning and night due to cooler temperatures and the absence of direct sunlight. (Fig. 11c and d) illustrate the increased drying rates during these particular periods. FBG sensors have found diverse applications in measuring water content in environments such as soil, concrete, and structures. These investigations aimed to verify the efficacy of FBG sensors under real-world conditions and evaluate their dependability for long-term monitoring. Notably, studies [135] conducted a field study utilizing FBG sensors to observe soil water content in an agricultural field. The results demonstrated that the FBG sensors delivered precise and uninterrupted measurements, underscoring their potential for precision agriculture and water resource management.

In addition to individual studies, comprehensive reviews and meta-analyses consolidate the findings of several studies on FBG sensors for water content measurement. These reviews provide a broader perspective on the current state of research in this field and identify promising areas for future exploration. A review was also conducted to examine the obstacles and prospects of employing FBG sensors for soil moisture monitoring, underscoring the need for uniform calibration procedures and sensor deployment strategies [91]. Recent studies in utilizing FBG sensors to monitor water content in real time have yielded promising results. Advances in sensor design, calibration methodologies, and on-site implementation have paved the way for more reliable and precise water content monitoring systems [136]. These advancements have improved the accuracy, sensitivity, and efficiency of measuring the water content in different mediums [63, 137]. As a result, industries such as agriculture, environmental monitoring, and water resource management can benefit from more accurate data for decision making and resource optimization [127, 136]. However, further research must address certain obstacles, including sensor drift, long-term stability, and scalability for large-scale applications.

In conclusion, FBG-based water content sensors provide many advantages compared to traditional measurement techniques, including fast response time, accuracy, stability, sensitivity, and potential cost savings in the long run. These sensors have been extensively studied and proven to be effective in various applications. However, it is important to note that the performance of FBG-based water content sensors may vary depending on factors such as sensor design, calibration methods, and environmental conditions.

6 Feasibilities Comparison of FBG Sensor over Other Sensing Technologies

With their unique operation based on wavelength modulation, FBG sensors are a special kind of sensing technologies that provide accurate readings in a range of environmental

situations. With features such as multiplexing, high precision, and distant sensing, they are advantageous for a range of measuring different parameters simultaneously, reducing the cost and complexity of agricultural monitoring systems. However, they require specialized equipment and expertise to install and maintain, making them more expensive than traditional electrical sensors in the short term [138]. However, their long-term benefits, such as their durability and low power consumption, offset these initial costs. FBG sensors may be used in high-temperature and high-radiation situations because they are resistant to electromagnetic interference. Depending on the particular needs of the application, the cost and complexity of other sensing technologies may change. The particular needs of the application, such as precision, environmental conditions, economic concerns, and scalability, determine whether FBG sensors or other sensing technologies are best. Based on data gathered from the existing literature, it was confirmed that when soil moisture measurement techniques are compared, it becomes clear that existing approaches are not up to the task of providing quick, accurate, automated, geographically dispersed readings that take into account factors unique to each soil (Table 3). These problems include the reliance on frequency, time commitment, and calibration for a particular location, problems with salinized soils, mobility challenges, health risks, and expensive equipment expenses. Techniques such as TDR and FDR currently on the market are unsuitable for this use. Presti et al. [11], confirmed that FBG can track the development of plants as well as real-world environmental variables such as humidity and temperature. The encouraging results demonstrate the practicality of FBG-based sensors in practical settings, which holds promise for the advancement of precise and continuous methods for monitoring plants health growths and development.

FBG sensors are superior to traditional electrical sensors due to their resistance to electromagnetic interference, making them ideal for agricultural environments (Table 4). They are smaller and lighter, making them easier to deploy in large numbers. Because of wavelength division multiplexing, FBG sensors also have increased sensitivity, which enables them to detect minute variations in the surrounding medium. This property makes them appropriate for accurate measurements such as temperature and moisture monitoring in the soil water content and humidity. Due to its sensitivity to strain and temperature fluctuations, its potential for grating functionalization with moisture-activated polymer for changes in relative humidity, and its multiplexing capacity, FBG technology is perfect for plant sensing [40, 59, 61]. These characteristics could provide special advantages for compact sensor systems, allowing the simultaneous monitoring of environmental factors and plant development in the agricultural industry. Furthermore, the results of using an FBG sensing-based quasi-distributed optical fiber sensing

Table 3 Comparison some sensing technologies in humidity and soil water content measurements

Sensor technologies	Flexibility	Response time	Measured parameter	Principles	Depth of measurement	Major specification
FBG sensor	In situ/Lab	Nanoseconds	Volumetric soil moisture content	Electromagnetic wavelength	Any depth	
TDR (time domain reflectometer)	In situ/Lab	28 s	Volumetric soil moisture content	Dielectric constant	0.3–0.6 m	Operating frequency 10–150 MHz
Tensiometer	In situ/Lab	2–3 h	Suction	Suction or negative tension created	0.15–0.6 m	0–1 atm (0–100 kPa)
Resistive sensor	In situ/Lab	2–3 h	Volumetric soil moisture content	Electrical resistance	0.1–0.3 m	1–15 atm (100–1500 kPa)
Conventional Thermogravimetric technique	Lab scale	24 h	Gravimetric soil moisture content	Evaporation/chemical action	Any depth	105 °C
Capacitance technique	In situ	Instantaneous	Volumetric soil moisture content	Dielectric constant	1 m	Operating frequency 10–150 MHz
Thermal dissipation block	In situ	2–3 h	Volumetric soil moisture content	Heat dissipation	0.1–0.3 m	50–200 mA
Neutron moisture meter	In situ	1–2 min	Volumetric soil moisture content	Neutron scattering	<0.3 m	Mean energy 5 MeV fast neutron is the input
FDR (Frequency domain reflectometer)	In situ	Instantaneous	Volumetric soil moisture content	Dielectric constant	1 m	Operating frequency 10–150 MHz

system to assess a geogrid reinforced sand slope model shows that the strain distribution of the geogrid could be accurately monitored by FBG sensors and demonstrated an empirical correlation between the strain of the geogrid and the model slope's factor of safety [139, 140]. However, due to the short duration of the test, the study failed to consider the impact of temperature on the FBG monitoring data. Thus, the temperature effect should be taken into account for long-term monitoring utilizing various compensation techniques depending on the field and additional research to determine whether it is feasible to use this technology-based approach to assess the stability of reinforced slopes.

7 Prospective Challenges/Limitations and Future Directions

FBG-based humidity and water content detection face several challenges that need to be addressed to obtain accurate and reliable measurements. Several research studies have confirmed that FBG sensing systems are a practical and reliable option for detecting humidity and water contents in the field. However, it is essential to remember that FBG sensors may only sometimes be the most effective choice. One limitation of FBG sensors is that they can only perform quasi-distributed monitoring, and the number of sensors in series is restricted [43]. FBG is a superior choice for humidity and water content instrumentation due to its precision and real-time measurement. While it is a pricier option, the

cost of FBG is expected to decrease significantly, making it more accessible [33]. Conventional and FBG sensor systems complement each other and are highly beneficial for remote monitoring. Validation of the field performance of FBG sensors requires the use of conventional sensors. However, only a few cases have been reported in which both technologies have been integrated to detect humidity and water contents. Advanced monitoring methods, appropriate sensor layouts, and an intelligent warning system are necessary to effectively monitor and predict humidity and water contents.

Additionally, FBGs have low humidity sensitivity due to the similarity in the refractive index between water vapor and air, which limits their usefulness in precise measurements and calls for improved sensitivity to humidity [141]. FBGs are sensitive to temperature, pressure, and strain changes, which can cause false and inaccurate readings of humidity such as fluctuation in temperature can cause strain expansion with the fiber, thereby causing a shift in the reflectance wavelength [92]. Developing techniques to ensure accurate measurements is crucial. Although FBGs can detect changes in strain or temperature caused by water content, accurately quantifying the absolute water content of a sample still poses a challenge due to the fact that measuring the amount of molecules within a sample is a complex process [82].

FBG sensors can be multiplexed on a single fiber optic cable, allowing the simultaneous monitoring of large agricultural fields at different intervals or close to each other. These microstructures can be sensitive to parameters other

Table 4 Principle and advantages of FBG sensors over the existing sensing techniques

Other sensing technologies	Types	Principles/uses	FBG sensor advantages
Electromechanical sensors	Strain Gauges Load cells	Measure strain by changes in electrical resistance and uses for monitoring soil moisture, temperature, and crop health	Higher sensitivity and accuracy Immunity to electromagnetic interference Multiplexing capability for distributed sensing
Optical sensors	Infrared (IR) and ultraviolet (UV) sensors	detect changes in light intensity or wavelength and use to monitor crop health and environment	Measures temperature, pressure, strain Offers higher sensitivity and resolution Ideal for precision agriculture applications
Acoustic sensors	Piezoelectric sensors Ultrasonic sensors Dynamic microphones	Generate electric charge in response to mechanical stress which is non-contact measurement and high sensitivity to monitor soil moisture, and water quality	High accuracy and reliability No signal processing algorithms needed No external power source required for operation Higher resistance to harsh environments Multiplexing capability for distributed sensing
Chemical sensors	Biosensors pH sensors Electrochemical sensors Gas sensor	For monitoring soil nutrients, pH levels, and crop health, offering high specificity and sensitivity but having limitations compared to FBG sensors	Immune to environmental factors
Wireless sensor networks (WSNs)	Pressure sensors Temperature sensors	More cost-effective for simple pressure measurements but may lack the versatility and accuracy	Measure strain induced by pressure changes Offer high accuracy and stability in temperature sensing Multiplexed for distributed pressure sensing High-precision sensing
	Capacitive sensors	More vulnerable to external variables like dampness and electromagnetic interference, however they are still appropriate for some applications	Immune to capacitance-related interference High accuracy and stability in various environments
	Micro-electro-mechanical systems (MEMS)	Use miniaturized mechanical structures to measure various parameters	Higher accuracy and stability over time Immunity to electromagnetic interference Suitable for long-term monitoring applications
	Accelerometers	Use for vibration monitoring and dynamic measurements	Provide static/dynamic strain measurements Offer temperature sensing Ideal for distributed sensing and high accuracy applications

than strain or temperature, making it possible to create multifunctional sensors to measure pressure, acceleration, and displacement [107]. By using a single optical source, it is possible to address each sensor, and adding more sensors to the same fiber only results in a minimal loss of signal quality, while also eliminating any interference if specific spectral portions of the light spectrum are allocated to each sensor. They also enable remote monitoring and data collection through wireless communication technologies, reducing the need for manual intervention. Advanced data analysis algorithms are being developed to process the vast amount of data collected, facilitating predictive modeling for improved decision-making in agriculture [128, 142]. FBG sensors are being miniaturized to enhance cost-effectiveness and ease of deployment in various agricultural applications. They can measure strain in agricultural structures, monitor soil temperature, improve water management, and assess crop health by measuring leaf temperature, humidity, and light intensity. Integration of FBG sensors in agriculture represents a significant technological advance that enables data-driven decision making and optimizes resource utilization.

On the basis of this review, the future of FBG-based sensors for detecting humidity and water contents will depend on addressing the limitations and challenges to improve their performance and expand their applications. The following potential solutions and improvements on the FBG sensor are recommended:

- Modifying the fiber's surface or coating it with materials that can absorb or interact with water molecules more effectively. This can increase the strain or temperature changes induced by humidity variations, leading to improved sensitivity.
- Exploring novel sensor configurations and signal processing algorithms to minimize cross-sensitivity and improve accuracy of humidity measurements.
- Investigating alternative sensing mechanisms in combination with other sensors such as capacitive or resistive sensors, to directly measure the absolute water content rather than relying on indirect measurements through strain or temperature changes.
- Adoption of advanced techniques or using multiple FBGs with different spectral responses can measure multiple parameters in a single FBG sensor, making it more versatile in various applications.
- Using high-temperature stable materials or a hybrid structure of a high-temperature stable fiber and a standard FBG with a larger core size. Implementing these methods can make FBGs capable of functioning in severe temperatures exceeding 100 °C.
- Developing techniques like narrowband filters, shielded fibers, and reference FBGs can eliminate or reduce the noise. It can improve their accuracy and reliability

because FBGs can encounter various forms of noise, such as thermal, mechanical, and signal leakage.

- Developing advanced techniques includes large-scale fabrication, new materials with built-in gratings, and printing/coating for FBGs, which can significantly reduce the cost and increase the scalability of FBG fabrication, enabling their widespread adoption in various applications.
- Integrating FBGs with microelectromechanical systems, nanotechnology, and artificial intelligence to create advanced sensing systems. This integration will enable the measurement of dynamic parameters, real-time monitoring, and sensor data analysis and expand the potential applications of FBGs in industries such as healthcare, aerospace, and automotive.

In summary, the future prospects for FBGs are bright, driven by advances in fabrication techniques, novel applications in agricultural fields, and integration with other technologies. As research and development efforts continue, we can expect to see further improvements in FBG performance, expanded areas of application, and increased adoption in various sectors.

8 Conclusions

In conclusion, this review paper has explored the recent applications of Fiber Bragg Grating (FBG) in agriculture especially in humidity and water content detection. FBG sensors have shown great potential in agriculture due to their numerous advantages such as high sensitivity, fast response time, and immunity to electromagnetic interference. The review began by providing an overview of FBG technology and its working principle. It highlighted the importance of detecting humidity and water content in various industries such as agriculture, environmental monitoring, and industrial processes. The article then delved into the different types of FBG-based humidity and water content sensors, including direct and indirect measurement methods in agriculture. Several recent applications of FBG in the detection of humidity and water content were discussed in detail. The review highlighted the advantages of FBG sensors in each application, such as their ability to provide real-time measurements, non-invasiveness, and compatibility with harsh environments. Additionally, the paper addressed the challenges and limitations associated with FBG-based humidity and water content sensors. These challenges include temperature cross-sensitivity, hysteresis effects, and signal drift over time. Various techniques for mitigating these challenges were also discussed, such as using temperature compensation algorithms and employing specialized coatings on the FBG sensors. Its wide range of applications and advantages

make it a valuable tool for researchers and industries alike. However, further research is still needed to address the remaining challenges and optimize the performance of FBG-based sensors in this field. This review paper aims to provide researchers, engineers, and industry professionals with a comprehensive understanding of the recent developments and applications of FBG technology in humidity and water content detection. By shedding light on the advancements, challenges, and future prospects, this paper aims to inspire further research and innovative applications in this domain.

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Declarations

Competing interests The authors declare that they have no competing interest.

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