

Polyimide-Coated S-Shaped Optical Fiber Interferometer for Non-Contact Skin Humidity Detection

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Abstract: Skin humidity detection is a vital biomarker for monitoring human health and safety conditions. This study presented the development of a non-contact skin humidity sensor that utilizes an S-shaped optical fiber coated with polyimide and employs the Sagnac interferometric technique. To position the polyimide coating closer to the fiber core, two channels were machined into the cladding, forming an S-shape while maintaining the fiber strength. The sensor operated based on the moisture absorption and swelling of the polyimide film, which induced a wavelength shift in the interference spectrum. The sensor demonstrated the sensitivity of $-1.49 \text{ nm}/\% \text{RH}$ over the RH range of 30%–95%, where the RH is relative humidity. To compensate for temperature variations, a fiber Bragg grating was integrated into the exposed section of the S-shaped fiber, providing the temperature sensitivity of $10 \text{ pm}/^\circ\text{C}$. The sensor exhibited excellent accuracy, linearity, reversibility, and low hysteresis. Moreover, non-contact skin humidity sensing was evaluated on both human and prosthetic hands, highlighting its potential applications in biomedical fields.

Keywords: Fiber Bragg grating; humidity; interferometer; polyimide coating; S-shaped optical fiber

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1. Introduction

Recent years have witnessed significant advancements in flexible sensors, driving their widespread adoption in fields ranging from the artificial skin to medical diagnostics [1–4]. A key application generating considerable interest is the non-invasive, real-time monitoring of human biomarkers [5, 6]. Among these, skin humidity

detection has emerged as a prominent focus, as continuous moisture tracking provides valuable insights into metabolism, physiological conditions, and wound healing [7–9]. While skin humidity sensors are traditionally categorized into contact and non-contact types, the latter is becoming increasingly vital. Contact-based wearable sensors risk mechanical wear and the transmission of diseases, creating a pressing need for remote

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monitoring solutions [10]. Non-contact humidity sensors are particularly valuable in scenarios where preserving environmental integrity is paramount, such as with cultural artifacts or delicate materials, to avoid damage or contamination [11, 12]. Recent advances in the structural design of non-contact humidity sensors have helped reduce the risk of bacterial transmission and decrease mechanical wear resulting from direct contact, thereby garnering increased attention in this area. A prominent example is the integration of thin-film humidity sensors into surgical masks to enable real-time monitoring of respiration [13]. Moreover, physiological conditions can be continuously and remotely tracked by observing changes in skin humidity, as fluctuations in the health status often influence the surrounding moisture environment [14].

Non-contact sensors not only prevent mechanical wear and reduce the risk of cross-infection, but also enable unobtrusive monitoring in medical, cultural, and environmental settings. With the rapid development of artificial intelligence, non-contact sensing is revolutionizing fields such as non-invasive medical diagnostics and contactless human-machine interaction, including drone and robot control [15–17]. These sensors are increasingly important for personal healthcare monitoring, infection prevention, and precision agriculture, where they help optimize water usage and improve the crop yield [18, 19].

In parallel with electronic flexible sensors, optical fiber sensors have emerged as a powerful alternative for humidity monitoring. These sensors offer advantages, such as robustness in harsh environments, and immunity to magnetic fields, electromagnetic interference, and radiation [20]. Their compact size, long lifespan, and high accuracy also enable real-time monitoring over extended distances [21–23]. In order to optimize the performance of humidity sensors, various types of optical fibers have been explored for their suitability

in humidity sensing applications, such as the polarization-maintaining fiber, multicore fiber, hollow-core fiber, and D-shaped fiber [24–30]. To enhance sensitivity, optical fiber humidity sensors commonly incorporate a sensing film around the sensing head that adsorbs water molecules, resulting in mechanical deformation as the molecules permeate the film. This deformation can induce secondary effects such as changes in the refractive index or strain on the sensing fiber, leading to shifts in the output spectrum or variations in intensity [30]. The selection of a suitable hygroscopic material is crucial for optical fiber humidity sensors, as it can expand to induce strains on the sensing fiber, playing a vital role in sensitizing the sensor heads. Examples of such materials include the chitosan, graphene oxide, polyimide, and polyvinyl alcohol [21, 24, 27, 31]. However, designing practical sensors for demanding applications remains challenging, requiring considerations of the biocompatibility for biosensing applications, as well as the ability to prevent contamination of the sensor head from the surrounding environment. Additionally, humidity sensors that require intricate probe fabrication methods may be susceptible to power fluctuations and could exhibit reduced sensitivity or increased fragility in certain circumstances.

To address these needs, this study developed a simple, durable, flexible, and highly sensitive optical fiber sensor for non-contact humidity monitoring, with robust temperature compensation and strong potential for wearable and biomedical applications. The proposed system utilized an in-house fabricated polyimide-coated S-shaped fiber (SF) within a Sagnac interferometer (SI). The fiber featured a unique structure with two channels offset from the core, forming an S-shape in the cross-section, which enabled effective humidity sensing. The sensor detected changes in humidity levels by analyzing the spectral response of the SI, which was influenced by the amount of water molecules present in the thin

polyimide coating. As moisture was absorbed, the polyimide expanded, causing the fiber to enlarge and shifting the resonance dip towards a shorter wavelength in the interference spectrum. Skin humidity sensing on both human and prosthetic hands was evaluated, demonstrating the sensitivity of $-1.49 \text{ nm}/\% \text{RH}$ over the RH range of 30% RH–95% RH, where the RH is relative humidity. To mitigate temperature cross-sensitivity, a fiber Bragg grating (FBG) was integrated, providing the temperature sensitivity of $10 \text{ pm}/^\circ\text{C}$. This approach enabled sensitive and non-contact skin humidity sensing, which is essential for disease management, and preventing skin damage and premature aging.

Main contributions of this work include 1) scalable fabrication of an S-shaped optical fiber with engineered birefringence and a polyimide coating for enhanced humidity sensitivity; 2) development and calibration of a fiber-based sensor for simultaneous humidity and temperature measurement, including the quantification of key performance metrics; 3) quantitative evaluation of the effects of coating thickness, fiber length, and ambient conditions, with robust temperature compensation via integrated FBGs; 4) real-time, non-contact skin humidity measurement under varying distances, ambient humidity levels, and skin conditions; 5) analysis of the sensor's dynamic and step-change response, highlighting its suitability for wearable and biomedical applications.

The remainder of this paper is organized as follows. Section 2 describes the mode field distribution and sensing principle of the proposed sensor. Section 3 presents the fiber fabrication, sensor preparation, and measurement methods. Section 4 reports the sensor characterization and application results, including the humidity sensing performance, temperature responses, non-contact skin humidity sensing, and dynamic as well as step-change humidity responses. Section 5 discusses the sensor performance in comparison with previous studies, together with the advantages and limitations

of the proposed approach. Finally, Section 6 concludes the paper.

2. Theoretical background

2.1 Mode field distribution

The mode field distribution determines how the guided light interacts with the fiber's geometry and is particularly important in fibers with engineered asymmetry. The SF used in this work features an elliptical core, resulting in strong birefringence and an asymmetric optical mode profile. The finite element method (FEM) simulations were performed for an elliptical core ($6.8 \mu\text{m} \times 19.7 \mu\text{m}$) with a refractive index of 1.449 1. Figure 1(a) shows the simulated fundamental mode at 1 550 nm, while Fig. 1(b) presents the corresponding transverse field

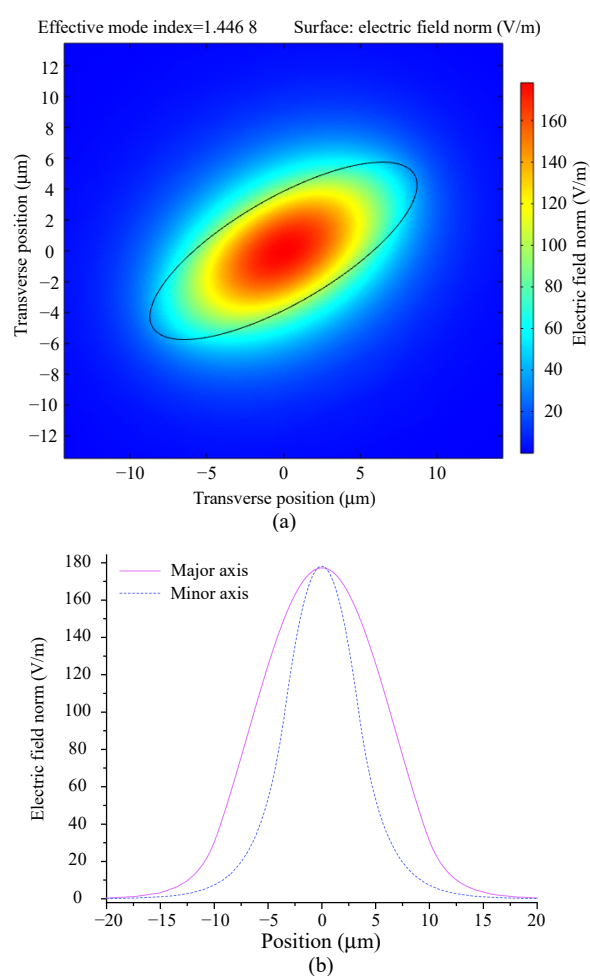


Fig. 1 Optical mode characteristics of the S-shaped fiber: (a) simulated fundamental mode distribution and (b) transverse field profiles along the major and minor axes.

profiles. The optical field is strongly elliptical, exhibiting greater confinement along the minor axis and a broader extension along the major axis. The calculated effective mode index was 1.446 8.

The mode field diameters along the major and minor axes were 11.54 and 6.38 μm , respectively, with an effective mode area of 113.68 μm^2 [32]. These results confirm that the elliptical-core SF supports a well-confined and asymmetric fundamental mode. This modal asymmetry is consistent with the non-circular core geometry that gives rise to intrinsic birefringence.

2.2 Relative humidity sensing principle

The SI technique utilizes the interference of two counter-propagating light beams in a closed loop. Variations in measured physical parameters, such as the RH, induce changes in the fiber's refractive index or length, which alter the optical path in the interferometer and consequently affect the interference pattern [33]. In this study, as the polyimide coating absorbed moisture, it underwent hygroscopic swelling. This induced strain altered the optical path length of the sensing fiber, leading to alterations in the interference pattern and enabling humidity measurement.

The transmission optical intensity T of the SI can be mathematically represented as $T=[1-\cos(\varphi)]/2$, where φ is the phase difference between the two counter-propagating beams of light within the interferometer. The phase difference φ can be calculated using the equation $\varphi=2\pi LB/\lambda$, where λ is the operating wavelength; L is the length of the SF; B is the birefringence of the fiber, which is determined by the effective refractive index difference between the slow and fast axes [34].

The strain-induced wavelength shift $\Delta\lambda$ of the transmission minimum or maximum can be determined using $\Delta\lambda=S\Delta\phi/2\pi$, where S is the wavelength spacing between adjacent valleys, and $\Delta\phi$ is the phase change induced by an external strain [24]. The external strain ε resulting from the

expansion of the coating can be defined as $\varepsilon=\Delta L/L$, where ΔL is the change in the fiber length due to variations in the humidity level.

The phase change $\Delta\phi$ induced by the external strain can be expressed as $\Delta\phi=2\pi/\lambda(B\Delta L+L\Delta B)$, where $\Delta B=\Delta n_s-\Delta n_f$ denotes the variation in birefringence resulting from changes in the effective refractive index of the slow (Δn_s) and fast (Δn_f) axes. The change in the effective refractive index in the fiber core is related to the applied strain and the effective photoelastic constant in the fast and slow axes. Thus, the wavelength shift of the spectrum resulting from the strain induced by humidity changes can be determined using $\Delta\lambda=\lambda(1+p_e)\Delta\varepsilon$, where p_e is the photoelastic coefficient that characterizes the strain-induced variation of the birefringence of the SF, and $\Delta\varepsilon$ is the change in the strain induced by humidity variations.

3. Materials and methods

3.1 Fiber fabrication and characterization

The fabrication process of the birefringent SF utilized a commercially available Ge-doped preform (J-fiber S59, j-fiber GmbH, Germany), the featuring core and cladding diameters of 0.8 mm and 13.6 mm, respectively. To enhance the strain-induced effect and bring the coating closer to the core, two channels were milled into the cladding region using a computer numerical control (CNC) milling machine (CNC Baron, CNC Masters, USA) [33, 35]. These channels, as depicted in Figs. 2(a) and 2(b), had dimensions of 1.5 mm in width and 6.6 mm in depth. They were positioned deep inside the cladding and arranged in an offset, which was a tangential configuration relative to the core of the preform. This resulted in an S-shaped configuration in the cross-section of the preform. The ground S-shaped preform, with a length of 110 mm, was then drawn into a fiber at a temperature of 1 920 $^{\circ}\text{C}$, while the tension of 0.7 N was maintained.

The minor/major axes for the core and cladding were 6.8 μm /19.7 μm and 153 μm /157 μm for the

S-shaped fiber-1 (SF1), and $6.9\ \mu\text{m}/17.4\ \mu\text{m}$ and $157\ \mu\text{m}/159\ \mu\text{m}$ for the S-shaped fiber-2 (SF2). The high temperature during fiber drawing caused the channels in the preform to collapse, particularly at the waist of the S-shape, resulting in deformation of the fiber core from a circular to an elliptical shape. Consequently, the core dimension along the major axis became more than 2.5 times longer than that along the minor axis. This core deformation induced birefringence in the fiber, causing it to exhibit different refractive indices along the minor and major axes. The core and cladding dimensions were determined through the structural design of the machined preform and optimization of the fiber drawing process. The selected dimensions were chosen to achieve the desired birefringence and maintain good optical and mechanical properties. Preliminary fibers with an acrylate coating were fabricated and tested under varied drawing conditions to evaluate geometry and birefringence. The reported values reflect the optimized outcome of this process.

Drawing and coating were performed as a synchronized and continuous process, with in-line

diameter monitoring used to ensure dimensional consistency. Both uncoated and coated fiber diameters were monitored in real time during the drawing process using in-line diameter gauges (ODAC 18XY, Zumbach, Switzerland), and the cross-sectional geometry was further verified by inspection of representative samples with a video microscope (VM-1V, Meiji Techno, Japan) and a scanning electron microscope (SEM, Phenom, FEI, USA). A polyimide coating was applied during fiber drawing at a speed of 6 m/min. To study the effect of the coating thickness on the humidity response, two different coating thicknesses were produced by using dies of different sizes in the coating cup. Specifically, the SF1 was fabricated using a $170\text{-}\mu\text{m}$ coating die, while the SF2 utilized a $270\text{-}\mu\text{m}$ die. Although the coating die size was used to adjust the coating condition, additional factors such as the polyimide viscosity, fiber drawing speed, and thermal curing conditions also affected the final coating thickness. Oblique and cross-sectional SEM images of the polyimide-coated SFs are shown in Figs. 2(c)–2(e), and their parameters are summarized in Table 1.

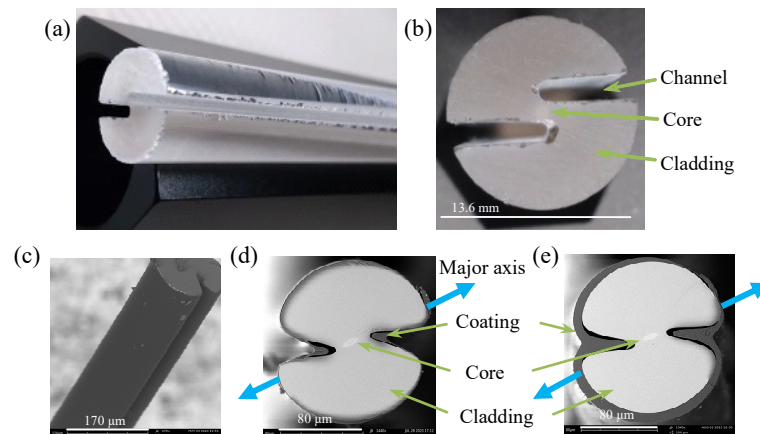


Fig. 2 Structural characterization: (a) the machine-ground SF preform, (b) its cross-section, and the SEM images of (c) the longitudinal and (d) cross-sectional views of SF1, as well as (e) the cross-section of SF2.

Table 1 Parameters of the SFs.

Fiber	Core diameter (μm)	Waist length (μm)	Cladding diameter (μm)	Coating diameter (μm)	Coating thickness in channel (μm)	Birefringence
SF1	6.8×19.7	35.9	153×157	157×161	9.3×13.5	$(5.04 \pm 0.05) \times 10^{-5}$
SF2	6.9×17.4	35.1	157×159	171×174	18.7×43.8	$(4.06 \pm 0.06) \times 10^{-5}$

During the coating process, a curing temperature of 160 °C was maintained to ensure a smooth coating layer on the fiber surface. The coating was thicker inside the channels and thinner at the cladding perimeter. For SF1, the coating thickness ranged from 1 μm to 9 μm , and for SF2, it ranged from 5 μm to 19 μm . As shown in Table 1, the average coated diameters were 159 μm for SF1 and 172.5 μm for SF2. During thermal curing, small gaps between silica and the coating remained, particularly around the waist of the fiber. The weak adhesion of the coating to the glass allowed for convenient detachment of the coating from the silica fiber using a razor blade, making the cleaving and splicing process easier.

The refractive index difference between the core and cladding of the SFs was measured to be 5.05×10^{-3} using a refractive index profiler (nPA-400, Arden Photonics, UK). The fiber attenuation, determined through the standard cutback method, was found to be 0.48 dB/m. When spliced with a single mode fiber (SMF), the average splice loss of 0.8 dB per splice was observed, primarily due to the mismatch in the core size and shape between the fibers. Furthermore, the presence of channels near the fiber core resulted in increased bending losses. At a wavelength of 1 550 nm, the measured bending losses were 0.33 dB/loop and 0.53 dB/loop, when the fiber was bent with a radius of 10 mm along the minor and major axes, respectively.

3.2 Experimental setup, FBG inscription, and sensor packaging

The experimental setup, shown in Fig. 3(a), featured a Sagnac loop created by splicing a segment of the SF to one side of a 3-dB coupler. The polarization state was controlled using a polarization controller (PC). The transmission spectra were recorded using an optical spectrum analyzer (OSA, AQ6370D, Yokogawa, Japan) with the resolution of 20 pm and a supercontinuum source (SC-5, YSL Photonics, China). Reflection spectra were measured

using an interrogator (sil55, Micron Optics, USA) operating in a wavelength range of 1 500 nm–1 600 nm, with wavelength accuracy of 1 pm.

Figure 3(b) illustrates the schematic configuration of the skin humidity sensing setup. To test the humidity changes with a prosthetic hand, a wet wipe with dimensions of 20 mm×20 mm was attached to the hand model to ensure that the humidified area fully covered the sensor's effective sensing region. The humidity source was the water content of the wipe. The RH produced by evaporation from the wipe surface was experimentally estimated using a commercial humidity meter positioned adjacent to the sensor. The PC was omitted in the SI for practical purposes. Figure 3(c) presents the interference spectra of the SI comprising SFs with a length of 2 m. SF1 and SF2 exhibited birefringence values of $(5.04 \pm 0.05) \times 10^{-5}$ and $(4.06 \pm 0.06) \times 10^{-5}$, respectively, around the wavelength of 1 550 nm. Resonance valleys were observed in the 1 460 nm–1 620 nm range, with extinction ratios exceeding 15 dB in most cases.

An FBG was inscribed in the 2-m-long SF1 for temperature compensation. The FBG inscription process involved subjecting fibers to hydrogen loading for one week, followed by exposure to a 248-nm excimer laser. After removing the coating from a 14-mm section of the fiber, an 8-mm-long FBG was directly inscribed onto the bare fiber. The reflection spectrum of the FBG in the SF1 had a 3-dB bandwidth of 0.12 nm, and its peak was located at a wavelength of 1 552.04 nm, as shown in Fig. 3(d). For a compact sensor package, a short FBG was inscribed using a femtosecond laser with the point-by-point technique, resulting in an FBG length of 1.5 mm within a bare fiber length of 4 mm. The FBG reflection spectrum is displayed in Fig. 3(e), with a 3-dB bandwidth of 0.52 nm and a peak wavelength at 1 543.3 nm.

For practical demonstration, a flexible sensor

package was prepared by coiling ~ 1.8 m of SF1 onto a 0.21-mm-thick Teflon film. The fiber was loosely coiled to avoid any impact on sensor performance. The coiled fiber diameter was about 23 mm, and the 1.5-mm-long FBG was positioned near the end of

the SF1, ensuring that the bare fiber section was not affected by the coiling process. This configuration produced a flexible, wearable, and easy-to-use sensor head. An image of the sensor package is shown in Fig. 3(f).

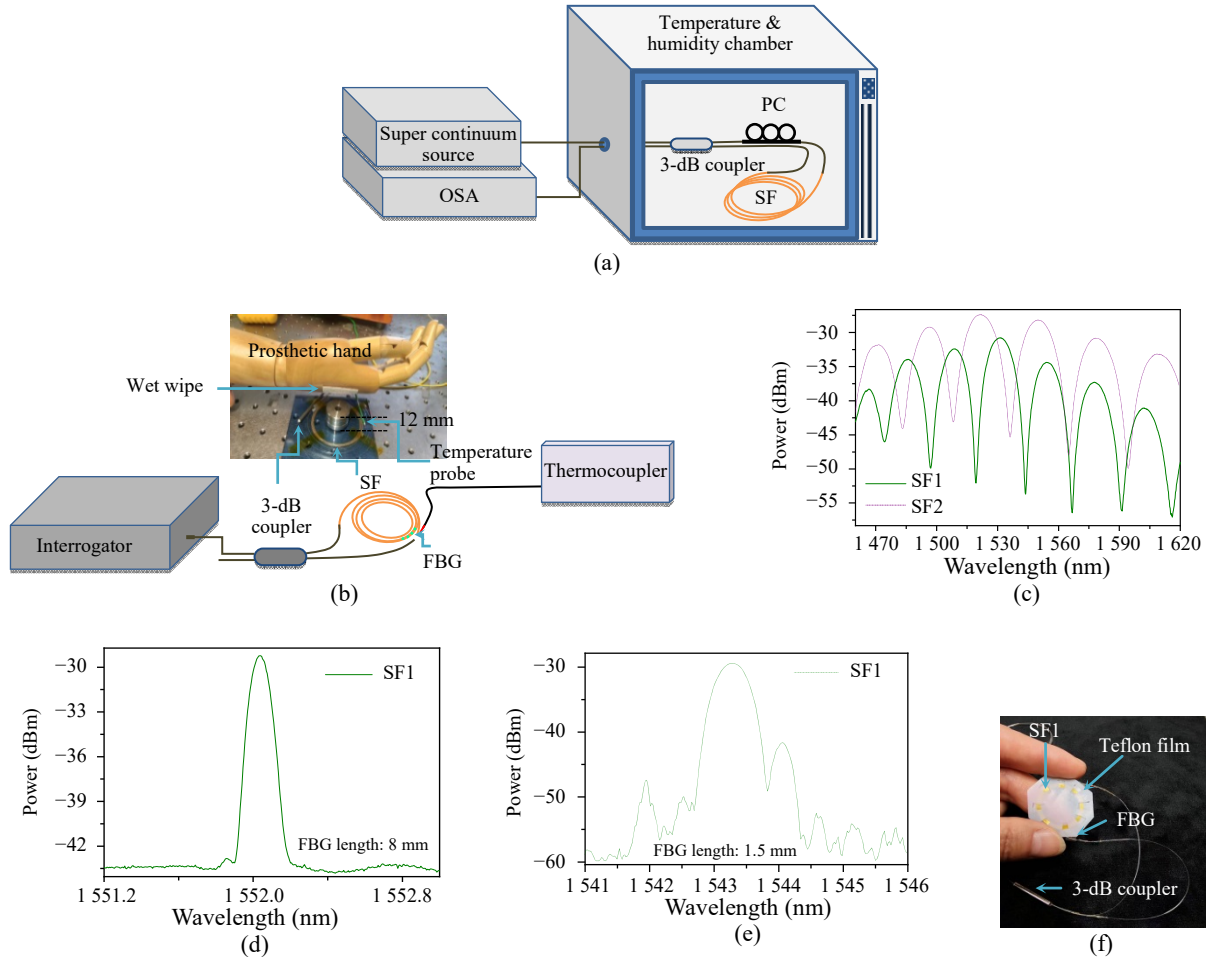


Fig. 3 Experimental setup and spectral characteristics: (a) the schematic diagram for measuring humidity and temperature using SF in a SI, (b) the experimental setup for measuring skin humidity, (c) interference spectra of the SFs, (d) the reflection spectrum of the FBG inscribed in SF1, (e) the reflection spectrum of the 1.5-mm-long FBG written with an fs laser, and (f) the flexible sensor package with SF1.

3.3 Relative humidity and temperature measurement methods

For the humidity sensing performance of SFs, the RH was varied within an environmental chamber (SH-641, ESPEC, Japan), ranging from 30% to 95% in 10% increments, while the temperature was held constant at 30 °C. To assess sensor repeatability, measurement was performed three times for both increasing and decreasing humidity levels. Sensor stability was assessed by monitoring the resonance

valley in the reflection spectrum. Due to limitations in the interrogator's wavelength range, ascending humidity steps were performed between the 30% RH and 80% RH in 10% RH increments. Each step was recorded for 1.5 h at a constant temperature of 30 °C.

To calibrate the temperature dependence of the SFs within the SI, the temperature was varied from 20 °C to 50 °C in 5 °C increments, while maintaining an RH level of 60% inside an environmental chamber. To mitigate the influence of

high-temperature effects on the sensor, an 8-mm-long FBG was fabricated on an uncoated SF. The temperature sensitivity of the FBG was calibrated using the same temperature and humidity control procedures as those employed in the SI technique.

For non-contact skin humidity sensing, the sensor package (with the 1.5-mm or 8-mm FBG) was tested at ambient temperatures of 21.5 °C–24 °C and varying ambient humidity levels. To characterize the distance-dependent response, the sensor package (SF1, 1.8 m; a 1.5-mm FBG) was placed 1 mm from the hand (skin humidity $\sim 89\% \pm 2\%$ RH), stabilized for 30 s, and then moved away in 2-mm increments up to 21 mm. Measurement was conducted under three ambient humidity conditions, including 42% RH, 53% RH, and 65% RH. The ambient humidity levels were established by adjusting room conditions with a humidifier or dehumidifier prior to each experiment, and measurement was conducted only after the humidity stabilized at the desired value. To ensure that the sensor was evaluated under realistic physiological conditions, variations in the skin humidity (58% RH to 89% RH) were achieved by measuring distinct anatomical regions, including the fingers, back of hand, and forearm. During non-contact measurement, the sensor package was positioned at controlled distances from the skin using a micrometer stage, and the wavelength shift was monitored at each distance. Both humid and dry hand conditions were tested. A commercial electronic RH sensor was placed alongside the fiber sensor as a reference.

To evaluate the dynamic response with human and prosthetic hands, a 2 m-long SF1 fiber with an 8-mm FBG was employed at a room temperature of 24 °C and an indoor humidity level of 54%. A temperature probe was placed near the sensor to monitor temperature variations caused by the skin and unwanted environmental temperature changes. Response time was determined by rapidly

alternating the sensor's exposure between ambient and humid conditions, ensuring that the observed response reflected the sensor's inherent dynamics rather than slow environmental stabilization processes.

To monitor the sensor's step-change response to a localized humidity source, a stable moist surface was created by partially dissolving sodium chloride with a small amount of water, providing the reference humidity of approximate 60% RH under ambient conditions. The salt mixture was spread into a flat surface with a diameter of 55 mm. Measurement was conducted in a semi-enclosed environment to minimize airflow disturbances. The RH near the salt surface was continuously monitored with a commercial humidity meter (DT-625, CEM, China) to ensure that the RH remained close to 60% throughout the experiment. The sensor (SF1, 1.8 m; a 1.5-mm FBG) was mounted at distances of 1 mm, 3 mm, and 6 mm from the salt surface. The sensor's response to step changes in the distance from the humidity source was recorded, with the response and recovery time analyzed. For each measurement, the wavelength shifts were recorded for 3.5 min. Initially, the wavelength shifts were recorded in the ambient humidity of 52% RH. The wavelength shifts stabilized for about 1 min, while wet salt was close to the sensor and then it was moved away.

To study the step-change humidity response with temperature cross-sensitivity, the sensor's sensitivity to ambient humidity was also evaluated by placing it in a small container and rapidly injecting humid air using a humidifier. Wavelength shifts in the interference spectra and FBG were recorded as the ambient humidity changed from the 57% RH to higher levels.

4. Results

4.1 Relative humidity sensing performance in chamber

The results of the humidity sensing experiment using a 1-m-long SF1 in the SI setup are shown in

Fig. 4. To evaluate the effect of hysteresis on the sensor's performance, the humidity response was examined by increasing or decreasing the RH within the range of 30%–95%. Figure 4(a) shows the measured wavelength shift of a valley as the RH is varied. Figure 4(b) presents the recorded interference spectra specifically for ascending the RH. Note that extinction ratios in interference spectra were not linear, which changed with varying RH levels, and the valleys were measured to be -53.1 dBm, -64.6 dBm, and -57.0 dBm at 30% RH, 60% RH, and 95% RH, respectively. As humidity increased, the polyimide coating within the channels swelled, causing the fiber to expand. This expansion affected the interference, shifting the resonance dip towards shorter wavelengths. The measured data, represented with error bars from three repeated tests,

were fitted with straight lines. The sensitivity for ascending and descending RH was measured to be -1.49 nm/%RH and -1.52 nm/%RH, respectively. The wavelength valley at the 30% RH shifted beyond the starting value. The small difference in sensitivity between ascending and descending RH cycles was due to the intrinsic hysteresis of the polyimide coating, which was typically driven by the viscoelastic nature of the polymer. This observed hysteresis (0.03 nm/%RH) was minimal and did not compromise the sensor's repeatability. The limit of detection was calculated by dividing the wavelength resolution of the interrogation system (1 pm) by the sensor's sensitivity in the ascending direction (1.49 nm/%RH), resulting in a limit of detection of 6.7×10^{-4} %RH. The sensor exhibited a strong linear relationship between the wavelength shift and RH

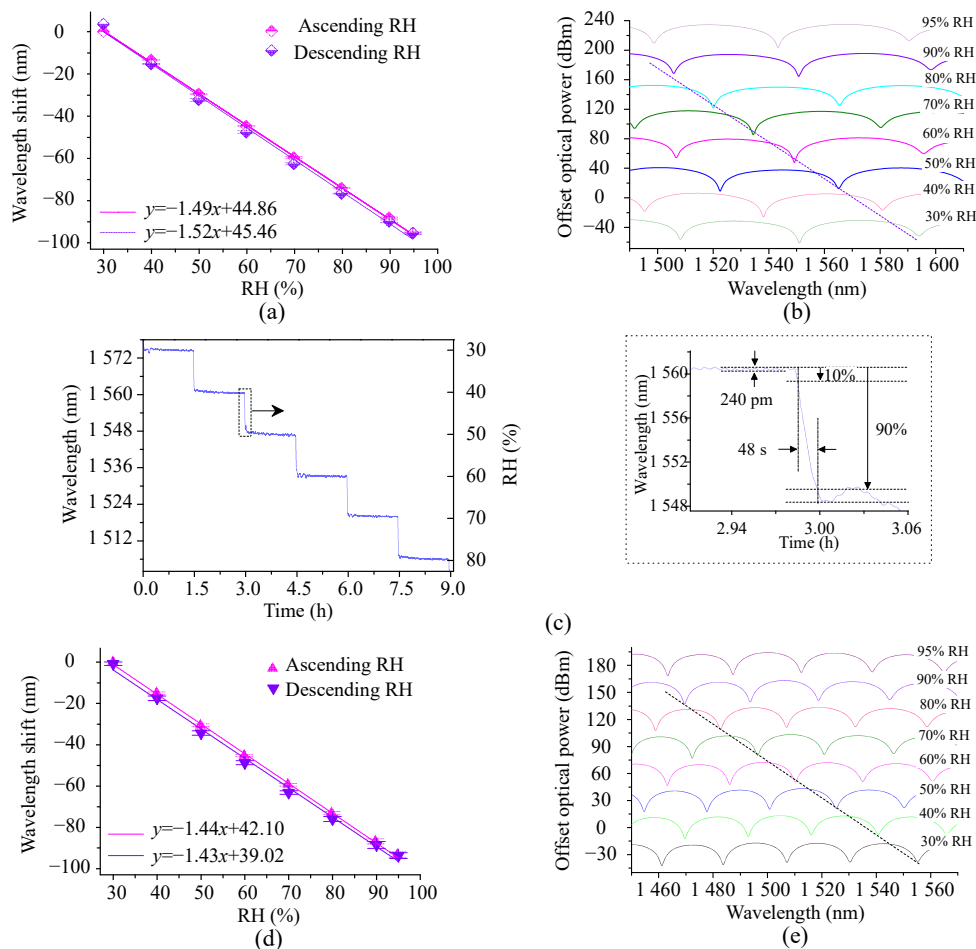


Fig. 4 Humidity response and stability performance: (a) the resonance wavelength shift of the sensor in response to ascending and descending RH, with a 1-m-long SF1 in the SI, and (b) corresponding interference spectra recorded during the ascending RH, (c) stability performance of the sensor utilizing a 1-m-long SF1, (d) resonance wavelength shifts in response to ascending and descending RH, using a 2-m-long SF1, and (e) related interference spectra recorded during the increasing RH.

change for both ascending and descending humidity levels. By fitting the data with a linear regression model ($y=ax+b$), the corresponding coefficient of determination (R^2) was greater than 0.995, with average errors of 0.25 nm for ascending humidity and 0.42 nm for descending humidity. No significant parasitic torsional effects were observed in our experiments. The swelling-induced strain of the polyimide coating translated primarily to the longitudinal strain on the fiber core, as demonstrated by the linear relationship between the wavelength shift and RH.

Sensor stability, assessed as described in Sub-Section 3.3, is presented in Fig. 4(c). Throughout the calibration process, the sensor exhibited consistent and reliable performance, as the resonance valley remained stable across all humidity steps. The inset [the right part of Fig. 4(c)] shows the peak-to-peak wavelength fluctuations of ~240 pm, resulting in a minimum detectable humidity of 0.16% RH. This wavelength fluctuation is inherent to the SI design [36]. Changes in the interference pattern extinction ratio at different RH levels contributed to fluctuations of 190 pm–360 pm, corresponding to a minimum detectable humidity range of 0.13%–0.24% RH. However, the fluctuations observed between the time points 3.00 h and 3.06 h were attributed to humidity and thermal stabilization of the environmental chamber. The sensor's response time measured in the environmental chamber, from a 10% minimum wavelength shift to a 90% maximum wavelength shift during the transition from 40% to 50% RH, was determined to be 48 s. It is important to note that the response time of the sensor is influenced by the performance of the environmental chamber, which requires time to reach the desired humidity level during both ascending and descending humidity changes.

To investigate the influence of the sensing fiber length on sensitivity, the sensor's response was

recorded using a 2-m-long SF1 for both the ascending and descending RH, as depicted in Fig. 4(d). The corresponding interference spectra captured during the ascending RH are illustrated in Fig. 4(e). The results showed the sensitivity of -1.44 nm/%RH and -1.43 nm/%RH for ascending and descending RH changes, respectively. The sensor demonstrated linearity with $R^2 > 0.995$, and average measurement errors of 0.71 nm and 0.44 nm, respectively. Although the sensitivity was slightly lower and the error range was larger than those of the sensor with a shorter fiber length, the overall sensor performance was comparable for both the 1-m and 2-m SF configurations.

In Fig. 5, the sensitivity of sensors with thicker polyimide coatings is investigated to explore the relationship between coating thickness and humidity detection. A 2-m-long SF2 was used in the study, and the results show that the sensor with a thicker polyimide coating achieved the higher sensitivity of -1.72 nm/%RH within the ascending RH range of 60%–90%. The average measurement error was 1.05 nm, and the R^2 was 0.996. It is worth noting that the interference spectrum of SF2, which featured a thicker polyimide coating, exhibited a reduced extinction ratio at certain humidity levels. This was likely due to excessive swelling at high humidity and non-uniform mechanical contraction at lower levels. As a result, the sensor was calibrated within the 60%–90% RH range to ensure accurate measurement. Increasing the thickness of the polyimide coating enhanced the sensor's sensitivity to humidity changes, as a thicker polyimide film underwent a more pronounced swelling effect, resulting in a greater strain-induced effect on the fiber. The SF2 showed 15% higher sensitivity than the SF1, which had an over 2 times thinner coating. While the SF2 sensor showed higher sensitivity and accuracy, it also increased the error range and limited the measurable RH range.

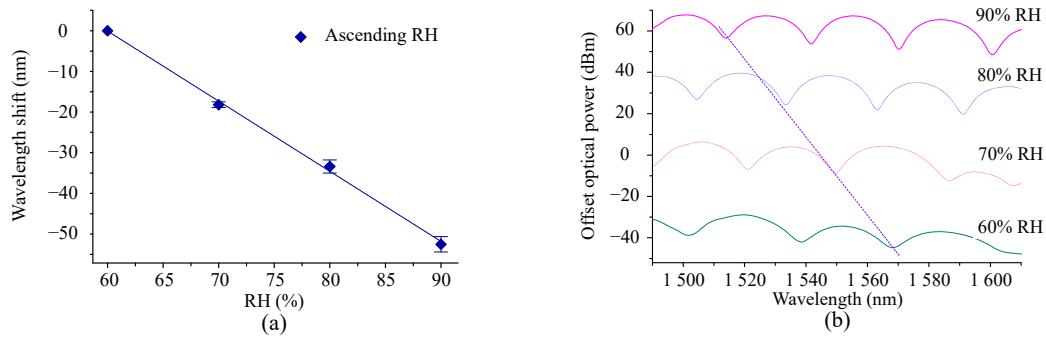


Fig. 5 Humidity response: (a) the wavelength shift as a function of the RH using a 2-m-long SF2 in the SI and (b) the corresponding interference spectra.

4.2 Temperature sensitivity and compensation

To evaluate temperature perturbations, both SF1 and SF2 were tested using a 2-m length in the SI. Figure 6(a) presents the temperature dependence of the sensors, while Fig. 6(b) shows the interference spectra of SF2. The temperature sensitivity of SF1 and SF2 was determined to be $-1.58 \text{ nm}/^\circ\text{C}$ and

$-2.05 \text{ nm}/^\circ\text{C}$, respectively. The sensors exhibited a faster shift toward shorter wavelengths as the temperature increased, indicating that the sensing structure was highly sensitive to changes in the surrounding thermal environment. The sensor with a thicker polyimide coating demonstrated 30% greater temperature sensitivity compared to the one with the thinner coating.

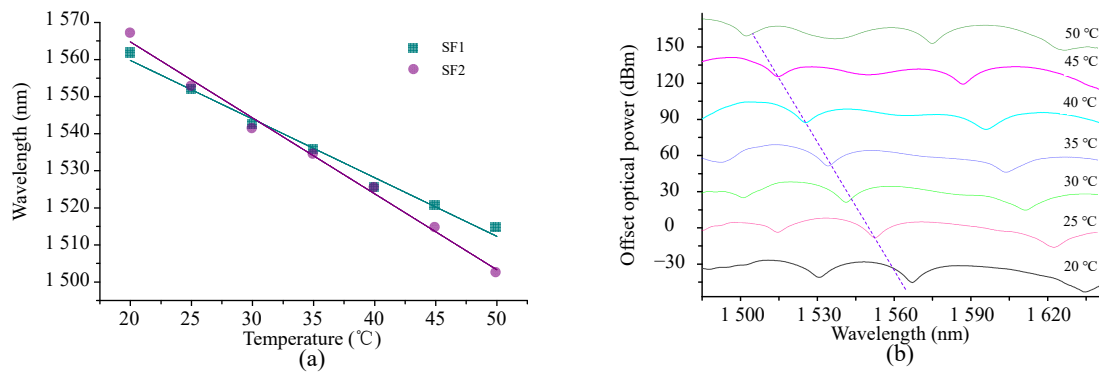


Fig. 6 Temperature response: (a) temperature dependence of SF1 and SF2 using a 2-m fiber length in SI, and (b) interference spectra of SF2 as a function of applied temperature.

Figure 7(a) shows the temperature sensitivity of the 8-mm FBG in a sensor constructed using a 2-m-long SF1 in a Sagnac loop. The corresponding reflection spectra are also presented in Fig. 7(b), with the inset demonstrating their variations with the temperature. The FBG peaks were not prominent when they were overlapped with the SI spectrum. Therefore, the FBG with the higher reflectivity was preferable to improve the extinction ratio and ensure accurate temperature compensation. By using an uncoated fiber, the FBG could directly interact with the surrounding environment, enabling accurate temperature measurement without the effects of the

coating. The FBG exhibited the temperature sensitivity of $10 \text{ pm}/^\circ\text{C}$, which was similar to that of the SMF. The humidity response of the FBG, compared to the wavelength shifts in the interference spectra detected at two separate resonance valleys, is plotted in Fig. 7(c). The interferometer-based sensitivity ranged from $-1.31 \text{ nm}/\% \text{RH}$ to $-1.53 \text{ nm}/\% \text{RH}$, depending on the detected wavelength. In contrast, as shown in Fig. 7(d), the FBG exhibited no responses to humidity changes, as it was not encased in any coating, ensuring that the compensation was specific to temperatures. By leveraging this characteristic, the FBG could effectively function as

a temperature sensor. Its response to temperature variations enables compensation for temperature-induced changes in the system, thereby enhancing

the performance and reliability of the sensor and allowing for precise measurement even in challenging and dynamic environmental conditions.

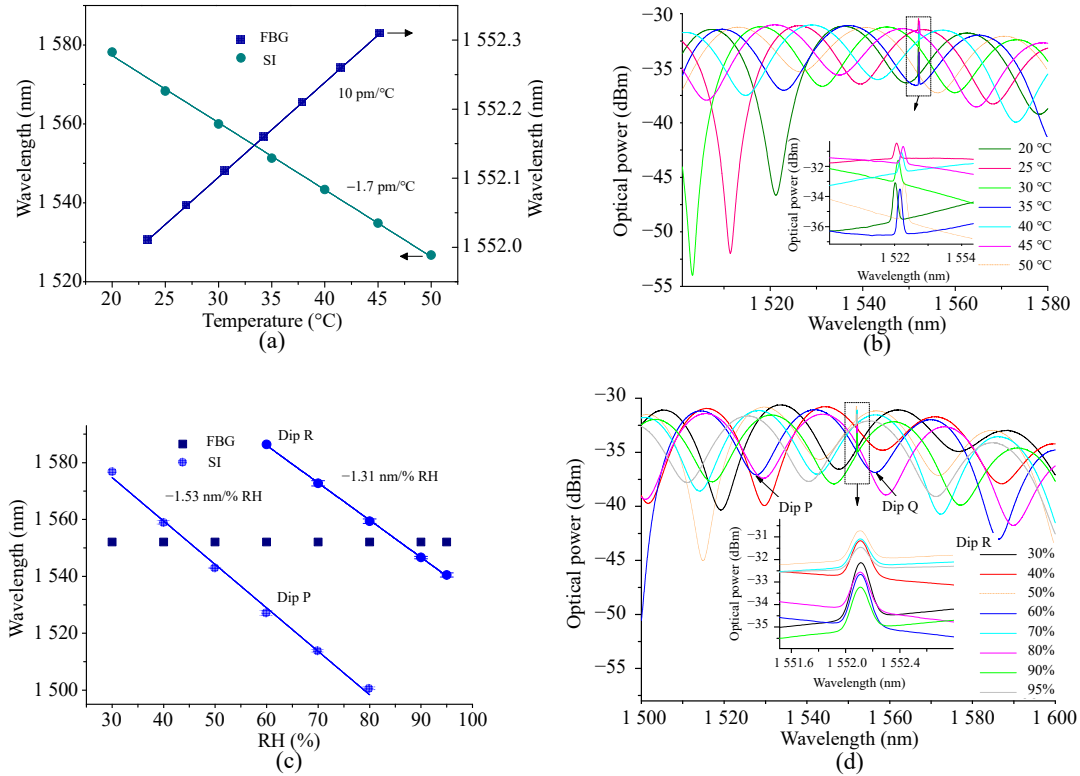


Fig. 7 Temperature sensitivity and compensation with FBG integration: (a) temperature sensitivity of the 8-mm FBG and the 2-m-long SF1 in the SI, (b) reflection spectra of the FBG in SF1 at different temperatures, (c) comparison of humidity responses: FBG versus the wavelength shifts in the interference spectra at two resonance dips, and (d) reflection spectra of the uncoated FBG in the SI, confirming its insensitivity to humidity.

4.3 Non-contact skin humidity sensing: effects of the distance, ambient humidity, and skin condition

The proposed sensor was used for real-time, non-invasive monitoring of skin humidity across a range of sensing distances, ambient humidity conditions, and skin moisture levels. As detailed in Sub-Section 3.3, the distance-dependent response was evaluated by varying the sensor-to-skin distance for a hand with the skin humidity of approximately $89\% \pm 2\%$ RH, under ambient humidity levels of 42% RH, 53% RH, and 65% RH. As shown in Fig. 8(a), both the total wavelength shift (which included humidity- and temperature-induced effects) and the detection distance decreased with increasing ambient humidity, as ambient air rapidly diluted the humidity gradient near the skin. The maximum

wavelength shifts were $-12.69 \text{ nm} \pm 0.50 \text{ nm}$, $-9.24 \text{ nm} \pm 0.23 \text{ nm}$, and $-5.86 \text{ nm} \pm 0.36 \text{ nm}$ for ambient humidity levels of 42%, 53%, and 65%, respectively. The sensor exhibited high sensitivity at distances below 11 mm. At the 42% RH ambient humidity, a clear response was observed up to 19 mm, while at the 53% RH, the response range was reduced to 15 mm.

After compensating for temperature effects, the humidity-induced wavelength shifts are shown in Fig. 8(b). The sensor's response to skin moisture is distinguishable from ambient RH changes. The maximum humidity-induced wavelength shifts were -9.84 nm , -6.39 nm , and -3.02 nm for ambient humidity levels of 42% RH, 53% RH, and 65% RH, respectively. Because the sensor's response varied with the distance from the skin, all measurement

was analyzed as a function of distance. For quantitative skin humidity analysis, the workable sensing distance was determined using the criterion that the wavelength shift at a given distance must be at least three times greater than the associated error bar and above 10% of the maximum observed shift. This ensured robust and accurate measurement across different ambient and skin humidity

conditions. The effective detection distance varied depending on both ambient and skin humidity levels. Accordingly, the reliable measurable distances for humid skin humidity sensing at ambient humidity levels of 42% RH, 53% RH, and 65% RH were up to 15 mm, 13 mm, and 9 mm, with corresponding humidity-induced wavelength shifts of -1.97 nm, -1.50 nm, and -1.06 nm, respectively.

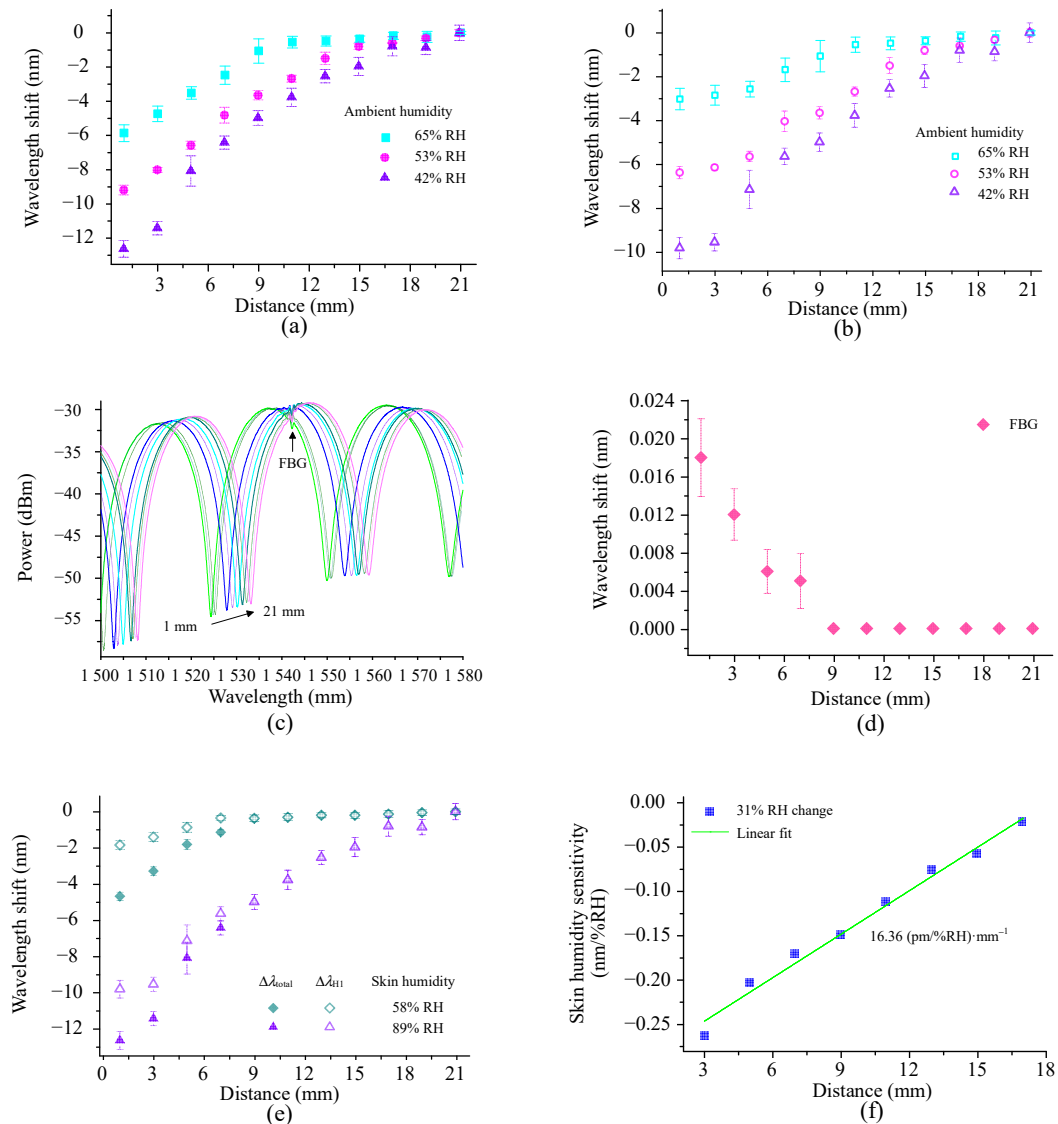


Fig. 8 Non-contact skin humidity sensing: (a) total wavelength shift as a function of distance for non-contact skin humidity sensing with $\sim 89\%$ RH at different ambient humidity levels (42%, 53%, and 65% RH), and (b) humidity-induced wavelength shifts after temperature compensation, corresponding to data in (a). (c) Transmission spectra recorded at various sensing distances under ambient humidity of 53% RH, (d) temperature-induced wavelength shift of the FBG as a function of sensing distance, and (e) comparison of wavelength shift versus distance for sensing humid (89% RH) and dry (58% RH) skin under ambient humidity of 42% RH. Filled symbols represent the total wavelength shift ($\Delta\lambda_{total}$), while open symbols denote the humidity-induced wavelength shift ($\Delta\lambda_{HI}$) after temperature compensation. (f) Calculated skin humidity sensitivity as a function of distance, derived from the $\Delta\lambda_{HI}$ corresponding to the change in RH from 58% to 89% as shown in (e).

Figure 8(c) presents the transmission spectra at various distances for ambient humidity of 53% RH, and Fig. 8(d) shows the temperature-induced wavelength shift of the FBG as a function of sensing distance. Temperature-induced wavelength shifts were detected in the FBG at distances up to 7 mm, but not at 9 mm and beyond. The maximum temperature increase was $1.8\text{ }^{\circ}\text{C} \pm 0.4\text{ }^{\circ}\text{C}$ at a 1-mm distance from the sensor, corresponding to an FBG wavelength shift of $18\text{ pm} \pm 4\text{ pm}$. The error bars reflect variations in the hand temperature under different environmental conditions. Notably, when the hand temperature dropped to $32\text{ }^{\circ}\text{C}$, no obvious wavelength shifts were detected in the FBG during the non-contact test. To verify the FBG's temperature response during non-contact sensing, the sensor was tested using a temperature-controlled metal plate heated to $35\text{ }^{\circ}\text{C}$ to simulate the human hand temperature. Consistent with the hand-sensing results, wavelength shifts occurred at distances of 1 mm–7 mm, while no shifts were observed at 9 mm and beyond. This confirmed the sensor's selectivity for non-contact humidity sensing, effectively eliminating the temperature interference at greater distances.

The sensor response to the variation in skin humidity was further investigated by comparing humid and dry hand conditions, maintaining ambient humidity at 42% RH. As shown in Fig. 8(e), for a dry hand (skin humidity $58\% \pm 1\%$ RH), the maximum total wavelength shift ($\Delta\lambda_{\text{total}}$) was $-4.69\text{ nm} \pm 0.19\text{ nm}$, which was reduced to -1.85 nm after temperature compensation (the humidity-induced wavelength shift, $\Delta\lambda_{\text{HI}}$). As the distance between the hand and the sensor increased, the wavelength shift decreased. A significant wavelength shift of -0.87 nm was observed at a measurable distance of 5 mm, after which the response gradually diminished. For a humid hand (the skin humidity: $89\% \pm 2\%$ RH), the sensor maintained a higher response over a longer distance. Figure 8(f) shows the distance-related skin humidity

sensitivity derived from Fig. 8(e) after accounting for temperature effects. The sensitivity was calculated to be $16.36\text{ (pm/\%RH)} \cdot \text{mm}^{-1}$ over the 3 mm–17 mm interval. The detection range depended on both ambient and skin conditions. For dry skin, the reliable measurement was possible up to 5 mm, while for the humid skin, the range extended up to 9 mm without significant temperature effects.

4.4 Dynamic response with the human and prosthetic hand

Immediate response tests were performed using both a human hand and a prosthetic hand equipped with a wet wipe to detect humidity variations from the physiological heat/airflow and controlled moisture release. The moisture level of the hands was approximately $84\% \pm 2\%$ RH, with ambient humidity of 54% RH. Humidity was measured by placing the hand 12 mm away from the sensor. Figure 9 presents the results of the humidity responses for repeated hand movements, and the inset (the right part of Fig. 9) shows the determination of response time for the human hand. The hands were approached to the sensor and immediately removed without stabilization. The wavelength shifted to lower values, indicating the presence of the moisture content when the hand was placed over the sensor, and it subsequently shifted back to longer wavelengths as the humidity returned to the ambient value after removal. While both hands produced distinct wavelength valleys, a minor baseline deviation was observed in the human hand, likely caused by the hand-induced airflow, which was less pronounced in the static and controlled moisture release of the prosthetic hand. While ambient fluctuations manifested as the gradual baseline shifted, the skin moisture flux produced rapid and distinct wavelength shifts synchronized with hand proximity. Therefore, environmental stabilization is recommended to ensure high-precision differentiation between skin-emitted moisture and ambient humidity effects. The average

response time and recovery time were measured to be approximately 1.6 s and 6.7 s for the human skin, and 1.7 s and 8.5 s for the prosthetic hand,

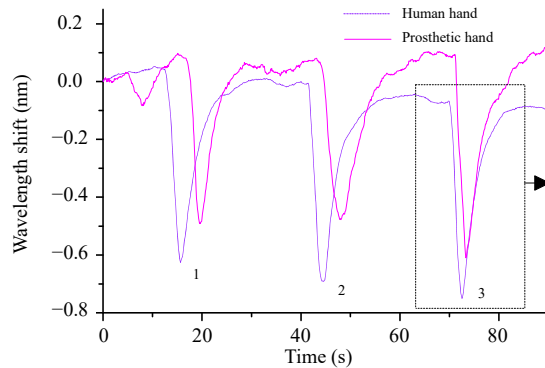


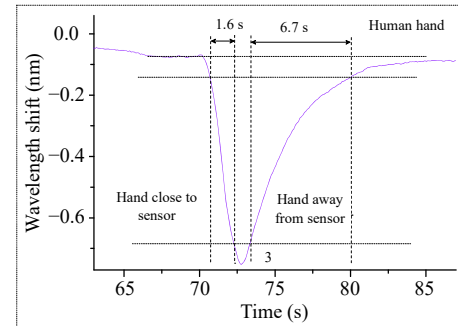
Fig. 9 Evaluation of non-contact skin humidity sensing using both a human hand and a prosthetic hand; the inset graph highlights the response time of the RH sensor when exposed to a human hand.

4.5 Step-change humidity response: influence of sensing distance and ambient humidity

To assess the step-change response to a localized humidity source at different sensing distances, the sensor package was also used for real-time monitoring of humidity above wet salt (the 60% RH in ambient humidity of 52% RH). Figures 10(a) and 10(b) show the wavelength responses of the sensor with varying distances and the determination of response time when the sensor was 3 mm away from the wet salt. The wavelength shifts were $5.26 \text{ nm} \pm 0.30 \text{ nm}$, $4.46 \text{ nm} \pm 0.22 \text{ nm}$, and $3.52 \text{ nm} \pm 0.32 \text{ nm}$ for distances of 1 mm, 3 mm, and 6 mm, respectively. The corresponding response time was 7.9 s, 5.2 s, and 9.1 s; recovery time was 28.6 s, 32.7 s, and 23.6 s; these durations include the time required for sensor positioning and removal. The response time and recovery time were determined using the 10%–90% criterion based on the temporal wavelength change, and reflected the sensor's intrinsic behavior under fast humidity transitions. These time values were shorter than those measured in the environmental chamber, where the chamber stabilization time was a significant factor.

Additionally, step-change tests were performed to determine the response time of the sensor under various ambient humidity conditions. The sensor was exposed to rapid changes in ambient humidity

respectively. These reported response time values may not cover both the diffusion of humidity from the skin/air and the sensor's intrinsic response.



from 57% RH to 64% RH, 72% RH, and 75% RH. As shown in Fig. 11(a), the total wavelength shifts were 8.96 nm, 18.3 nm, and 21.19 nm, with the response time of 2.1 s, 5.4 s, and 5.3 s, respectively, which was much faster than the 48-s response time of the environmental chamber. The total wavelength

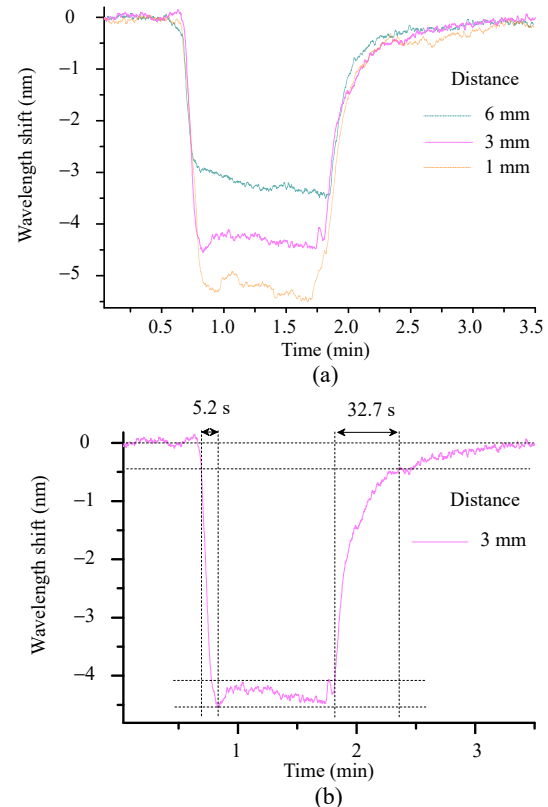


Fig. 10 Step-change humidity at specific distances: (a) responses of the sensor under 60% RH wet salt with varying distances and (b) the response time of RH with a distance of 3 mm.

shifts ($\Delta\lambda_{\text{total}}$) were the sum of the humidity-induced shift ($\Delta\lambda_{\text{H1}}$) and the temperature-induced shift ($\Delta\lambda_{\text{T1}}$): $\Delta\lambda_{\text{total}} = \Delta\lambda_{\text{H1}} + \Delta\lambda_{\text{T1}}$. Using the interferometer's humidity sensitivity (S_{H1}) and temperature sensitivity (S_{T1}), the wavelength shift related to the changes of humidity (ΔH) and temperature (ΔT) was $\Delta\lambda_{\text{total}} = S_{\text{H1}}\Delta H + S_{\text{T1}}\Delta T$. Since the FBG was only sensitive to the temperature, the temperature change was a function of the FBG wavelength shift ($\Delta\lambda_2$) by its temperature sensitivity (S_{T2}): $\Delta T = \Delta\lambda_2 / S_{\text{T2}}$.

Figure 11(b) shows the spectral response of the sensor under varying RH levels from 57% RH to 75% RH. As shown in the inset (the one on the far right in Fig. 11), the FBG's temperature response was recorded as 0.02 nm, corresponding to a temperature drop of 2 °C. Because the temperature effect ($\Delta\lambda_{\text{T1}} = S_{\text{T1}}\Delta T = 3.16$ nm) worked in the opposite direction of the humidity effect, the compensated sensitivity for the 18% RH change was found to be around -1.2 nm/%RH.

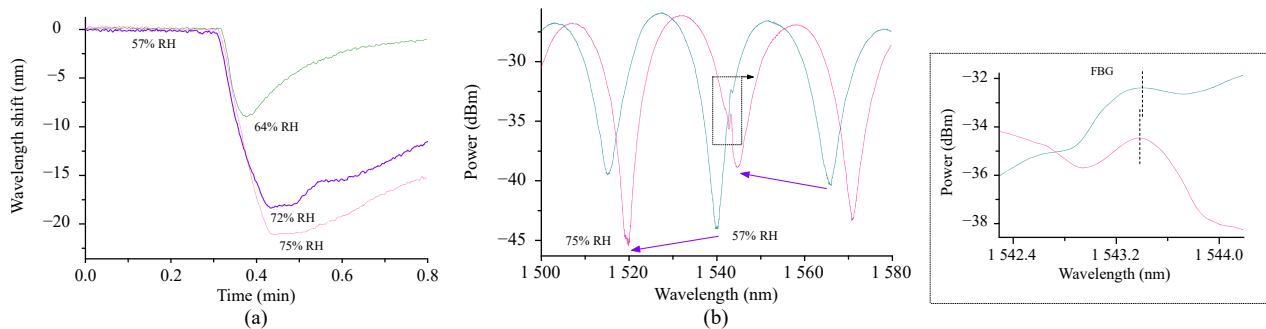


Fig. 11 Dynamic response in ambient humidity: (a) the wavelength shift recorded at step-changes of the sensor with varying RH levels at the ambient humidity of 57% RH and (b) the spectral response in reflection spectra as the ambient humidity increases from 57% RH to 75% RH, and the inset (the far right one) shows the wavelength response of the FBG with the temperature under the simultaneous change of RH.

5. Discussion

5.1 Performance analysis of the proposed humidity sensor

A summary of the proposed sensor's performance under various test conditions is provided in Table 2, demonstrating its sensitivity, response, and recovery time across different humidity sources and ambient environments. The sensor output is influenced by both ambient and skin-generated humidity, as moisture emitted from the skin creates a vapor gradient with the highest concentration near the skin surface. Accurate measurement of skin humidity under different ambient conditions therefore requires careful consideration of the ambient humidity background. In this study, ambient RH was monitored using a commercial RH sensor, and reliable skin humidity measurement was obtained by analyzing the

differential sensor response relative to the ambient condition, supported by reference measurement.

Since the skin serves as a localized moisture source, it establishes a humidity gradient that diminishes with the distance from the skin. As the sensor moves farther away, the local humidity is increasingly diluted by the surrounding air, resulting in less water absorption by the polyimide coating and a smaller wavelength shift. At the lower ambient RH, the greater difference between the skin and environmental humidity produces a stronger gradient, enabling the sensor to detect the skin-generated vapor over longer distances. Conversely, at the higher ambient RH, the reduced gradient causes skin-emitted moisture to be diluted more rapidly, resulting in a shorter effective sensing distance and a smaller wavelength shift. This explains the observed decrease in the reliable measurable distance from 15 mm at 42% RH to 9 mm at 65% RH.

Table 2 Summary of non-contact humidity sensing results.

Test condition	Sensing distance (mm)	Wavelength shift (nm) (max)	Response time (s)	Recovery time (s)	Ambient humidity (% RH)
Skin (89% RH)	1–15	9.84	–	–	42
Skin (89% RH)	1–9	3.02	–	–	65
Skin (58% RH)	1–5	1.85	–	–	42
Skin (84% RH)	12	0.68	1.6–1.7*	6.7–8.5*	54
Wet salt (60% RH, open air)	1, 3, 6	3.5–5.3	5.2–9.1	23.6–32.7	60
Step-change (57% RH→64% RH)	–	8.96	2.1	–	57–64
Step-change (57% RH→75% RH)	–	21.19	5.3	–	57–75

*The immediate response to humidity change.

Previous studies have typically tested non-contact humidity sensors within 1 mm to 10 mm for respiration and skin humidity monitoring, with the detection range limited by sensor performance and the nature of the measurement [37–39]. As the distance between the sensor and the object increases, the sensor performance decreases due to dilution of the humidity gradient. Therefore, determining the maximum detection range is crucial for practical applications. In our study, the sensor-to-hand distance was varied systematically, and the sensor demonstrated a response up to 15 mm depending on ambient and skin humidity conditions. The summarized results in Table 2 further highlight the sensor's performance across various test conditions. The sensor exhibited high sensitivity and rapid response for non-contact skin and ambient humidity sensing, with the ability to detect subtle changes in skin humidity at a distance up to 13 mm under moderate ambient humidity. However, the detection distance decreased with either an increase in ambient humidity or a decrease in skin humidity, reducing to 5 mm for a dry hand (skin humidity $58\% \pm 1\%$ RH). The use of wet salt as a reference humidity source confirmed the sensor's reliability and repeatability at different distances.

Although the humidity measurement ranges were expressed as 30% RH–95% RH and 60% RH–90% RH for SF1 and SF2, respectively, these ranges represented the sensor's detectable RH levels under laboratory conditions. For real-time measurement, the actual workable range is

determined by the free spectral range (FSR), the wavelength spacing between adjacent dips in the interference spectrum. The FSRs of SF1 were measured to be approximately 43 nm and 23 nm for fiber lengths of 1 m and 2 m, respectively. Based on the sensitivity of -1.49 nm/%RH and FSR range, the sensor with SF1 could detect up to 28% RH change for a 1-m fiber and $\sim 15\%$ RH change for a 2-m fiber, ensuring reliable operation within these ranges.

Step-change experiments validate the intrinsic fast response of the sensor, independent of environmental stabilization. Cross-sensitivity analysis showed that the sensor's response to the temperature can be effectively compensated using the FBG wavelength shift, ensuring accurate humidity measurement even in fluctuating thermal environments. Incorporating temperature compensation was essential for the effective product design, especially considering the varying heat levels emitted by the human body. The proposed sensor demonstrated significant potential for non-contact, accurate, and reliable skin humidity sensing. It is well-suited for applications in personal healthcare, sports physiology, and skincare, with the capability to monitor and manage skin conditions like eczema or psoriasis by tracking skin hydration [11, 12, 40].

5.2 Comparison with existing optical fiber humidity sensors

The performance of the proposed sensor was evaluated by comparing it to prior optical fiber-based humidity sensors that used different fiber

structures, materials, and techniques. Table 3 provides the comprehensive analysis, summarizing the sensitivity (based on the wavelength variation), measurement range, and response time. For example, one study demonstrated that a polyimide-coated FBG sensor achieved a wider humidity range of 11.3% RH–97.3% RH compared to others [21]. The effect of the coating thickness on humidity sensitivity has also been investigated. Increasing the coating thickness from 12 μm to 15 μm resulted in an increase in humidity sensitivity from 13.5 pm/%RH to 17.8 pm/%RH [21].

Among the different sensing techniques, a humidity sensor based on surface plasmon resonance demonstrated the rapid response time of 0.251 s [27]. This was achieved by detecting the shift in the resonant wavelength resulting from changes in the refractive index of the polyvinyl alcohol and gold coatings. Various fiber structures have been explored to improve the sensor performance, employing different sensing techniques, such as the Mach-Zehnder

interferometer, Fabry-Perot interferometer, and air-gap long period grating, and other plasmonic methods. In the D-shaped fiber, S-taper fiber, and hollow-core fiber coated with different materials, the sensitivity ranging from 1.01 pm/%RH to 1.36 pm/%RH has been observed [26–28, 41].

To enhance humidity sensitivity, the sensing fibers were etched or polished. Etching significantly increased the sensitivity from 16 pm/%RH to 81 pm/%RH as seen with a chitosan coating on a polarization-maintaining fiber [24]. Another approach involved utilizing a cladding-etched SMF coated with a thin film of the tin oxide, which achieved the sensitivity of 1.9 nm/%RH [42]. Alternatively, to expose the core to the external environment, a twin-core fiber, a D-shaped polymer fiber, and an eccentric hole-assistant dual-core fiber were side-polished. The polished side of these fibers was coated with humidity-sensitive materials. These studies reported the improved sensitivity of -2.72 nm/%RH, 4.98 nm/%RH, and -7.005 nm/%RH, respectively [31, 43, 44].

Table 3 Comparative analysis of optical fiber-based humidity sensors, including the proposed sensor.

No.	Fiber structure	Sensing material	Technique	Sensitivity (nm/%RH)	Measurement range (% RH)	Response time (s)	Ref.
1	SMF	Polyimide	FBG	0.013 5	11.3–97.3	1 320	[21]
2	Polarization-maintaining fiber	Chitosan	SI	0.081	20–95	–	[24]
3	D-shaped fiber	Polyvinyl alcohol film with gold	Surface plasmon resonance	1.01	40–90	0.251	[27]
4	S-taper fiber	Nanoparticles	Mach-Zehnder interferometer	1.171 8	83.8–95.2	–	[41]
5	Hollow-core fiber	Polyimide	Fabry-Perot interferometer	-1.309	40–80	4	[26]
6	D-shaped fiber	Calcium chloride	Air-gap long period grating	-1.36	55–95	–	[28]
7	Cladding-etched SMF	Tin oxide	Lossy mode resonator	1.9	20–90	1.5	[42]
8	Side-polished twin-core fiber	Graphene-oxide	Michelson interferometer	-2.72	40–75	3.6	[31]
9	Eccentric hole-assistant dual-core fiber	Gelatin	Directional coupling	-7.005	70–90	1.28–2.97	[44]
10	SF1	Polyimide	SI	-1.49	30–95	2.1–5.4	This work
	SF2			-1.72	60–90		

5.3 Advantages, limitations, and future improvements

In optical fiber-based humidity sensors, sensitivity is typically increased by modifying the

fiber structure through tapering, etching, or polishing. These techniques bring the sensing materials closer to the core, thereby enhancing humidity sensitivity. However, such modifications,

along with the recoating process, add complexity to sensor fabrication. Exposing the core to air also results in high insertion losses, and the structural changes may compromise the fiber's physical strength.

The proposed sensor featured a simple fabrication process that eliminated the need for any post-processing of the fiber. The SF design directly enhanced sensing performance in two ways. First, the offset channels induced core ellipticity, generating high birefringence that strengthens the SI's response. Second, by positioning the polyimide coating closer to the core, the design ensured that humidity-driven swelling produced the more effective strain transfer, resulting in larger and more sensitive wavelength shifts. This structural innovation was a key factor in achieving both high sensitivity and stable and repeatable sensor operation. Sensitivity to humidity could be effectively tuned by adjusting the thickness of the coating. Notably, the polyimide coating exhibited a lower but linear sensitivity, which was attributed to its low permeability. This characteristic reduced hysteresis, improved linearity, and enhanced the sensor's reversibility. Nevertheless, the limited permeability restricted water molecules' penetration, thus resulting in smaller strain changes and, consequently, lower sensitivity to the RH.

In the fabrication process, the SF was fabricated by one step drawing process, the same as the commercial SMF drawing except that the precise control of machine grinding by CNC was needed to prepare the S-shaped preform. Generally, a tedious stacking method with two-stage fiber drawing was needed for the fabrication of photonic crystal fibers. The consistency and precision achieved in the fiber drawing and coating process directly impacted the reliability and scalability of the sensing device. To minimize batch-to-batch variation, the strict control of the temperature, tension, and drawing speed was maintained, and careful alignment of the preform in the furnace was ensured during fabrication using a

standard silica fiber drawing tower. Once the preform geometry and drawing conditions were optimized, this process enabled consistent, repeatable fabrication and was readily scalable for mass production. The drawing tower included a preform self-centering mechanism and two in-line diameter gauges for real-time monitoring of the fiber diameter in orthogonal directions. For standard circular fibers, automatic diameter control was used; for the S-shaped non-circular fiber, manual adjustment was maintained to achieve the desired dimensions. Under these conditions, the fiber diameter variation was within $\pm 2 \mu\text{m}$ over lengths exceeding 100 m, resulting in only minimal impact on the integrity or uniformity of the coating. For the 2 m sensing length used in this work, such variations were negligible for device performance. The SF demonstrated mechanical robustness comparable to standard silica fibers with the same coating material, and no unusual fragility was observed during experimental handling. A more systematic mechanical characterization is planned for future work.

There is a trade-off between the sensitivity and measurable RH range as the polyimide coating thickness varies. While thicker coatings improve sensitivity by enabling the greater water absorption and strain transfer, they also reduce the usable RH range and may degrade spectral quality. As such, the optimal coating thickness depends on the intended application: thinner coatings are preferable for broad-range and stable humidity monitoring, whereas thicker coatings are advantageous for applications needing higher sensitivity within a narrower RH interval. Further research should focus on optimizing the fiber-coating interface to balance these factors and investigate whether reducing the distance between the fiber core and sensing material can further enhance sensitivity.

In this study, a compact, flexible, and coiled sensor package was developed, and its performance was evaluated under various environmental

conditions. In wearable configurations, fiber coiling might introduce additional optical losses. Nevertheless, the packaged sensor maintained an extinction ratio above 12 dB in the reflection spectra, as shown in Fig. 11(b), with consistent performance exceeding 10 dB, sufficient for reliable signal processing. The proposed package design also allowed secure attachment to the sensing body, and further modifications to the sensor holder can minimize vibration and environmental noise.

Overall, these findings highlight the sensor's potential for real-time, non-invasive monitoring of skin and environmental humidity in wearable and biomedical applications. The combination of the high sensitivity, fast response, and robust temperature compensation makes the proposed sensor a promising candidate for future development in personal health monitoring and environmental sensing.

6. Conclusions

In conclusion, the proposed sensor employed a polyimide coating on an S-shaped fiber to detect changes in RH using the Sagnac loop technique. The fabrication of the sensor was straightforward, without the need for any fiber post-processing that would otherwise add complexity and reduce the sensor's robustness. Two sensors with different coating thicknesses demonstrated the sensitivity of $-1.49 \text{ nm}/\% \text{RH}$ and $-1.72 \text{ nm}/\% \text{RH}$ within the humidity ranges of 30% RH–95% RH and 60% RH–90% RH, respectively. In the interferometer-based approach, the temperature sensitivity was calibrated to be $-1.58 \text{ nm}/^\circ\text{C}$ and $-2.05 \text{ nm}/^\circ\text{C}$, for the sensors with thin and thick polyimide coatings, respectively. To compensate for temperature effects, an FBG with the temperature sensitivity of $10 \text{ pm}/^\circ\text{C}$ was integrated into the uncoated S-shaped fiber. The sensor's performance was affected by temperature variations at close proximity (up to 7 mm from the skin). At greater distances (9 mm and above), temperature effects were negligible, enabling selective and reliable humidity sensing. The effective sensing distance was influenced by both

ambient and skin humidity levels, with reliable detection typically achieved within 3 mm–9 mm. The detection range was reduced under drier conditions or higher ambient humidity. Limitations of the sensor include a reduced extinction ratio at extreme humidity levels for thicker coatings and decreased sensitivity with the increasing distance or under dry skin conditions. While the flexible, coiled package facilitates deployment in wearable and biomedical applications, further optimization may be required to address sensing range constrained by the free spectral range and the physical package design.

In summary, the proposed sensor exhibited high accuracy, excellent repeatability, reversibility, linearity, and resistance to condensation, ensuring its reliability for real-time and non-contact humidity measurement. Its long-term stability, chemical resistance, and ability to transmit sensing information over long distances make it suitable for various applications, including industrial process control, medical facilities, food processing and storage, and environmental monitoring.

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Declarations

Ethics Approval and Consent to Participate Experimental processes were supervised by Shanghai Municipal Hospital of Traditional Chinese Medicine, China with No. 2025SHL-KY-02-02. All the volunteers signed the informed consent before data collection. All approaches performed in the study involving data collection and storage were conducted in accordance with the Good Clinical Practice (GCP) and the Declaration of Helsinki. The study was approved by the Ethics Committee of Shanghai Municipal Hospital of Traditional Chinese Medicine, China.

Conflict of Interest The authors declare that they have no competing interests.

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Use of AI Statement During the preparation of this work, the authors used ChatGPT to improve the readability and language of the manuscript. After using these tools, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the final publication.

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