A Dual Fiber Humidity Sensor Based on Calcium Alginate Nanodiamond Particle Hybrid Film

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Abstract: A dual fiber spherical lens structure is proposed, which coatings calcium alginate gel mixed with nano diamond particles on the surface of the spherical lens and solidifies into a film. The design of the probe structure not only combines the advantages of nano and block diamond, but also further increases the fluorescence collection intensity and reduces the required optical components while ensuring the functionality of the probe structure, improving the integration of the entire system. The environmental temperature and humidity were measured, and the humidity sensitivity of the experiment was reduced by 175 photon counting units for every 1% increase in RH. In temperature measurement, we found that the unique ZPL redshift and broadening phenomena of temperature changes can be utilized to self-calibrate the sensor without the need for cascaded fiber Bragg gratings, achieving dual parameter measurement of humidity and temperature.

Keywords: humidity sensor; optical fiber; nano diamond

1. Introduction

Humidity is one of the important physical quantities in human life, and the detection and measurement of environmental humidity are particularly important in various fields, such as agriculture, industry, meteorology, medical treatment, cultural relic protection, and military [1-3]. In the past decade, the development of fiber optic humidity sensors using optical fibers as carriers has been rapid. The two most common types are: fiber optic sensing humidity sensors and fiber optic transmission humidity sensors.

For fiber optic humidity sensors, fiber optic is the essence of humidity sensing. When the optical signal is transmitted through the fiber optic, water vapor gradually accumulates on the fiber optic as the humidity increases, causing a change in the refractive index near the sensing area and achieving humidity sensing. Typical structures include microsphere resonant cavity type [4], based on Mach Zehnder fiber type structure, F-P structure, FBG structure, etc. [5-11]. Fiber optic humidity sensors usually refer to humidity measurement based on humidity sensitive thin film materials. Generally, humidity sensitive materials are coated on the fiber structure. When the environmental humidity changes, the volume and refractive index of the thin film will change, thereby affecting the transmission parameters of light in the fiber, such as wavelength, phase, and light intensity. The use of materials such as humidity sensitive films can greatly improve the humidity sensitivity of fiber optic humidity sensors. However, it should be noted that humidity sensitive films should be minimized from interference from other physical quantities in the environment, with temperature crosstalk being the most significant.

In order to reduce the impact of temperature changes on sensors, a fiber optic grating is usually cascaded with a humidity sensor for calibration. However, cascaded fiber Bragg gratings not only reduce the integration and mechanical strength of sensors, but also cause new physical crosstalk. Due to the sensitivity of fiber Bragg gratings to physical quantities such as stress, new cross sensitivity may also be added during the measurement process, which can have a significant impact on the accurate measurement of sensors. In order to solve the above problems, it is necessary to propose a fiber optic humidity sensor with high integration, strong mechanical stability, no introduction of new crosstalk, and temperature calibration capability.

In this paper, an optical fiber humidity sensor is proposed, which integrates CaAlg hydrogel film containing nano diamond particles with a dual fiber probe and realizes the all-optical measurement of humidity. The humidity sensitivity reaches a decrease of 175 photon count units in peak fluorescence intensity for every 1% increase in RH. And further solves the problem of temperature crosstalk, allowing for self-calibration without the need to cascade other temperature sensors, achieving dual parameter measurement of humidity and temperature. For sensing probes, this greatly enhances their integration and mechanical stability, further expanding the application range of diamond NV color center measurement.

2. Sensor Fabrication and Principle

As shown in Figure 1, the microscopic image of the dual fiber spherical lens probe is presented. The production process first aligns two MMFs (MMF1 and MMF2) and fixes them in the detachable fixture of the fiber fusion splicer (Fujikura FSM-100P+). Then, the fiber optic fixture is placed in the fusion splicer. It should be noted that after adjusting the welding machine to motor drive, the two optical fibers are moved to the edge position of the screen image, and then arc discharge is performed. After multiple attempts, it was found that by adjusting the arc discharge power and discharge time appropriately, the curvature radius of the lens can be further changed.

By utilizing humidity sensitive thin film materials, the sensitivity of sensors can be greatly improved. Therefore, combining dual fiber probes with humidity sensitive thin films mixed with nano diamond particles is expected to produce high sensitivity fiber optic humidity sensors. Based on this, the selection of humidity sensitive materials is crucial. At present, common humidity sensitive materials include semiconductor materials, porous metal oxides, electrolytes, ceramic substrates, and polymer materials. Among them, hydrogel is one of the polymer materials, which has the characteristics of polymer electrolyte and three-dimensional structure. There are a large number of hydrophobic groups and hydrophilic residues in the cross-linked network structure. The hydrophilic residues combine with water molecules, and the hydrophobic groups expand, which can absorb a large amount of moisture particles and expand themselves [12]. Calcium alginate (CaAlg) hydrogel has excellent biocompatibility, adhesion and water retention. Its three-dimensional network structure can absorb and release water molecules, so it becomes an excellent humidity sensitive film material. Calcium alginate needs to be made from sodium alginate (NaAlg) and calcium chloride. The naturally occurring sodium alginate will undergo cross-linking reaction when encountering calcium chloride, generating sodium chloride and calcium alginate.

Figure 1. Optical microscopy of dual fiber probe.

A novel dual fiber humidity sensor is proposed by combining a dual fiber probe with CaAlg hydrogel mixed with nano diamond particles. The thickness of CaAlg mixed adhesive is approximately 20 μ m, and the concentration is still 20 mg/ml. Figure 2 shows the fluorescence spectrum obtained under the excitation power of 20 mW after the CaAlg mixed gel is coated on the surface of the dual fiber probe. The ZPL and fluorescence characteristic peaks can be clearly seen from Figure 2, which indicates that the fluorescence signal can still be stably excited and collected after the CaAlg hydrogel and nano diamond particles are mixed.

3. Experimental Results and Discussion

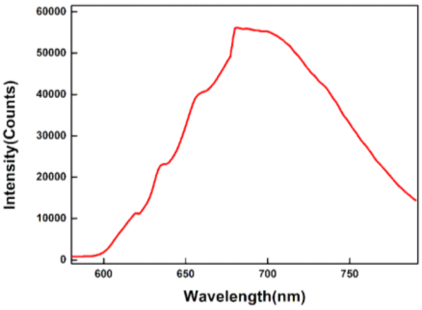

Figure 2. Fluorescence spectra collected by coupling dual optical fibers with CaAlg mixed adhesive.

We recorded the fluorescence spectra corresponding to four humidity values of the probe within the range of 30% to 60% humidity, with a constant ambient temperature of 20 ℃ during testing. The experimental results are shown in Figure 3(a). We can see that as the humidity in the environment increases, the intensity of the fluorescence characteristic peak will decrease. This is because as the humidity increases, the CaAlg mixed gel absorbs moisture and expands, leading to a decrease in refractive index. More fluorescence is leaked out of the mixed gel, resulting in a decrease in coupling efficiency and a decrease in the collected fluorescence intensity. There is a slight decrease in fluorescence intensity at the ZPL position, which is caused by the overall decrease in fluorescence intensity, and the ambient temperature is constant during humidity testing, so there is no redshift or broadening phenomenon in the ZPL. Figure 3(b) shows the fitting curve of fluorescence peak intensity with humidity variation. It can be seen that for every 1% increase in humidity, the corresponding peak fluorescence intensity decreases by 175 photon count units.

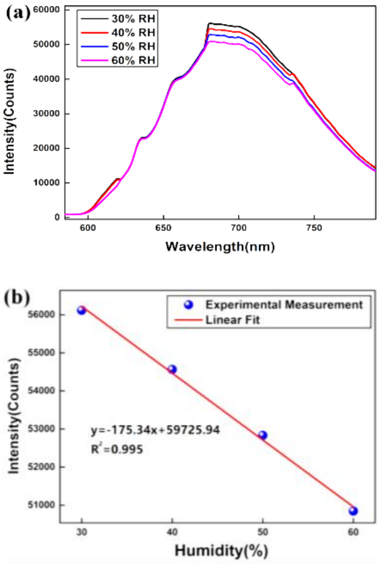

Figure 3. (a) Fluorescence spectra corresponding to different humidity environments; (b) fluorescence peak intensity fitting.

In order to test the stability of the humidity probe, under the same temperature conditions, the humidity of the humidity chamber was maintained at around 50% RH, and fluorescence spectra were taken every 10 minutes from 0 to 40 minutes, as shown in Figure 4 (a). It can be seen that their spectra almost overlap with very small fluctuations. Figure 4 (b) shows the variation of fluorescence peak intensity with time at five time points, indicating that the performance of the dual fiber probe humidity sensor is very stable.

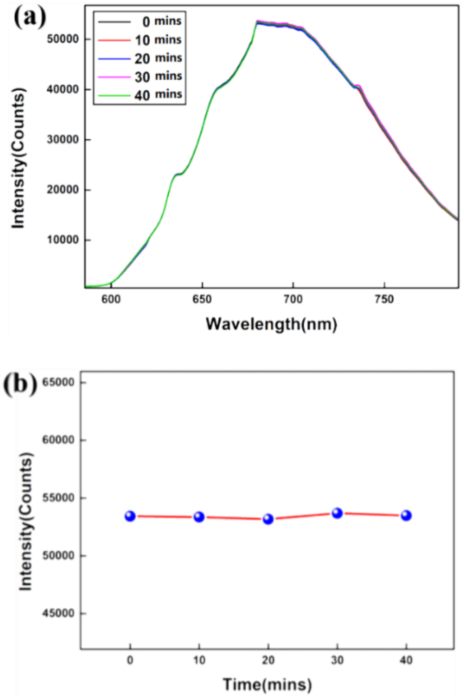

Figure 4. (a) Fluorescence spectrum of the sensing probe at 50% rh within 40 minutes; (b) changes in fluorescence peak intensity at different time points.

Finally, we measured the temperature cross sensitivity of the sensing probe, keeping the relative humidity constant. The temperature was changed from 20 ℃ to 60 ℃, and recorded every 10 ℃. The experimental results are shown in Figure 5 (a). When the temperature increases from 20 ℃ to 60 ℃, a significant decrease in fluorescence intensity can still be observed. This indicates that the CaAlg mixed adhesive film has a very obvious temperature response. When the temperature increases, the CaAlg mixed adhesive film expands due to heat, and the refractive index decreases, leading to fluorescence leakage. When the temperature rises from 20 ℃ to 60 ℃, the change in fluorescence intensity is 3743 photon counting units. As shown in Figure 5 (b), a fitting curve of the fluorescence peak intensity with temperature variation is presented. It can be seen that for every 1 ℃ increase in temperature, the corresponding peak fluorescence intensity decreases by 97 photon counting units. Therefore, the sensor is sensitive to both humidity and temperature, and an increase in temperature and humidity will cause a decrease in the refractive index of CaAlg mixed adhesive film, resulting in fluorescence leakage and a decrease in fluorescence collection intensity. We found that the redshift of the wavelength of ZPL in temperature measurement is about 1.8 nm, as shown in Figure 5(c), with a sensitivity of 0.0465 nm/℃ and accompanied by significant broadening. This phenomenon only occurs when the temperature changes, as shown in Figure 3(a), where changes in humidity do not cause redshift and broadening of ZPL. Therefore, by utilizing this, temperature self-calibration of the sensor can be achieved without cascaded fiber Bragg gratings, achieving dual parameter measurement of humidity and temperature.

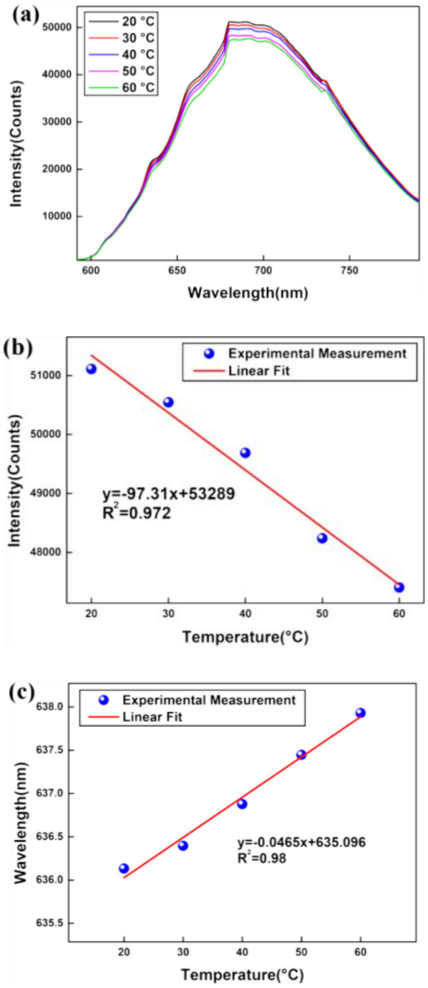

Figure 5. (a) Temperature fluorescence spectrum of the sensing probe; (b) fluorescence peak intensity fitting; (c) zpl wavelength drift fitting.

4. Conclusion

We proposed and fabricated an optical fiber humidity sensor based on the integration of CaAlg hydrogel film containing nano diamond particles and dual fiber probes. The change in humidity in the surrounding environment can indirectly affect the fluorescence collection efficiency excited by the NV color center, thereby achieving high sensitivity measurement of humidity. The humidity sensitivity of this experiment is that for every 1% increase in RH, the corresponding peak fluorescence intensity decreases by 175 photon counting units. In temperature measurement, we found that the unique ZPL redshift and broadening phenomena of temperature changes can be utilized to self calibrate the sensor without the need for cascaded fiber Bragg gratings, achieving dual parameter measurement of humidity and temperature.

Acknowledgments

This paper is supported by Science and Technology on Electromechanical Dynamic Control Laboratory, China (Grant No.6142601CX2201).

References

[1] J. G. Zhang, W. B. Li, N. Han, and J. M. Kan, “Forest fire detection system based on a ZigBee wireless sensor network,” Front. Forest. China 3, 369–374 (2008).

[2] M. A. Bratin, R. Oschmann, and P. C. Schmidt, “Influence of excipients and storage humidity on the deposition of disodium cromoglycate (DSCG) in the twin impinger,” Int. J. Pharm. 135, 53–62 (1996).

[3] I. Andersen and J. Korsgaard, “Asthma and the indoor environment: assessment of the health implications of high indoor air humidity,” Environ. Int. 12, 121–127 (1986)

[4] Deng S.; Meng H., et al. Graphene oxide-film-coated splitting ratio-adjustable Mach-Zehnder interferometer for relative humidity sensing. Optics Express, 2019, 27(6): 9232-9240.

[5] G. Berruti, M. Consales, M. Giordano, L. Sansone, S. Buontempo, G. Breglio, and A. Cusano, “Radiation hard humidity sensors for high energy physics applications using polymide-coated fiber Bragg gratings sensors,” Sens. Actuators B 177, 94–102 (2013).

[6] T. L. Yeo, T. Sun, and K. T. V. Grattan, “Fibre-optic sensor technologies for humidity and moisture measurement,” Sens. Actuators A 144, 280–295 (2008).

[7] W. C. Wong, C. C. Chan, L. H. Chen, T. Li, K. X. Lee, and K. C. Leong, “Polyvinyl alcohol coated photonic crystal optical fiber sensor for humidity measurement,” Sens. Actuators B 174, 563–569 (2012).

[8] W. Bai, M. H. Yang, J. X. Dai, H. H. Yu, G. P. Wang, and C. J. Qi, “Novel polyimide coated fiber Bragg grating sensing network for relative humidity measurements,” Opt. Express 24, 3230–3237 (2016).

[9] N. Liu, M. L. Hu, H. Sun, T. T. Gang, Z. H. Yang, Q. Z. Rong, and X. G. Qiao, “A fiber-optic refractometer for humidity measurements using an in-fiber Mach–Zehnder interferometer,” Opt. Commun. 367, 1–5 (2016).

[10] A. Urrutia, J. Goicoechea, A. L. Ricchiuti, D. Barrera, S. Sales, and F. J. Arregui, “Simultaneous measurement of humidity temperature based on a partially coated optical fiber long period grating,” Sens. Actuators B 227, 135–141 (2016).

[11] W. Xu, W. B. Huang, X. G. Huang, and C. Y. Yu, “A simple fiber-optic humidity sensor based on extrinsic Fabry–Perot cavity constructed by cellulose acetate butyrate film,” Opt. Fiber Technol. 19, 583–586 (2013).

[12] Luo H.,Liang L., et al. Relative Humidity and Temperature Sensing Characteristics of an Optical Fiber Probe Based on Hollow-Core Fiber and Calcium Alginate Hydrogel Film. IEEE Sensors Journal, 2018, 18(19): 8022-8026