Polyvinyl alcohol–coated hybrid fiber grating for relative humidity sensing

Xinyong Dong
Tao Li
Yang Liu
Yi Li
Chun-Liu Zhao
Chi Chiu Chan

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Xinyong Dong,ᵃ Tao Li,ᵃ Yang Liu,ᵃ Yi Li,ᵃ Chun-Liu Zhao,ᵃ and Chi Chiu Chanᵇ
ᵃChina Jiliang University, Institute of Optoelectronic Technology, Hangzhou, China, 310018
ᵇNanyang Technological University, School of Chemical and Biomedical Engineering, Singapore, 637457, Singapore

Abstract. A relative humidity (RH) sensor based on a hybrid fiber grating coated with polyvinyl alcohol is proposed and demonstrated experimentally. The hybrid fiber grating is formed by superimposing a normal fiber Bragg grating (FBG) and a tilted-FBG around the same position of a single-mode fiber so that it can work in the reflection mode. Optical power of the reflected signal changes with the refractive index of the moisture sensitive polyvinyl alcohol, and humidity measurement can be realized. Experimental results show that the measurement range is 30 to 95% with the maximum sensitivity of 0.737 nW/% RH. The average response time is ~2 s and the measurement is nearly insensitive to temperature. Compared with the wavelength detection method used in normal FBG-based relative humidity sensors, the intensity demodulation method in this report is simpler and more cost-efficient.
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1 Introduction

Humidity monitoring is widely required in biomedical areas[1,2] and industrial fields such as food processing, air conditioning, and papermaking. Compared with conventional humidity sensors based on the measurement of electrical resistivity or capacitance of various humidity-sensitive materials, optical fiber-based humidity sensors have many advantages, such as electrically passive operation and immunity to electromagnetic interference. In recent years, many optical fiber-based relative humidity sensors have been reported based on various sensing structures, including tapered fibers,[3] fiber Bragg gratings (FBGs),[4] long-period gratings (LPGs),[5] plastic optical fibers,[6] and tilted-fiber Bragg gratings (TFBGs).[7] Among them, TFBGs, which possess the merits of the FBGs and LPGs, have attracted considerable interest in sensing applications. TFBGs belong to the short-period gratings family, but the grating planes are slanted or blazed with respect to the fiber axis. The cladding modes of TFBGs are sensitive to external perturbations (strain, temperature, bending, refractive index, etc.),[8–11] but most TFBG-based sensors are operated in a transmission manner and have a wide attenuation band which causes difficulty in reading the exact wavelength of the loss.

In this paper, a hybrid fiber grating formed by superimposing a normal FBG and a TFBG around the same position of a single-mode fiber is proposed for humidity sensing by coating with a layer of polyvinyl alcohol (PVA), a polymeric material, whose refractive index (RI) is sensitive to moisture. It is envisaged that this sensing structure will find an application in biomedical engineering where the measurement of humidity with high sensitivity is often required. The transmitted optical power of the TFBG is sensitive to the surrounding RI, thus humidity measurement is

realized. Experimental results show that the measurement range covers 30 to 95% with the maximum sensitivity of 0.737 nW/% RH. The average response time is ~2 s and the measurement is nearly insensitive to temperature. The intensity demodulation method is simpler and more cost-efficient than the wavelength detection method used in normal FBG-based relative humidity sensors.

2 Design and Principle

The hybrid fiber grating used in our experiment includes a normal FBG and a TFBG superimposed around the same position of the fiber, as shown in Fig. 1. The TFBG is much longer than the FBG so the latter can be located at the rear part of the former. The key point is that the Bragg resonant wavelength of the FBG is selected to coincide with the wavelength region of the cladding modes of the TFBG.

The hybrid fiber grating was fabricated in a H2-load B/Ge co-doped photosensitive fiber with a 244-nm frequency-doubled Argon laser and the phase mask technique. The length of the TFBG is 2.0 cm and the tilted angle is about 5 deg. After the fabrication of the TFBG, a 0.3-cm Long normal FBG was superimposed at the rear part of the TFBG. The reflection and transmission spectra of the hybrid fiber grating are shown in Fig. 2. The FBG has the Bragg resonant wavelength of 1552 nm, while the TFBG has Bragg wavelength of 1566 nm. The reflection spectrum contains the Bragg mode and several cladding modes of the TFBG. As the FBG reflection covers some TFBG cladding-mode resonances, it presents a modulation depending on the optical power changes due to TFBG's core to radiation mode coupling. When the coupling coefficient changes with surrounding RI arising from humidity changed, the reflected optical power will be changed also. The obvious

Address all correspondence to: Xinyong Dong, China Jiliang University, Institute of Optoelectronic Technology, 258 Xueyuan Street, Xiasha-Hangzhou, Zhejiang 310018 China. Tel: 8657187676260; Fax: 8657186914576; E-mail: xydong@cjlu.edu.cn.
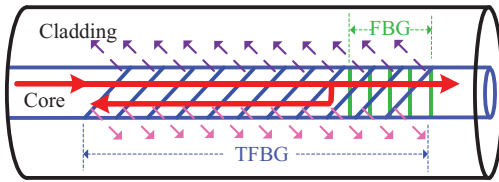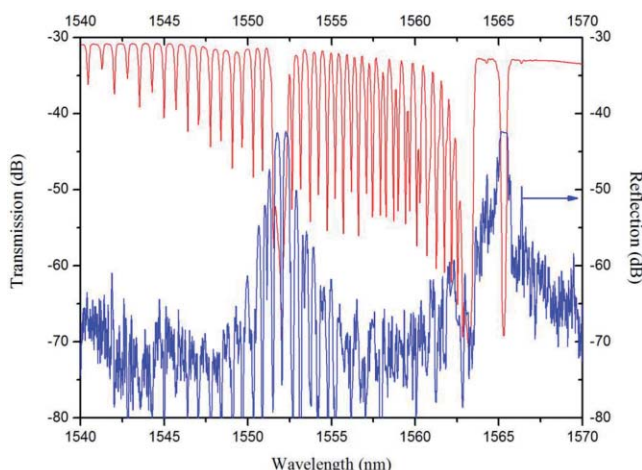
Fig. 1 Schematic of the hybrid fiber grating including a TFBG and a FBG.

advantages of this hybrid grating structure, in addition to its compact nature and the low-cost optical power measurement, is that it can work in reflection mode. The superimposed FBG acts as a reflective filter, reflecting a narrowband light with the wavelength located at the cladding modes area of the TFBG. The corresponding light transmits the TFBG twice due to the FBG's reflection; thus, its optical power is modulated twice by the TFBG. The proposed sensor setup, therefore, works in the reflection mode and an enhanced sensitivity is expected.

PVA was selected as the humid sensitive material and was coated outside the grating. It was reported that its RI will decrease from 1.49 to 1.35 when humidity increases from 20 to 95% RH.[7] When RI of the PVA is higher than that of fiber cladding (∼1.44) at low humidity level, the high-order cladding modes will be affected and transformed into radiation modes, resulting in the reduction in optical power. With the increase of humidity, the reflected optical power from the hybrid fiber grating will be increased too.

3 Experimental Results and Discussion

To coat the hybrid fiber grating with PVA, the PVA granules (dry) were mixed with deionized water to form a PVA solution (5%). The hybrid grating was first cleaned with deionized water and then coated by using the dip-coating process to achieve a 6-μm thick coating of PVA. The experimental measurement system is shown in Fig. 3. Light from a broadband source (BBS) was launched into the hybrid fiber grating through an optical fiber circulator (OC). The reflected light is guided into an optical spectrum analyzer (OSA) with resolution of 0.02 nm or
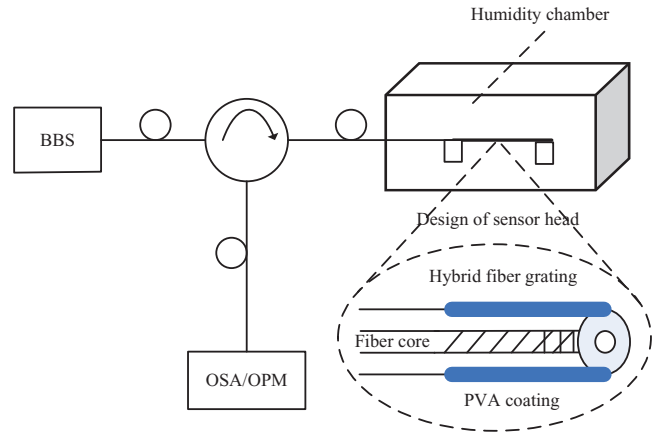

Fig. 3 Experimental measurement setup of the proposed humidity sensor.

an optical power meter (OPM). The hybrid grating coated with PVA was kept free from any strain and bending, and was placed in a humidity-controllable chamber.

Humidity measurements were carried out when the RH was changed from 30 to 95% RH under fixed temperature of 25°C. When the humidity was changed, the reflection spectrum and reflected optical power of the hybrid fiber grating were recorded. Figure 4 shows the measured reflection spectra of the hybrid grating under different humidity of 30, 80, and 95% RH. It can be seen that the reflection of the normal FBG is significantly changed with humidity, whereas the reflected power of the Bragg mode of the TFBG is almost unchanged. This is in good agreement with the theoretical prediction. Figure 5 gives the reflected optical power of the hybrid fiber grating under different humidity in both ascending and descending order. For the sensor tested in this paper, a small but acceptable degree of hysteresis (<5% RH) was observed. The resolution is about 1% RH. However, fluctuations of the light source power and transmission fiber loss caused by bending or whatever may change the sensor output. The error in the readout of the sensor was 7% RH. The sensor responded monotonically when humidity was changed from 30 to 95% RH. The average response time was ∼2 s. The maximum sensitivity was 0.737 nW/% RH, achieved within the range of 50 to 70% RH.

Fig. 2 Reflection and transmission spectra of the hybrid fiber grating.
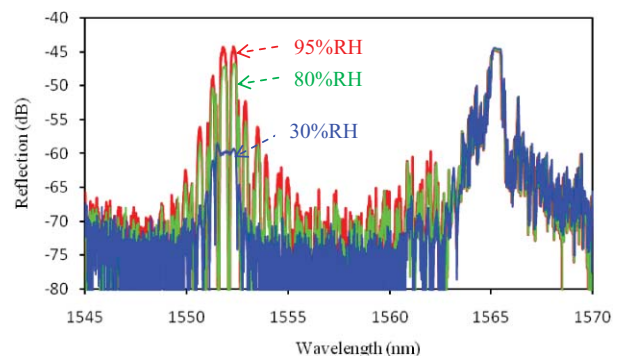
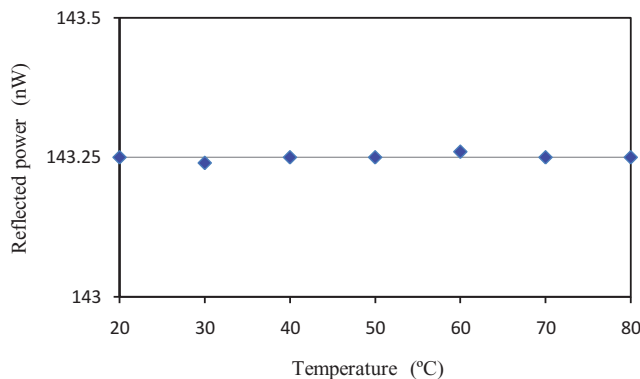**Fig. 4** Reflection spectra of the proposed humidity sensor exposed to humidity of 30, 80, and 95% RH.
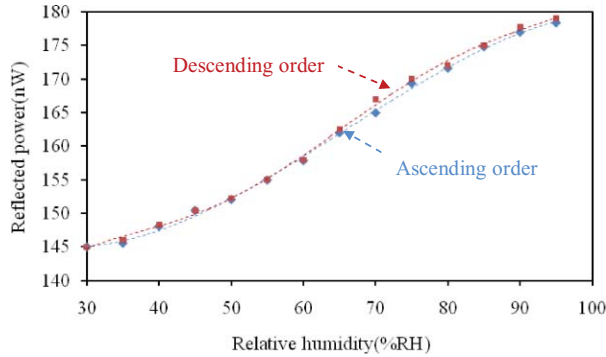
Fig. 5 Hysteresis of the proposed humidity sensor subjected to humidity change from 30 to 95% RH in both ascending and descending order.

Fig. 7 Stability test of the proposed humidity sensor under constant RH of 30 and 95% RH.
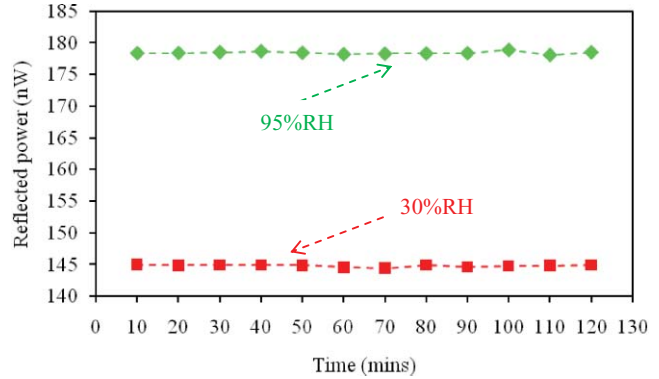
The minimum reflected power was 144.97 nW, which is relatively high because it included the Bragg mode of the TFBG. This part of the reflected power can actually be used as reference to remove the influences of power fluctuation of light source and fiber bending induced loss on the measurement. Here, it was not measured separately due to lack of a suitable wavelength-selective filter. It is difficult because the wavelength of the Bragg mode of TFBG is variable with temperature so the selected filter should also change in phase. However, this will be studied in our further experiments.

The thermal stability test measurement was carried out under a fixed humidity and varying the temperature form 20°C to 80°C. The measured results are shown in Fig. 6. The reflected Bragg mode and the cladding modes shifted simultaneously as a result of the thermo-optic effect and the thermal expansion of the fiber. But the wavelength shift did not affect the reflected optical power. Negligible variations less than 0.3 nW were recorded by the OPM. These experimental results show that the proposed humidity sensor is nearly temperature insensitive.

Figure 7 shows the stability test results of the proposed RH sensor under constant RH of 30% and 95%, respectively. Only a minor fluctuation of 3 nW has been observed over a period of 120 mins That may be caused by power fluctuation of the light source.

4 Conclusion

A PVA-coated hybrid fiber grating sensor for humidity measurement has been proposed and experimentally investigated. The hybrid fiber grating was formed by superimposing a normal FBG and a TFBG around the same position of a single-mode fiber so that it can work in reflection mode. Optical power of the reflected signal changed with refractive index of the moisture sensitive polyvinyl alcohol so that humidity measurement was realized. Experimental results show that the measurement range of 30 to 95% has been achieved with a maximum sensitivity of 0.737 nW/% RH. The average response time is ∼2 s and the measurement is insensitive to temperature. The intensity demodulation method is simpler and more cost-efficient than the wavelength detection method used in normal FBG-based relative humidity sensors.

Fig. 6 Reflected optical power of the proposed humidity sensor against temperature.

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