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Fiber optic sensing of relative humidity using a twin low coherence interferometer

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A fiber-optic implementation of psychrometer is reported. It consists of two Sagnac interferometers with twisted highly birefringent fiber that is used as a temperature sensitive element. One interferometer is used for dry-bulb temperature measurement and the other is for wet-bulb temperature monitoring. The interrogation technique for low coherence interferometric sensor with signal processing in spectral domain is described. The measurement uncertainties for temperature and relative humidity measurements no worse than 0.01°C and 4%, respectively, have been achieved experimentally.

Keywords: Fiber-optics sensors; sagnac interferometer; low-coherence interferometry; birefringent fiber; relative humidity.

En este trabajo se describe un sensor de humedad de fibra óptica que consiste en dos interferómetros de Sagnac con secciones de fibra óptica torcida de alta birrefringencia. Las fibras birrefringentes sirven como elementos sensibles a la temperatura que permiten medir simultáneamente la temperatura de bulbo seco y bulbo mojado. Se describe el método para interrogación de dos sensores de temperatura basados en la interferometría de baja coherencia con procesamiento de señales en el dominio espectral. La incertidumbre de la medición, estimada experimentalmente, es de 0.01°C y 4% para mediciones de temperatura y humedad, respectivamente.

Descriptores: Sensores de fibra óptica; interferometría de baja coherencia; fibra birrefringente; humedad relativa.

PACS: 42.81.Pa; 92.60.Jq; 07.60.Ly

1. Introduction

The importance of the humidity measurements in science and industry arises from the fact that many important natural and synthetic materials change their characteristics with moisture. In the chemical, electronics, food, pharmaceutical, and other industries the production and storage can be improved only with better control of humidity. The fiber optic humidity sensors offer important advantages of freedom from electromagnetic interference, intrinsic safety and remote monitoring. Different types of fiber optic sensors have been proposed and demonstrated, that are based on various physical effects: the color change in the same materials with humidity [1], changes of dimensions [2], refractive index [3], or reflectivity of optical materials [4].

In this work we demonstrate the fiber optic implementation of the hygrometer, which uses a simple, well known method for humidity measurement. This type of hygrometer is known as a psychrometer and consists of two thermometers, one of which is used for measurement of the air temperature; this is so-called dry-bulb thermometer, and the other thermometer is kept wet to measure the wet-bulb temperature. The difference between the readings of the two thermometers gives information about the humidity. This type of hygrometer has not been demonstrated with fiber optic thermometers, while the high accuracy and other advantages of fiber optic sensors indicate this will be a highly competitive device.

2. Experimental setup

Figure 1 shows a diagram of the experimental setup used for demonstration of the fiber optic psychrometer. The optical part of the setup includes two fiber optic Sagnac interferometers connected in series. Each interferometer consists of a non-polarization preserving coupler with output ports connected by bow-tie high-birefringent fiber (HBF) F-SPF supplied by Newport Corp. with a beat-length of less than 2 mm, a $4.2\ \mu\text{m}$ mode field diameter, and a 0.15 numerical aperture. This fiber serves as a temperature sensitive element. The sensing with HBF is based on interferometric monitoring of the optical path difference between polarization eigenmodes. The polarization mode interference in output port of the fiber coupler is insured by the twist of HBF [5,6]. Interrogation of two interferometers was possible due to difference in the lengths of the HBF, one of which had $L_1 = 51.5\ \text{cm}$ and the other $L_2 = 31.5\ \text{cm}$. As a low coherence light source we used a GaAlAs superluminescent diode (SLD) manufactured by Opto Diode Corp. with the spectrum centered at 880 nm and spectral bandwidth at a half-maximum of 80 nm. The two lead-fibers (HI 780 by Corning Corp.) that connect the first loop interferometer with SLD and the second one with the CCD-spectrometer were single-mode fibers with a mode diameter of $5\ \mu\text{m}$ and length of several meters. Sensor 1 was covered with a wet cloth and together with sensor 2 was placed in a test chamber with controlled humidity. Two standard electronic sensors were used for calibration of the fiber optic psychrometer namely a humidity sensor IQ6559

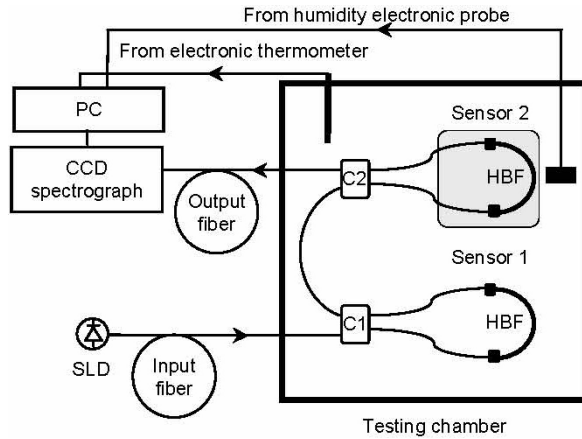


FIGURE 1. Experimental arrangement. C1 and C2 are the fiber optic directional couplers.

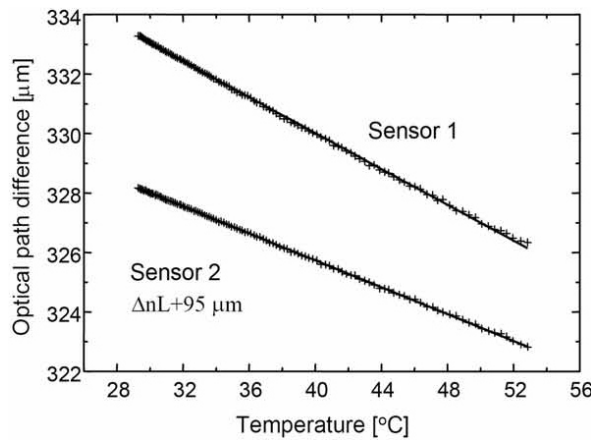


FIGURE 2. Optical path differences as functions of the temperature. For clarity of the graph, the data of sensor 1 are shifted vertically for 95 μm.

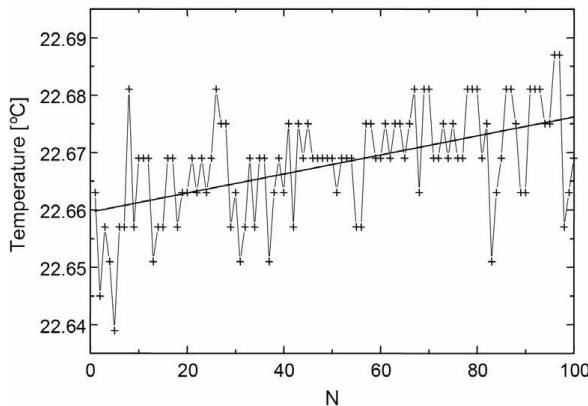


FIGURE 3. The results of 100 measurements of the temperature. The straight line indicates the best linear fitting of the experimental values.

and temperature sensor IQ65050A manufactured by PASCO Scientific. The spectrograph (InstaSpec IV, Oriel Corp.) used in this work has a CCD sensor with 1024 sensitive elements and spectra approximately 150 nm wide can be recorded into PC-computer for processing in real time.

The output intensity of the dual interferometer detected by the CCD-spectrograph can be written as

$$I(\lambda) = I_0(\lambda)[1 + m \cos \varphi_1 + m \cos \varphi_2 + \frac{1}{2}m^2 \cos(\varphi_1 + \varphi_2) + \frac{1}{2}m^2 \cos(\varphi_1 - \varphi_2)], \quad (1)$$

where $I_0(\lambda)$ is the input intensity on port 1 of the fiber coupler C1, m is the modulation index, φ_i is the phase mismatch between the polarization modes of HBF, $\varphi_i = (2\pi\Delta nL_i)/(\lambda)$, $i = 1, 2$, and Δn is the birefringence of HBF. As was shown earlier, the optical path difference of the HBF used depends linearly on the fiber temperature in least in the range 0-300 °C [6,7].

For separate measurement of wet and dry temperature, the dependencies of $\varphi_1(k)$ and $\varphi_2(k)$ are calculated using the output spectrum $I(\lambda)$, where k is the wavenumber, $k = (2\pi)/(\lambda)$. The dependence $I(\lambda)$ is transformed into dependence $I(k)$ and digitally filtered after fast Fourier transform (FFT) to extract the signals corresponding to the terms $\cos \varphi_i(k)$ in Eq. (1). The signals can be separated by filtering due to different length of HBF of each interferometer. The inverse FFT permits the cosine signal reconstruction, from which the phase dependence $\varphi_i(k)$ and then the optical path difference ΔnL_i are calculated.

3. Results

During the calibration, two fiber optic temperature sensors were placed inside the testing chamber and optical path differences were calculated simultaneously for both sensors, while the temperature was changed continuously. The result of calibration is shown in Fig. 2. The ratio between the optical path differences between sensor 1 and 2 is 1.4453 in the temperature range used for calibration. This value is in good agreement with the ratio between HBF lengths $L_1/L_2 = 1.45$.

To estimate the temperature measurement uncertainty, two fiber optic sensor were kept at approximately constant temperature and the sensor response was measured 100 times with a time interval between measurements of 5 s. The results are shown in Fig. 3, where the experimental points are presented as '+'. As one can see in Fig. 3, the temperature had a slow deviation from constant with typical for our laboratory rate of 0.01°C/ min. In our case of slow temperature change, the measurement uncertainty was calculated as a standard deviation of experimental data from the best linear fitting obtained by the method of least squares; this fitting is shown in Fig. 3 as a straight line,

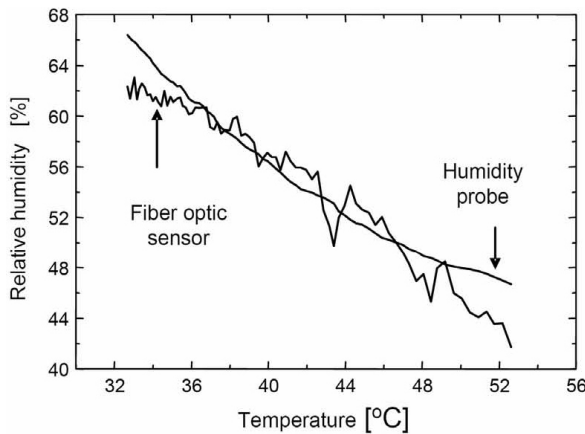


FIGURE 4. Comparison between the readings of fiber optic and electronic relative humidity sensors.

$$\delta T = \left[\frac{1}{N-1} \sum_{k=1}^N (T_k - \bar{T}_k)^2 \right]^{\frac{1}{2}}, \quad (2)$$

where T_k is the experimental value of the temperature, \bar{T}_k is the linear fitting of experimental data, and N is the number of measurements. In this experiment the uncertainty of the optical path difference was estimated as $\delta(\Delta nL) = 2$ nm, and the uncertainty of the temperature measurements as $\delta T = 0.01^\circ\text{C}$.

To demonstrate the humidity sensor functioning, a computer program was developed that allows the humidity calculation using the data of temperature sensors. The program is based on widely available relative humidity tables that give the approximate values of relative humidity directly from the readings of the air and wet-bulb temperatures for different atmospheric pressures (see, for instance, [8]). We found that for a broad enough range of atmospheric pressure, between 710 and 775 mmHg, the relative humidity can be calculated as

$$H = 100 - 7.6\Delta T + 0.1\Delta T(T_D - 20), \quad (3)$$

where T_D is the air temperature (dry-bulb temperature), and ΔT is the difference between T_D and the wet-bulb temperature expressed in $^\circ\text{C}$. This equation allows humidity calculation with the accuracy better than 2% in the range of the air

temperature 20-50 $^\circ\text{C}$. In the compliance with calibration the temperature readings of two fiber optic sensors were calculated as

$$T_i = T_{0i} + S_i(\Delta nL_i), \quad (4)$$

where $T_{01}=1064.4^\circ\text{C}$, $T_{02}=1135.2^\circ\text{C}$, the sensitivities of the temperature sensors $S_1=4.4223^\circ\text{C}/\mu\text{m}$, $S_2=3.3199^\circ\text{C}/\mu\text{m}$, and the HBF optical path difference ΔnL_i is presented in μm .

In the experiment with humidity measurement, sensor 2 was covered with a wet cloth that results in the difference ΔT between the reading of sensor 1 and 2 and permits the calculation of the relative humidity. The humidity was changed in the testing chamber by the temperature control. Simultaneously with the fiber optic sensor, the standard electronic sensor was used for humidity measurement. The experimental data presented in Fig. 4 show the concordance between the readings of the fiber optic and electronic humidity sensors. The measurement uncertainty of the fiber optic humidity sensor was estimated in this experiment as 4%.

4. Conclusions

We have demonstrated the fiber optic relative humidity sensor that exploits the psychrometer's principle of operation involving the dry- and wet-bulb temperature measurements. As temperature sensors, two loop interferometers connected in series were used, and the sections of twisted HBF of different lengths included in each loop served as the temperature sensitive elements. The low coherence interferometric technique was used for temperature decoding with signal processing in the spectral domain. Sensor interrogation was implemented using the digital filtering of the spectral signals. High precision temperature measurement has been demonstrated with a measurement uncertainty of 0.01%. Nevertheless, the humidity measurement uncertainty of 4% obtained experimentally is too high to be in agreement with this value. We believe that an imperfect design of the humidity sensor probe head is a plausible reason for this discrepancy. The improvement can be achieved by the reduction of temperature fluctuations of the air flow and by an increase in response time of the fiber optic temperature sensors that have to reduce the uncertainty in the measurement of temperature difference ΔT .

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