DEVELOPMENT OF AN OPTICAL FIBER-BASED MOISTURE SENSOR FOR BUILDING ENVELOPES

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ABSTRACT

Optical fiber-based moisture sensors have been developed to help detect moisture problems in building envelopes. The sensors are created with a coating on a long period grating that is written onto optical fiber. As the coating absorbs moisture from its surroundings, the refractive index of the coating changes, thereby changing the propagation of light down the fiber. In addition to the humidity sensors, temperature sensors based on Fiber Bragg Grating technology and Fabry-Perot interferometry have been developed to provide temperature compensation. Tests in a humidity chamber show significant sensitivity of the sensors to humidity, with a linear response to temperature. In addition to tests in the environmental chamber, the sensors were also tested as moisture content sensors on samples of gypsum board, oriented strand board, and pine. These tests again showed marked sensitivity to the moisture level. The sensors are very appealing because of their small size, durability, and ease of multiplexing and could potentially serve as a vital tool in detecting moisture issues in buildings.

KEYWORDS

Fiber optic, humidity, moisture, sensor.

INTRODUCTION

Moisture problems in buildings have been receiving an increasing amount of attention because of their causal relationship with mold, mildew, dust mites, and other allergens that thrive in wet environments. To combat these problems, a wide array of field and laboratory studies have been carried out to investigate moisture issues, and numerous guides to constructing buildings have proposed best practices for combating moisture problems in the building envelope (Lstiburek and Carmody 1996, Trechsel 1994). Computer modeling has also greatly aided the quest to find the best techniques for preventing water damage (Burch et al. 1995, Karagiozis and Kuenzel 1999).

Experimental work on moisture problems in buildings is plagued by an inadequacy of sensors. Reviews of the available instrumentation for moisture studies have shown that the technology has changed little over the last 20 years (Ten Wolde and Carll 1982, Derome *et al.* 2001, Healy 2003). Sensors can be difficult to use, lack the desired accuracy, and are often not packaged for use in buildings. As one example of this last issue, there is a great need to measure the surface relative humidity, defined here as the humidity that ambient air surrounding a surface would have should it be brought to the temperature of that surface. This quantity is critical in helping to predict the onset of mold and mildew. The International Energy Agency Annex XIV (1990) has set a guideline that the monthly average of surface relative humidity should be maintained below 80% in order to prevent mold and mildew growth. A direct measure of the humidity at surfaces would greatly aid in diagnosing such conditions.

In recent years, optical fiber has emerged as an attractive platform for various sensors (Krohn 2000, Udd 1991, Dakin and Culshaw 1988, Giallorenzi *et al.* 1982). Light can be effectively used as a sensing platform by measuring a change in intensity, a change in phase, or a shift in spectral response. A drawback of intensity-based sensors is that numerous components of the fiber can change the intensity independent of the quantity being measured, but technology based on shifts in wavelengths of light or interference patterns do not suffer from these problems. The implications of this fact are that the sensors are robust in a wider variety of conditions.

The use of optical fiber as a sensing platform has numerous advantages over conventional electrical wiring. Electrical noise has negligible effect on the light traveling through the fiber, and safety issues associated with passing electrical signals through sensitive areas are eliminated. Due to the advancements made in manufacturing optical fiber for the telecommunications industry, the fiber is very durable, its cost is low, and many of the main components needed to create the sensing system are commercially available. Another advantage of these sensors is their small size. Optical fiber has a diameter on the order of 250 μm, and the sensors are often written directly on the fiber with dimensions of the same order of magnitude. The small size is attractive to many applications. Another exciting aspect of optical fiber sensors is the wide array of multiplexing possibilities (Kersey 1991). The options for the use of optical fiber in sensing applications are vast, and the application of these sensors is evolving in many different fields where small size, immunity to electrical interference, and durability of wiring is needed.

While many applications exist where physical parameters such as strain and pressure are measured with optical fiber sensors, devices for sensing chemical or biological compounds have also demonstrated a promising future. This paper will discuss development of a sensor based on optical fiber technology that detects changes in relative humidity.

PRINCIPLE OF OPERATION

Luo *et al.* *(2003)* present a detailed description of the theory, construction, and operation of the optical fiber-based humidity sensor. The present discussion will provide a general overview of the major components of the technique; the reader is referred to Luo *et al.* for further details. The foundation for the moisture sensor system is the optical fiber long period grating (LPG) (Vengsarkar *et al.* 1996). These well-established components scatter light out of the grating at different optical wavelengths as the index of refraction around the sensing element changes. Figure 1 shows a schematic of the sensor. The wavelength that is scattered by the grating (coupling wavelength) is a function of the difference in the refractive indices of the guide (i.e., core) and the cladding as described by Equation 1:

$$\lambda = (n_g - n_{cl})\Lambda \tag{1}$$

where λ is the coupling wavelength, n_g and n_{cl} are the effective indices of refraction for the guide

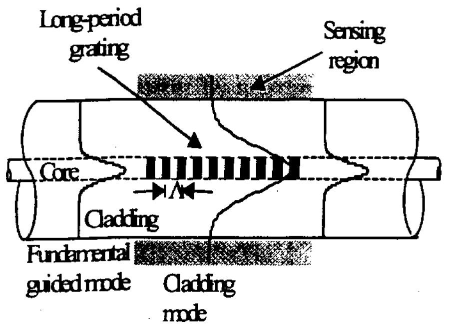

Figure 1. Schematic of optical fiber-based moisture sensor.

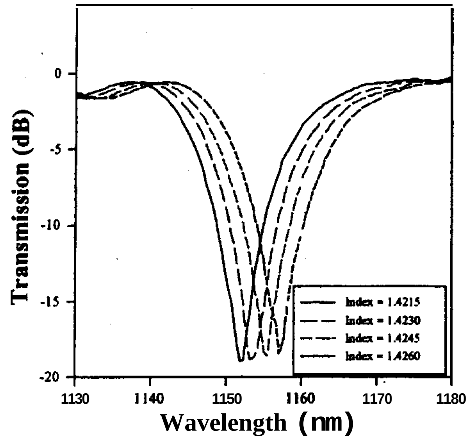

Figure **2.** Shift in transmitted spectrum with changes in refractive index of coating, **as** a function of wavelength, λ.

and the cladding, respectively, and **A** is the grating period. Since n_g and **A** are essentially constant, any change in λ comes about because of changes in the refractive index of the cladding. **As** the refractive index changes around the LPG, λ changes, and the transmitted spectrum of light, therefore, indicates the change in refractive index **as** shown in Figure 2.

A mirror is applied on the end of the fiber ***so*** that the light that is transmitted through the grating passes back down the fiber to a spectrometer that is placed in the same box as the broadband diode. This arrangement allows only one box to be used for both emitting and detecting and reduces the length of fiber needed to reach the measurement location. Proprietary software examines the return signal to find the coupling wavelength. The detector system resolves wavelengths with an uncertainty of ± 0.001 nm. The sensor that has been developed for detecting moisture uses this principle to translate the humidity around the sensor to a transducer output. If the core can be surrounded with a material that changes its refractive index depending upon the moisture in the air, the humidity can be determined by detecting the dip in the frequency spectrum as displayed in Fig. 2. The challenge, therefore, was to find a coating that had a suitable response to moisture yet had the strength to remain attached to the fiber after installation. Several polymers and hydrogels that expand or contract in the presence of water (and, hence, experience changes in refractive index) were investigated to determine the best coating. Carboxymethylcellulose (CMC) and the polymer polyethylenimine (PEI), after being covalently bonded to the fiber, were found to produce significant and repeatable responses to changes in humidity. Details of the both bonding processes can be found in Luo ***et*** *al.* (2003).

Temperature sensor

Temperature sensors were also created on the fiber. Both Fiber Bragg gratings and extrinsic Fabry-Perot interferometers were manufactured and tested in the study. Details of the results from those tests **will** not be given here, but it should be noted that provisions were made ***so*** that temperature is measured along with relative humidity for the added information and for any temperature corrections needed to the RH measurements.

RESULTS

Sensor performance in air

Preliminary tests of the sensors in air showed significant sensitivity to humidity in a range of 0 % to 90 %. Those tests also showed that the response was a function **of** temperature, a trait similar to the response of most humidity sensors. To better determine the performance **of** the sensors over a range **of** temperatures and relative humidities, the moisture and temperature sensors were tested in a two-pressure temperature and humidity chamber having an uncertainty of ± 0.5 % **RH** and ± 0.05 °C. The sensors were either tested in steps of RH at a constant temperature, **or** in steps **of** varying temperature at constant RH. Relative humidity was varied **from** 20 % to ***95*** %, and temperatures ranged from 15 "C to **34** "C. The chamber was allowed to equilibrate to a steady state, a process that took approximately 25 min, and *A* was recorded when steady state was assured. The uncertainty in *A* is ± 0.01 nm.

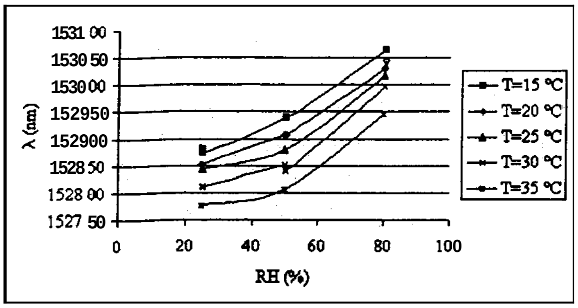

Figure 3. Response of CMC moisture sensor with humidity and temperature (lines are meant to simply guide the reader's eyes rather than suggest that data points exist between those plotted).

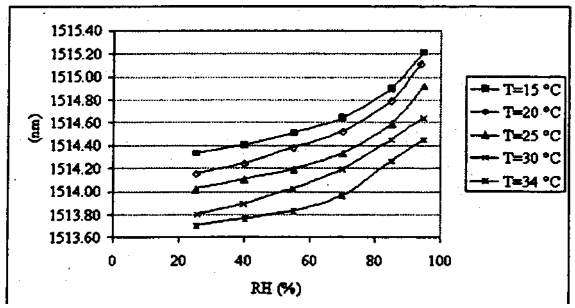

Figure **4.** Response of PEI moisture sensor with humidity at various temperatures (lines are meant to simply guide the reader's eyes rather than suggest that data points exist between those plotted).

Figure **3** shows the response of the CMC sensor to changes in relative humidity as a function **of** temperature. **A** rather significant dependence **of** *A* on the relative humidity is apparent, with the sensitivity of the sensor increasing at higher relative humidity. The wavelength decreases nearly linearly with increasing temperature. Figure **4** shows the response of the PEI moisture sensor with humidity at different temperatures. **As** with the **CMC** sensor, the PEI sensor shows significant sensitivity to relative humidity, and *A* increases nearly linearly with decreasing temperature. The PEI sensor also shows increasing sensitivity **as** RH increases. This characteristic could have beneficial implications for the building community, **as** the regions of greatest concern are those in which the relative humidity is high.

Sensor performance on a substrate

For many building science applications, sensors need **to** be placed directly onto a substrate. In this configuration, the sensor can be used to determine the moisture content of the substrate as has been done in previous investigations where humidity sensors are used along with sorption isotherms to determine the moisture content of materials **(Hosni** ***et*** *al.* 1999, Cunningham 1999).

Because of the small size of the optical fiber sensors, it is surmised that the sensor may be used in this manner to detect the moisture content at the surface of a substrate. To investigate this possibility, the sensors were placed on conditioned samples of sugar pine, oriented strand board (OSB), and gypsum board. The samples were conditioned in jars containing either saturated salt solutions or desiccant at a temperature of 20 °C ± 1 °C to create an environment of constant humidity ranging from approximately 0 % to 98 %, with an uncertainty of ± 1 % RH (Greenspan 1977). The samples were first dried in desiccant chambers to obtain their dry weights and were then placed in the jars to reach equilibrium moisture content. Steady-state conditions were assumed when the weight change between readings taken one week apart was less than 0.1 %.

The sensor was taped onto the substrate immediately after removing the samples from the jars and weighing them. This step created a partially sealed cavity above the substrate in which the sensor sat. For all tests, room temperature was maintained at 20 "C ± 1 "C. Initial tests with unprotected fiber sensors showed that the strain induced on the sensors when they were placed on the substrate disturbed the readings to an unacceptable extent. The CMC sensor, however, was enclosed in a small polyetheretherketone (PEEK) sheath that provided structural support for the fiber and created a small amount of clearance between the surface of the material and the optical fiber. These sensors did not suffer from the same strain issues that were observed during testing of the unsheathed sensors. The response of the CMC sensor placed on the three substrates is displayed in Figure 5. One location on the OSB and pine was examined, but three different measurements were made on the gypsum board owing to its inhomogeneity. The sensor was placed on both of the paper-faced sides of the sample as well as the side of the specimen that was unfaced. Despite being exposed to air on one side of the sensor, the small size of the optical fiber successfully differentiated the varying moisture contents of the sarnples, or, more appropriately, detected the humidity level at which the sample was conditioned.

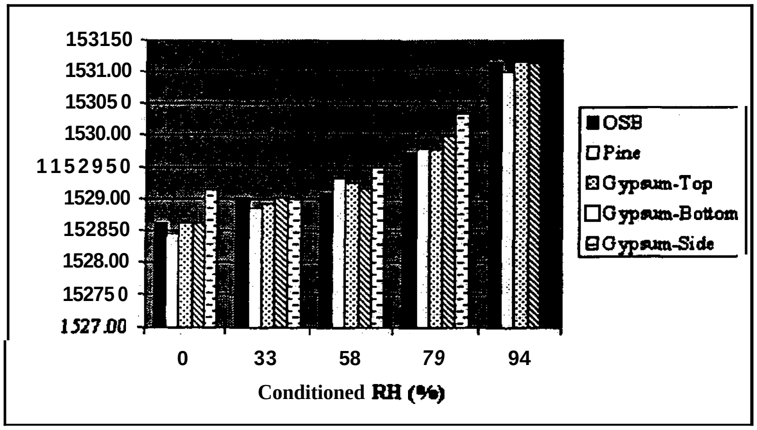

Figure 5. Response of CMC sensor when placed upon surface of building materials conditioned in chambers of varying relative humidity.

DISCUSSION

Tests have shown that the optical fiber-based humidity sensor is sufficiently responsive to moisture changes to be a viable tool in the hands of building scientists. Before its use can be made widespread, however, several modifications are required. First, a packaging scheme needs to be developed for the sensor to provide protection from strains induced by touching surfaces while not sacrificing the size advantages of optical fiber. To better describe the performance of the sensor, the hysteresis behavior should be better characterized to determine the possible errors that can be expected in use. The robustness of the sensor also needs to be investigated. The tests discussed here were done over a short time, but performance over several years is likely needed for an effective moisture sensor in building cavities. The behavior in a condensing environment should also be characterized to determine effects of liquid water on the sensor.

CONCLUSION

An optical fiber-based moisture sensor has been developed that can be used in small spaces within building envelopes to assess moisture conditions that might lead to various hazards. The very small size of the sensor along with the durability of the optical fiber presents an interesting alternative to conventional sensors. Tests on initial prototypes have shown that long-period gratings coated with CMC hydrogel and PEI polymer produce a noticeable shift in the wavelength that is filtered from a broadband beam of light transmitted through the fiber. This shift in wavelength can be correlated with the relative humidity surrounding the sensor. Additional tests were performed to assess the ability of the sensor to determine the moisture content of a substrate. While the sensor did show a definite response to this parameter, further work is needed on the sensor packaging to achieve the desired measurement. Combined with optical fiber-based temperature sensors that were developed, the sensor could provide valuable information on the health of a building with a very small footprint on the wall or roof structure.

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