Measuring Humidity & Moisture with Fiber Optic Sensors

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Abstract

Polyimide coated fiber Bragg gratings have a linear response to changes in relative humidity and temperature. Blue Road Research is using this technology to monitor relative humidity and using acrylate-coated gratings to monitor temperature. This paper describes some of the sensors and readout systems for simple and multiplexed relative humidity and temperature sensors. Additionally, an indirect method for monitoring soil moisture is described.

Keywords: relative humidity, moisture, temperature, grating, sensor

1. Background and Introduction

Humidity and moisture sensors are currently used for determining the following characteristics:

- corrosion & erosion
- road conditions
- living/lab/workplace conditions
- weather predictions & measurement
- soil moisture for agriculture, forestry, and geography
- livestock feed moisture levels
- water seepage

Fiber optic sensors were considered for measuring these environmental characteristics because they are extremely high bandwidth, can be multiplexed to add many signals onto one line, are extremely small and lightweight, and are robust, in addition to having high sensitivity. Because they can transmit optical signals easily over several miles, sensing in remote areas does not have any electrical requirements. In addition, they are immune to electrical interference that adds error to electrical sensors.

The United States Department of Energy (DOE) funded a Phase II research program to develop a fiber sensor for soil moisture determinations that correlate with gravimetric soil moisture determinations.

DOE currently uses a neutron probe (Figure 1) for moisture content determination. These probes take one data point at a time, contain radioactive materials, and are expensive. Distributed sensing with this type of probe is not only cost prohibitive, but somewhat hazardous. Economical fiber optic moisture sensors may offer an alternative that is cost effective and can be designed for distributed sensing.

Figure 1: Neutron probe monitoring soil moisture

2. Fiber Grating Humidity Response

Blue Road Research's focus on fiber Bragg grating based relative humidity sensors led to the investigation of the response of several materials to this parameter. Several materials were evaluated and it was seen that certain optical fiber coatings, such as polyimide, respond linearly to changes in relative humidity, as seen in Figure 2. Additionally, thicker coatings increased the response magnitude, in agreement with previous studies[i]. Further tests showed that the cure schedule for the coating significantly affected the stability of the relative humidity measurements.

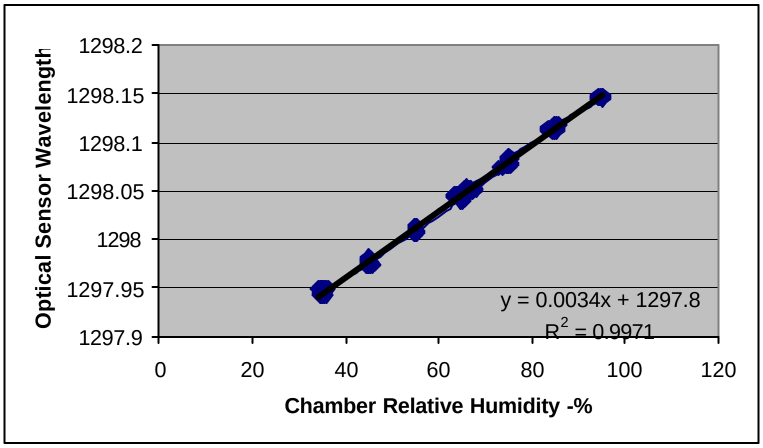

Figure 2: Linearity of response for a polyimide coated fiber optic humidity sensor

Humidity changes can be detected when the coating over a fiber grating sensor shrinks or swells in response to humidity. The humidity sensors currently used by Blue Road Research have a coating that swells as the humidity increases. Figure 3 shows that this swelling lengthens the grating, which causes a wavelength shift. Due to the thermal expansion of the glass, the sensors also have a linear response to temperature changes. At constant temperature, the humidity can be calculated directly. If both temperature and humidity vary, the temperature changes must be recorded in order to adjust the measured wavelength shift to show only the response due to humidity.

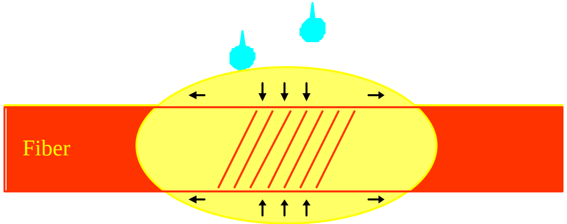

Figure 3: Fiber sensor coated for humidity response

3. Demodulation Techniques

To evaluate the wavelength shift (and thus the environmental effects acting on the grating, such as strain, humidity, etc.), several techniques can be used. The most direct is to illuminate the grating with a broadband light source and view the light reflected by the wavelength-selective grating on an optical spectrum analyzer (OSA). This yields broad data in a very turnkey package, though it rarely captures data faster than a few hertz at low resolution. For this configuration, the biggest drawback is the high cost of the OSA.

In order to obtain higher speed and resolution at a much lower cost, Blue Road Research uses a patented configuration[ii], which measures sensor wavelength by masking it behind a fiber grating filter of similar wavelength. Any wavelength change is then detected as an intensity change, with the intensity change being dependent upon the slope of the filter being used. For example, the typical configuration that is used gives a positive intensity change for a positive change in wavelength by aligning the sensor to the shorter wavelength side of the filter and observing the reflected light from the filter. This technique provides an unnecessarily high bandwidth for moisture sensors (up to 2 megahertz) but has the distinct advantage of using inexpensive photodetectors to measure the resulting unfiltered light. Some humidity cycles measured by this system are shown in Figure 4; note the consistency of the fiber humidity sensor with the humidity measured by the RTD sensor in the environmental chamber.

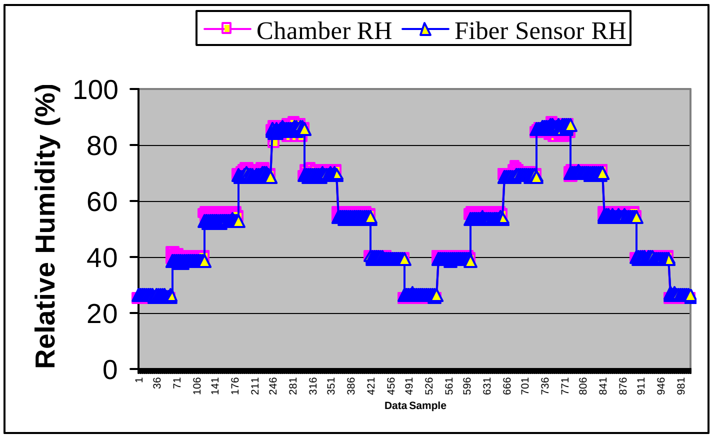

Figure 4: Comparison graph showing fiber sensor performance with industrial RTD sensor in a humidity-controlled chamber

An added bonus to this procedure is that temperature effects on the humidity sensor can be minimized if the filter grating is selected with only a response to temperature and is collocated with the sensor. In this combination, the filter wavelength and the sensor wavelength shift simultaneously with temperature, yielding no net intensity change, leaving only the humidity effects. Figure 5 shows one of the demodulation systems Blue Road Research produces to monitor fiber sensors by this method.

Figure 5: Flight test sensor system

4. Indirect Moisture Sensing by Monitoring Evaporation Rates

The process of testing these fiber sensors in wet soil highlighted the difference between humidity and soil moisture. As can be seen in Figure 6, soil measurements saturated the fiber sensor near 4% gravimetric soil moisture (4% percent moist soil was created by weighing the desiccated soil, weighing a known amount of water, then mixing the two and leaving it to equilibrate). The fiber sensor did not increase its response above the reading of 100% relative humidity, even when more moisture was added to the soil. Therefore, the basic humidity sensor range fell far short of the 2-18% targeted soil moisture range.

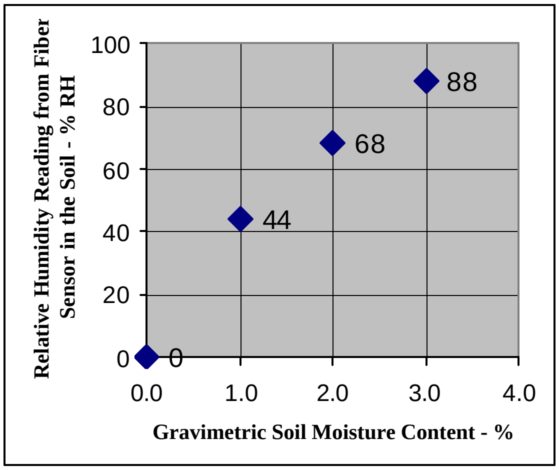

Figure 6: Relative humidity in the soil vs. moisture content of the soil

Since the fiber grating sensor was able to measure humidity, but ineffective within soil greater than 4% moisture, an alternate technique was developed in which sensors that were isolated from the soil were used to infer the moisture level by monitoring evaporation rates.

To accomplish this, two fiber sensors were placed in a tube, each on a optical fiber strand: one that responded to relative humidity (RH) and temperature, referred to as the humidity sensor, and one that responded to temperature only. The tube was perforated near the location of the two sensors and buried so that the perforated area was covered with sandy loam soil at a known moisture level. In this configuration, moisture was free to evaporate from the soil into the tube through the perforations, where the humidity and temperature were monitored by the fiber sensors. The temperature variations were then subtracted from total response of the humidity sensors. Figure 7a shows a variation of this setup where both sensors are on one fiber strand. Also shown in the diagram are the spacing tabs that prevent the sensors from touching the insides of the tube, should it become wet. Figure 7b is the prototype tube that was used for experimentation at Blue Road Research's Fairview, Oregon facility.

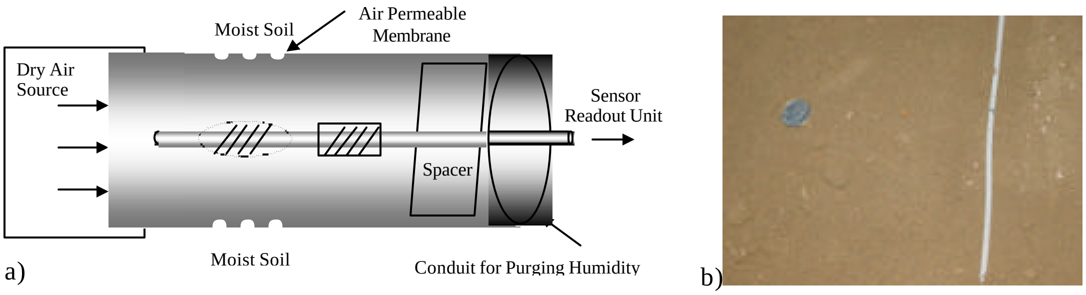

Figure 7: a) Diagram of sensing moisture system for fiber sensors and b) the moisture evaporation tube for the fiber sensor, soon to be buried

Because the air in the tube would approach 100% relative humidity as moisture evaporated from the soil (assuming soil above 4% moisture gravimetrically), the moist air needed to be evacuated from the tube, allowing the soil moisture to evaporate uninhibited. This was done by blowing a dry gas through the tube, allowing the moisture-swollen coating of the fiber sensor to dry.

Nitrogen was used as the dry air source, and the tube was purged for a set amount of time for each reading. The sensors' responses to both the purge and recovery after purging ceased were recorded. Those responses are plotted in Figure 8. The highest line represents the humidity in the tube when the soil was near 18% soil moisture. From its initial equilibrium humidity state, the humidity level in the tube shows a continuous drop for the duration of the approximate two-minute nitrogen purge, then a characteristic recovery as the humidity of the air in the tube climbed back to saturation (in response to evaporation from the moist soil).

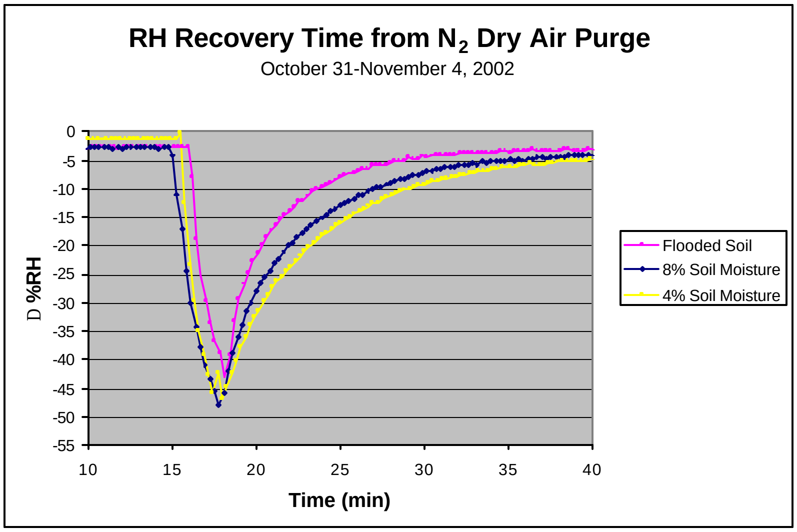

Figure 8: Graph showing fiber sensor tracking of the evaporation rates for three soil moisture levels

The soil moisture level can be determined from this method by recording the time elapsed between two humidity levels as the humidity recovers, or by noting the humidity regained by a certain time limit from a common starting humidity (both of which are proportional to soil moisture levels, since the rate of RH recovery is the evaporation rate into the tube). The data chart in Table 1 is taken from the graph in Figure 8. It shows the recovery time to various humidity levels within the conduit, relative to saturation. Note how the differences in recovery time for each soil moisture level become easier to distinguish as the sensors return closer and closer to saturation, though a difference is obvious in less than a minute. Resolution increases with data collection time, until saturation.

Although sixty seconds seems like a long time required to take a data point, dozens or hundreds of these sensors can be monitored simultaneously with proper optical equipment, and further experimentation will likely reveal that the recovery slope (rate of change) or the integral of recovery curve can yield data even more quickly. Other untested options include carefully measuring the purge with a known and controlled quantity of gas, or comparing the sensor response to very short purges.

Table 1: Chart of minutes required for humidity recovery for three soil moisture levels after purging tube to –45% of saturation

	Humidity Recovery Time (min)			
Soil Moisture	**-35%**	**-25%**	**-15%**	**-5%**
4%	1.45	3.65	7.45	20.37
8%	1.17	2.8	5.9	15.3
Flooded	0.56	1.4	3.57	10.1

Of course, the laundry list of other factors that will effect the evaporation rate include the temperature of the soil, the temperature of the air at the soil interface, the humidity of the air in the tube, the vapor pressure, the granularity and area of the exposed soil (or holes in the tube). However, fiber grating sensors seem ideally suited to this configuration, since they can be easily multiplexed by inscribing several gratings on each fiber line at most any desired spacing, and monitored simultaneously. These fiber lines will easily fit into a protective tube over long distances, and many of the conditions that cause uncertainty in traditional evaporation measurement experiments may be controlled over the short duration required for each humidity reading.

5. Conclusion

Fiber gratings controlled by specialized coatings increase the number of environmental characteristics that can be monitored by fiber optic sensors to include humidity and moisture in long-life solutions unaffected by electromagnetic interference. These sensors can potentially monitor humidity for numerous applications, including material erosion & corrosion, highway conditions, agricultural studies, living conditions, as well as laboratory research applications such as environmental chambers. By using fiber humidity sensors to monitor evaporation rates, soil moisture levels and moisture in organic materials can be inferred. These experiments have proved beneficial, allowing Blue Road Research to two new sensors that can be measured one at a time with high resolution and accuracy, or monitored in high quantities of 50 or more per fiber strand.

6. Acknowledgements

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Some of the concepts and configurations described in this paper are protected by patents owned or licensed by Blue Road Research.

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[ii] US Patent 5,380,995; more at http://www.bluerr.com/patents.htm