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Polyimide-Coated Fiber Bragg Grating Sensors for Humidity Measurements

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<http://dx.doi.org/10.5772/53551>

1. Introduction

Humidity is one of important environmental parameters, which refers to the water vapor content in the air. As one of the fundamental abiotic factors, humidity determines an environment where animals and plants can thrive, also influences the human life. There are three items commonly used to describe humidity, which are absolute humidity (AH), relative humidity (RH) and specific humidity (SH) [33]. In daily life and industrial measurement fields, relative humidity is one of the important and most commonly used parameters.

With the developments of sciences and technologies, in the recent years, humidity measurements and controls are becoming more and more important and required greatly in a wide range of areas, such as in environmental monitoring for meteorological services, in agriculture for seed storage, in industrial fields for chemical, biomedical, food, and electronic processing, and in civil engineering for bridge and building constructions, as well as in daily life for air conditioner in living rooms, hospitals, museums and libraries [24, 33]. Besides the humidity measurements, moisture measurements also are very important, such as in high voltage engineering for measurements of water content in transformer oils. At present, there are various types of humidity sensors available for humidity or moisture measurements, which can be categorized into capacity, resistive, gravimetric and mechanical types based on the sensing principles used [5, 11, 30, 34]. Most of the humidity sensors need a layer of humidity sensitive material, such as polymers or hydrogels. It is clear that no one humidity sensing technology can cover for all applications, however the sensors with a wide detection range, linear response, small hysteresis and fast exchange with water vapor will offer the best potential for use in a broad range of applications.

Compared to the conventional mechanical and electrical/electronic humidity sensors, fiber-optic based humidity sensors [6, 14], including silica glass fiber and polymer optical fiber (POF) based sensors [28, 46], demonstrate many unique advantages, such as small size and low weight, immunity to electromagnetic interference, corrosion resistance, potentials for remote operation and distributed sensing. In fiber-optic sensor family, the fiber grating

based sensors are playing the important role in wide range of industrial measurement fields [12, 15]. The fiber grating sensors with many intrinsic characteristics as mentioned above can further offer the potentials of multiple-parameter sensing, embedding into other structures [37], and multiplexing in a single mode fiber to form an all-fiber sensor network [26]. In the past several decades, a lot of types of fiber grating sensors have been proposed and developed for measurements of strain, temperature and pressure as well as acceleration/vibration in structural health monitoring [4, 8, 24, 38]. These types of sensors can be roughly classified into Bragg grating, chirped grating and long period grating (LPG) as well as in-line grating based interferometer types. In the family of fiber grating based sensors, however, the uniform fiber Bragg grating (FBG) based sensors have been accepted widely, owing to their simplicity in structure as well as in fabrication.

Fiber-optic based humidity sensors can be realized by means of FBG technology and the polymer coating process. Polyimide is a class of thermally stable polymers that are often based on stiff aromatic backbones, which demonstrates many excellent properties—mechanical and tensile strength, heat resistance and adhesiveness to various substrates as well as unique hygroscopic property. When the polyimide resin is coated on the FBG sensor to form the moisture sensitive layer, this polyimide coating will undergo a volume expansion as the water molecules migrate into it, which directly induces a strain imposed on the FBG and in turn results in a proportional shift of the Bragg wavelength of the FBG sensor. Based on this sensing mechanism, the humidity measurements are carried out by directly reading this wavelength shift through spectrum analysis methods [9, 16, 31, 36, 42–45].

One important topic in sensor applications is how to extend the sensor system ability to achieve the simultaneous detections of multiple physical parameters within a single measurement process [1, 23, 26, 27, 29, 37]. In many applications, for example, in the pump system, the vibration and temperature are two important parameters that often are used for evaluating working states of the pump system, especially of bearings, shafts and gear box subsystems. In the high-voltage transformer case, the vibration, temperature and moisture in the insulation oil are three important parameters that should be detected simultaneously and analyzed real time. A transformer in a good state will produce low levels of inherent vibration. Signatures in vibration signals with respect of intensity and frequency reflect well the working state of the transformer and indicate if there is part loosing occurring. The frequency response of a sensor system for transformer condition monitoring, often is required to be capable of detecting vibration signal in a wider frequency range, such as ranging from 5 Hz to 1000 Hz. A rapidly increasing in the temperature implies some short-turned events happening inside the transformer's coils. The moisture in the insulation oil inside the transformer easily induces the partial discharge occurring, which also should be real-time monitored. The fiber laser sensor system equipped with multiple polyimide-coated FBG sensors working in a multi-wavelength lasing mode can provide this diversity to integrate several sensing functions in a sensor system configuration.

The aim of this chapter is to give an introduction to the polyimide as an excellent moisture sensitive coating material used to form the fiber-optic humidity sensors. The remainder of this chapter will be arranged as follows: a brief review on the structure, optical properties and sensing principles of polyimide-coated FBG humidity sensor as well as preliminary experimental results for investigating the sensor properties are given in Section 2. In Section 3, we will demonstrate a prototype of semiconductor optical amplifier (SOA) based fiber laser sensor system used for multiple physical parameter measurements and present

some experimental results on the simultaneous measurements of vibration, temperature and humidity, based on our multi-function FBG sensor and interrogation techniques developed recently. Finally a conclusion for summarizing our work is given to close this chapter.

2. FBG humidity sensors

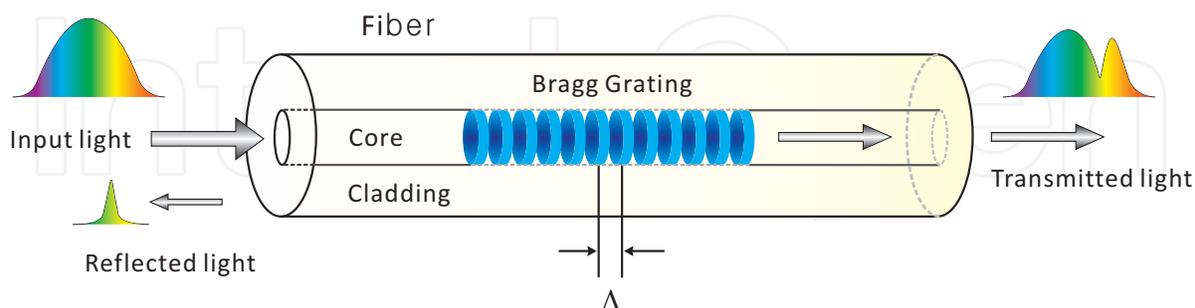


Figure 1. Structure and principle of a FBG

2.1. Theory

A uniform FBG sensor contains a periodically varied refractive index, distributed along the core of the optical fiber within a selected length, as illustrated in Figure 1. When a photosensitive optical fiber is irradiated by an ultraviolet (UV) laser beam with a wavelength band within 230~250 nm, through a phase mask or by holographic recording process, a periodic refractive index variation along the fiber core is permanently recorded and a fiber Bragg grating is produced in this way. As an important optical property, the FBG shows the wavelength selectivity in its reflection spectrum or transmission spectrum. When a broad-band light beam propagating along the optical fiber will interact with each grating plane where the only the part of light beam with a specific wavelength met with the Bragg condition will be reflected and propagate in opposite direction, and other parts of light beam will pass through this grating without an obvious optical loss. According the mode coupling theory, this Bragg condition can be expressed as

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where λ_B indicates the Bragg wavelength or called the center wavelength of the Bragg grating; n_{eff} denotes the effective refractive index of fiber core; Λ is the pitch length of grating plane or called the grating period. From this equation, it is clear that any external perturbation will alternate λ_B through modifying n_{eff} and/or Λ .



Figure 2. Illustration of a FBG sensor with polyimide coating

The FBG humidity sensor is fabricated by coating suitable hygroscopic film on the surface of fiber cladding covering the Bragg grating section, as illustrated in Figure 2. The polyimide

resin can be selected as ideal coating material for making FBG humidity sensor, because of its linear response in volume swelling with respect to the humidity level. After a grating is inscribed in the fiber, the fiber should be taken an annealing treatment first, and then dipped into the polyimide solution for 5~10 minutes and dried in a drying cabinet for a short thermal treatment at 150 °C, in order to get a uniform polyimide film on the surface of the fiber. This process will be repeated several times in order to obtain the desired film thickness. As a final step, the coated sensor is put into an oven for curing at 180 °C for about 60 minutes, which will stabilize the adhesion of the coating to the fiber. The thickness of the polyimide film determines the sensing sensitivity and the response time. In addition, the experimental results indicated that a multiple layer coating can significantly improve the sensor sensitivity to moisture. However the stable time after the sensor is placed into a humidity environment will become longer than that of the sensor with single polyimide layer. The fabricated FBG humidity sensor should be well packaged with an appropriately designed casing before it can be practically used in the field for humidity measurements.

As indicated by other researchers, the Bragg wavelength λ_B is sensitive to ambient temperature and strain imposed on the fiber, so this property can be utilized for sensing applications. When an axial strain ε is imposed on the FBG, the grating period Λ will alter due to a change of fiber physical length, and the effective refractive index of the fiber core n_{eff} also will alter through the photoelastic effects in the fiber core. The shift of Bragg wavelength induced by ε , therefore, can be obtained with a total differential operation of Equation 1, given as

$$\Delta\lambda_{B,S} = \lambda_B \left(\frac{\Delta\Lambda_S}{\Lambda} + \frac{\Delta n_{eff,S}}{n_{eff}} \right) = \lambda_B(1 - P_e)\varepsilon \quad (2)$$

where $\Delta\Lambda_S/\Lambda = \varepsilon$, $\Delta n_{eff,S}/n_{eff} = -P_e\varepsilon$ denotes the change of effective refractive index induced by through the photoelastic effects, and P_e is a photoelastic constant of the fiber [25], expressed as

$$P_e = \frac{n_{eff}^2}{2} [P_{12} - \mu(P_{11} + P_{12})] \quad (3)$$

where μ is the Poisson ratio; P_{11} and P_{12} are two elasto-optic tensor coefficients (Pockel's coefficients) along the fiber axis.

For a temperature change ΔT , the grating period Λ will alter with ΔT through a thermal expansion effect in the fiber, and the effective refractive index of the fiber core n_{eff} also will alter through a thermo-optic effect. Therefore, in same way, the shift of Bragg wavelength induced by the temperature change ΔT is given as

$$\Delta\lambda_{B,T} = \lambda_B \left(\frac{\Delta\Lambda_T}{\Lambda} + \frac{\Delta n_{eff,T}}{n_{eff}} \right) = \lambda_B(\alpha_T + \zeta)\Delta T \quad (4)$$

where α_T is the thermal expansion coefficient of the fiber, expressed as

$$\alpha_T = \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \quad (5)$$

and ζ denotes the thermo-optic coefficient

$$\zeta = \frac{1}{n_{eff}} \frac{\partial n_{eff}}{\partial T} \quad (6)$$

With Equation 2 and Equation 4, the shift of Bragg wavelength of the FBG sensor under the external perturbations from strain and temperature changes, expressed as

$$\Delta\lambda_B = \Delta\lambda_{B,S} + \Delta\lambda_{B,T} = \lambda_B [(1 - P_e)\varepsilon + (\alpha_T + \zeta)\Delta T] \quad (7)$$

For the polyimide-coated FBG humidity sensor, when ambient temperature and the humidity level change, the Bragg wavelength will shift through strains induced by thermal longitudinal expansion and hygroscopic longitudinal expansion of the polyimide film. The strain imposed on the FBG due to thermal expansion of the polyimide film therefore can be expressed as

$$\varepsilon_T = (\alpha_{RH} - \alpha_T)\Delta T \quad (8)$$

where α_{RH} is the thermal expansion coefficient of hygroscopic material (polyimide film). When the polyimide film absorbs or desorbs the moisture, its volume changes proportionally to the moisture quantity absorbed within a unsaturation range. This volume change causes directly an axial strain on the fiber, called humidity-induced strain [2], which is defined as

$$\varepsilon_M = \int_{RH_1}^{RH_2} \beta(RH, T) dRH \quad (9)$$

where β is humidity-induced hygroscopic longitudinal expansion coefficient of polyimide film; T is temperature; RH is relative humidity. The saturation absorption of polyimide film decides the maximum change range of humidity-induced strain. If in the interest humidity measurement range, ε_M only is a linear function of relative humidity in a given temperature range, which can be approximately expressed as

$$\varepsilon_M = \bar{\beta}\Delta RH \quad (10)$$

where $\bar{\beta}$ is an average moisture expansion coefficient, and $\Delta RH = RH_2 - RH_1$ is the humidity difference. $\bar{\beta}$ can be determined through experimental measurements.

Finally, the total strains imposed on the FBG humidity sensor can obtained according to a superposition principle, expressed as

$$\varepsilon = \varepsilon_T + \varepsilon_M \quad (11)$$

or

$$\varepsilon = (\alpha_{RH} - \alpha_T)\Delta T + \bar{\beta}\Delta RH \quad (12)$$

Combining Equation 7 and Equation 12, the total shifts of Bragg wavelength of the polyimide-coated FBG humidity sensor, under a conjunct influence from relative humidity and temperature, can be obtained accordingly, expressed as

$$\Delta\lambda_B = \lambda_B \{(1 - P_e)[(\alpha_{RH} - \alpha_T)\Delta T + \bar{\beta}\Delta RH] + (\alpha_T + \zeta)\Delta T\} \quad (13)$$

or

$$\begin{aligned} \Delta\lambda_B &= \lambda_B \{(1 - P_e)\bar{\beta}\Delta RH + [\alpha_{RH} - P_e(\alpha_{RH} - \alpha_T) + \zeta]\Delta T\} \\ &= \lambda_B (S_{RH}\Delta RH + S_T\Delta T) \end{aligned} \quad (14)$$

here S_{RH} and S_T are sensitivity coefficients of humidity and temperature of the polyimide-coated FBG humidity sensor, respectively [16].

It should be noted that for a polyimide-coated FBG humidity sensor, actually there is a humidity-temperature cross sensitivity [27]. Therefore in an actual humidity sensing application, one should consider to take an effective temperature compensation to reduce this cross-sensitivity influence. This can be achieved by writing another normal FBG with different wavelength in same fiber close to the FBG humidity sensor to detect the temperature surrounding the sensors or by using other thermometers to obtain the actual ambient temperature value, or by utilizing an athermal package for the sensor [24].

2.2. Humidity sensing experiments

In this section, we will demonstrate some fundamental experimental results on measurements of relative humidity and moisture in industrial oils with our fabricated polyimide-coated FBG humidity sensors.

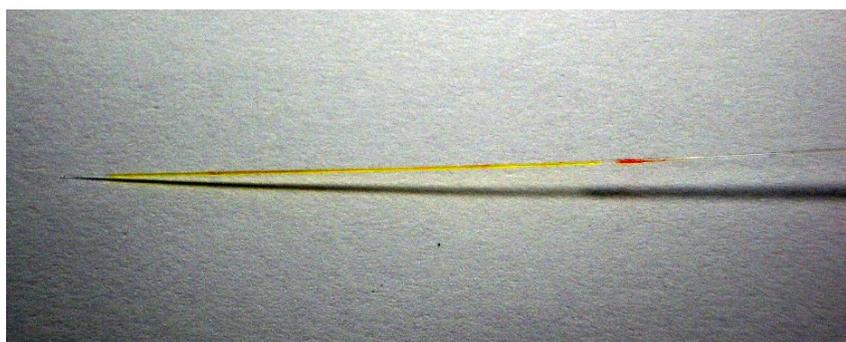


Figure 3. Photograph of fabricated FBG sensor with polyimide coating used for humidity sensing

Five pieces of FBG sensors with same Bragg wavelength were fabricated. Each Bragg grating was written into the core of a single-mode fiber (SMF-28, Corning Inc.) that was hydrogen-loaded beforehand, by using the irradiation method with an ArF Excimer laser ($\lambda = 248 \text{ nm}$) and a phase mask. The sensors then were re-coated with the hygroscopic material (polyimide solution, PI-2560). The coating process adopted is one as described in above section. The dip coating was repeated ten times in order to form a ten-layer polyimide film. The average coating thickness in these sensors was estimated to be $35 \pm 1,0 \mu\text{m}$. Figure 3 is the photograph of one of fabricated polyimide-coated FBG humidity sensors.

The primary experiment for characterization of the polyimide-coated FBG sensor was conducted based on an experimental setup as illustrated schematically in Figure 4. In this work, a sensor with a Bragg wavelength at $1540,58 \text{ nm}$ at 25°C was used. A super-luminescent emitting diodes (SLED) as a broadband light source was used to provide the probe light that was launched into the sensor through an optical circulator. The sensor was placed inside an environmental chamber (ESL-64KAD, Espec, Guangzhou) with a temperature and relative humidity controllable environment. The light reflected from the sensor firstly passed through the optical circulator again and then was fed into an optical spectrum analyzer (OSA, YOKOGAWA AQ6370B) with a fine resolution bandwidth of $0,01 \text{ nm}$, in which the shift of Bragg wavelength of the sensor as the relative humidity changes was observed and recorded.

A group of the reflection spectrums under different relative humidity levels is illustrated in Figure 5. In this experiment, the chamber temperature was fixed at 35°C and the relative humidity level was adjusted from 30 \%RH to 80 \%RH in a step of 10 \%RH . From these results,

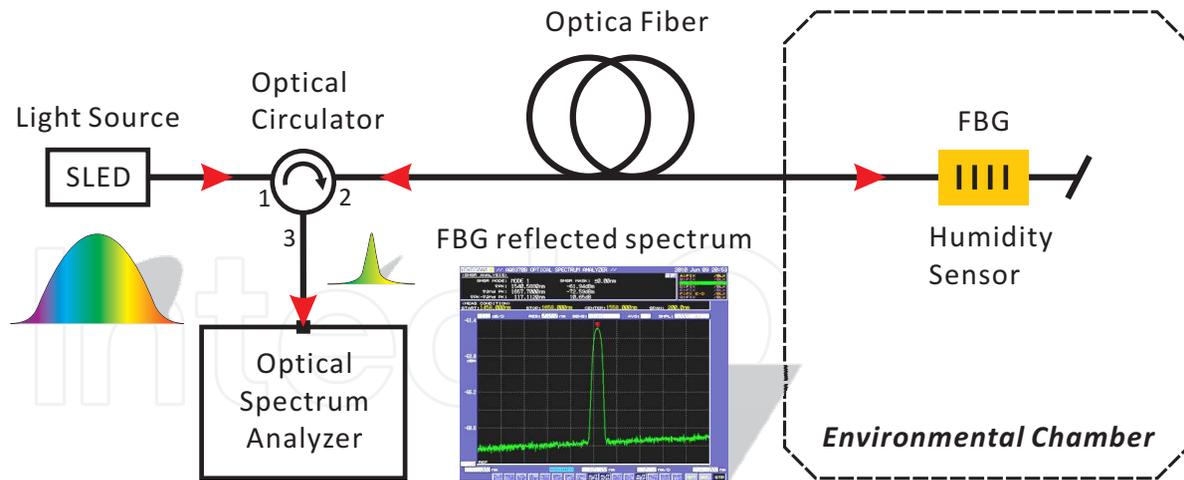


Figure 4. Schematic of experimental setup. Inset is a reflected spectrum of FBG humidity sensor at room condition (25 °C, 60 %RH)

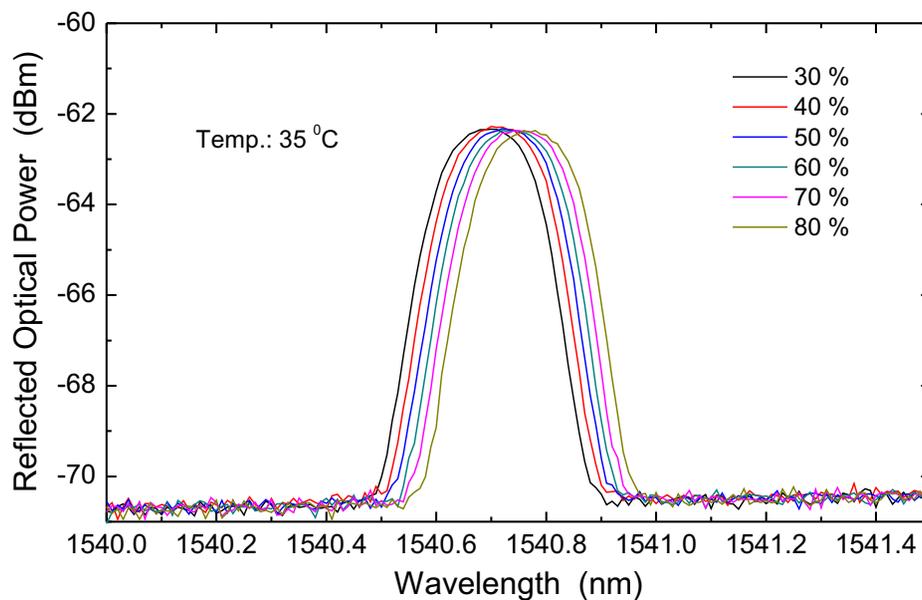


Figure 5. Measured reflection spectra of sensor under different relative humidity levels

it is clearly seen that the Bragg wavelength of the polyimide-coated FBG humidity sensor shifts toward the long-wavelength direction (red shift) as the relative humidity level increases.

Figure 6(a) is another group of measured results on Bragg wavelength shifts under different environmental conditions, where the temperature in the environmental chamber was respectively set at 25 °C, 35 °C and 45 °C and the relative humidity level was changed from 30 %RH to 80 %RH in a step of 10 %RH. From these results, a good linear relation between the Bragg wavelength and the relative humidity level can be confirmed. However the Bragg wavelength shifts in high temperature range are apart little bit from this linear relation. This is considered that the polyimide coating on the FBG humidity sensor fabricated is not uniform all over whole FBG section as well as the adhesiveness of polyimide coating to the fiber will decrease in high temperature condition, which brought the FBG humidity sensor a complicated humidity sensing property. Figure 6(b) is a group of measured results on the long-term stability of the sensor during humidity measurements. In this experiment, the

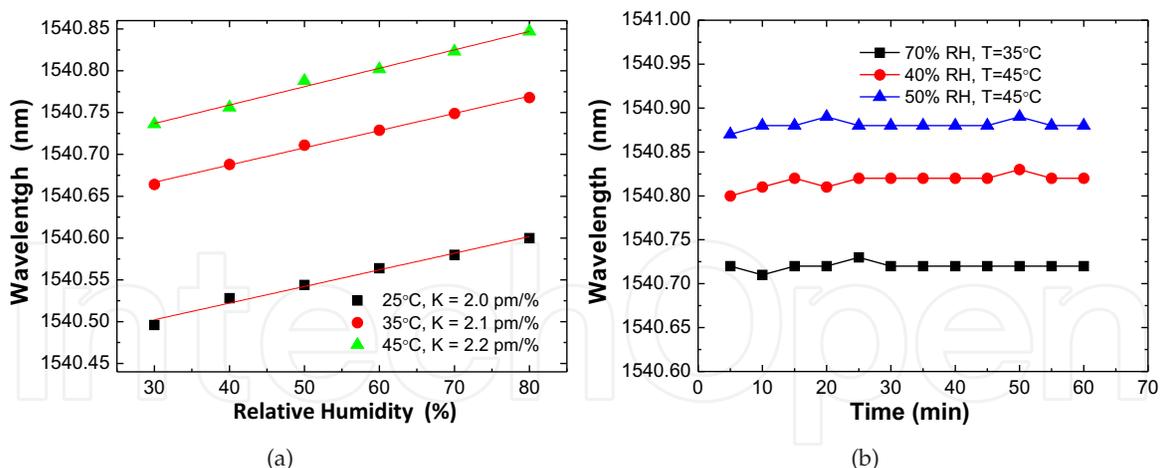


Figure 6. Measured results, (a) Bragg wavelength shifts under different environmental conditions, (b) long-term sensing stability

Bragg wavelengths were recorded within 60 minutes at different temperatures and relative humidity levels. These results show that this fabricated polyimide-coated FBG humidity sensor has a stable sensing property for a long-term relative humidity monitoring.

2.3. Moisture sensing experiments

The monitoring of the moisture in oil and in soil has become very important recently in the industrial field as well as in agriculture, forestry and geography [18, 46]. In the industrial field, the moisture in oil may induce the corrosion on the surfaces of metal parts in the engine and the occurrences of partial discharges in high-voltage electrical transformers. In these cases, compared to conventional electrical sensors, the fiber based moisture sensors play a very important role. Two experiments for measuring the moisture quantity in oil were carried out by using one of our fabricated polyimide-coated FBG humidity sensors. In these experiments, in order to simulate the actual diffusion process of the moisture in oil, we first poured a certain amount of water into the oil and stirred them with a mixer for several minutes, and then inserted the FBG humidity sensor into the oil and waited for 15 minutes before starting a stable measurement. Figure 7 is a set of photographs showing our experimental appliances used in the experiments.

In these experiments, two types of industrial oils were utilized as samples, one was the engine oil as the lubrication oil used in the gear box and the other one was the insulation oil used in high-voltage transformers. Figure 8(a) is a group of experimental data on the measurements of water contents in 20-ml engine oil at two temperatures, 25 °C, 35 °C, respectively. In this experiment, 1-ml pure water was poured each time into the oil. Figure 8(b) is a group of long-term measurement results at different temperatures by adding 3-ml water into 20-ml engine oil. From these results, a stable sensing property of the FBG humidity sensor has been verified.

Figure 9 is the measured data in another experiment on the water contents in the insulation oil, where 100-ml insulation oil was used and 1-ml, total 12-ml, water was added into the insulation oil each time. The experiment was carried out at room temperature (25 °C) and Bragg wavelength of the sensor was measured after a stabilization time of 15 minutes. From

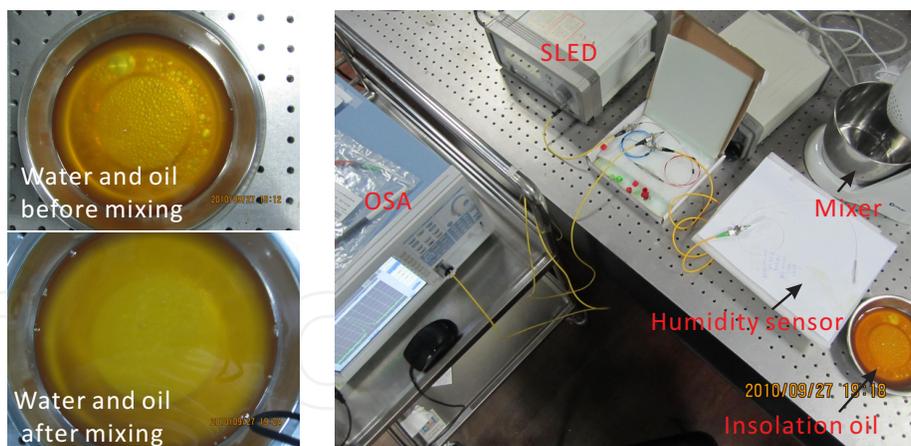


Figure 7. Experimental appliances used in measurements of moisture in oil

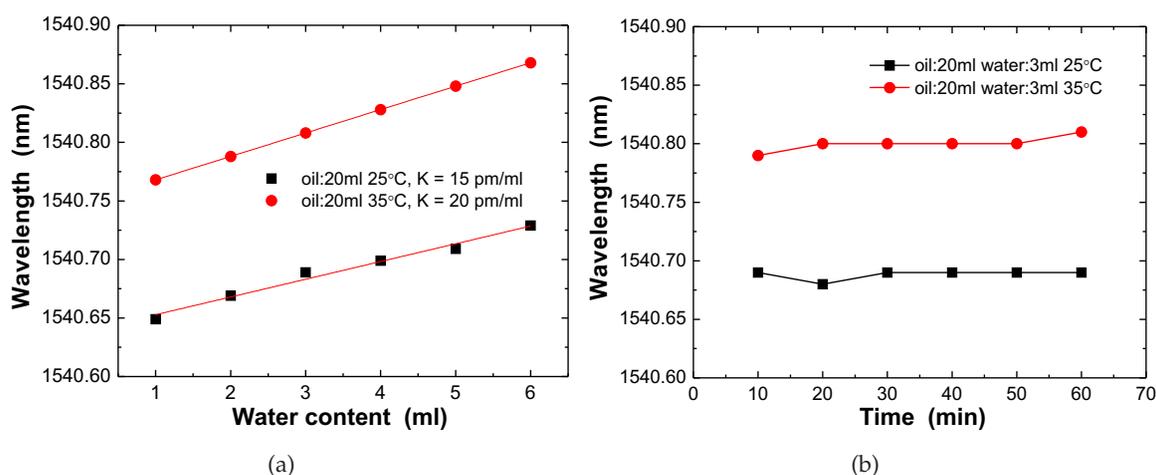


Figure 8. Measured results, (a) Bragg wavelength shifts with water contents in engine oil at two temperatures, (b) long-term sensing stability

the measured results, an increasing shift of the Bragg wavelength following the increase of water contents in the insulation oil can be verified.

From a practical view for moisture monitoring with the FBG humidity sensor, considering a fact that the moisture distribution in oil is not uniform, in order to obtain a credible result, it is important to install multiple sensors at different positions in the oil container and need to take an average operation with the measured values from all sensors installed at different locations.

3. SOA-based FBG fiber laser for multiple parameter simultaneous measurements

3.1. Technical background

Based on the phenomenon of the Bragg wavelength of FBG changing with many physical parameters, FBG sensors are mainly used for measurements of temperature, strain, pressure, and vibration [3, 39]. On the other hand, incorporated with recently developed fiber laser technologies, fiber laser sensors as active sensor systems with many unique advantages, such

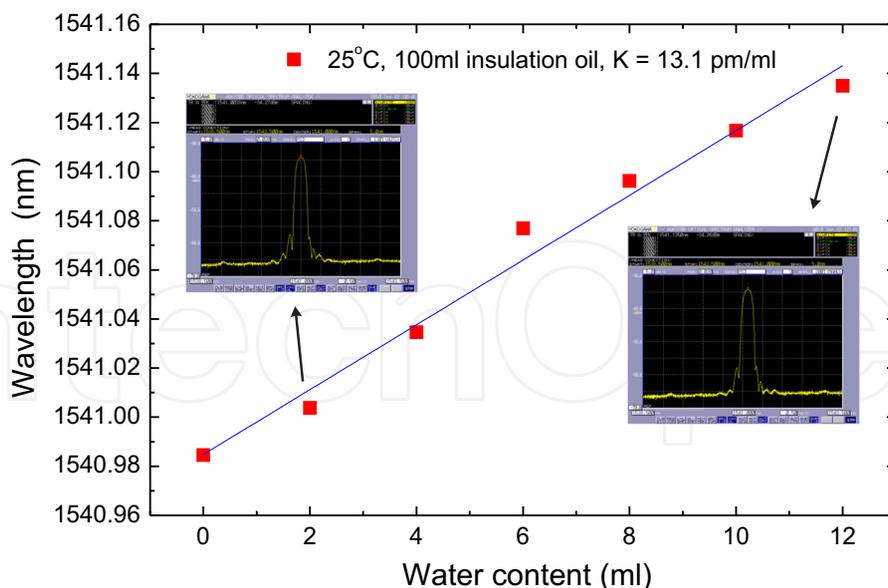


Figure 9. Bragg wavelength shifts with water contents in insulation oil at room temperature. Insets are two reflected spectrums measured at corresponding water contents

as high detection sensitivity, large dynamic range and quickly responding speed, as well as easily achieving remote sensing, recently have been developed well and widely employed in many measurement fields [23, 32, 41]. In addition, it is well known that when the fiber is coated by the polyimide resin, its mechanical strength, especially tensile strength and sensitivity to pressure will have an obvious enhancement, almost up to 30 times over those of the bare fiber [19, 35]. This property is very suitable for FBG sensors used in many specific applications for large-scale measurements, such as for measurements of strain, pressure and acceleration, where high mechanical strengths in FBG sensor itself often are required.

In many types of fiber laser systems, the recently-developed semiconductor optical amplifier (SOA) as a gain medium with an inhomogeneous broadening bandwidth over 40 nm and ultra low polarization dependency has been widely used in the construction of multi-wavelength fiber laser system with a stable lasing output [22]. The FBGs incorporated in this kind of fiber laser system are taken not only as wavelength selective mirrors, but also as sensing components to transfer various physical parameters into the changes of the system property in terms of lasing wavelength and output optical power.

In previous work, we had presented a novel SOA-based fiber laser sensor system with an ability of simultaneously measuring vibration, temperature and humidity [23]. In this proposed system, two polyimide-coated FBG sensors were used as the vibration or temperature sensor and the humidity sensor, respectively. Other two FBGs as wavelength reference elements inside the interrogator were employed, with which the required measurands in terms of temperature and humidity could be deduced from the Bragg wavelength shifts of sensors. The experimental results showed that this proposed fiber laser sensor system had an ability of simultaneously measuring the mechanical vibration in a wide frequency range from 40 Hz to 1 kHz and the temperature increase up to 110 °C as well as the relative humidity level ranging from 25 %RH to 85 %RH. In following parts of this section, we will firstly give a brief description of sensing principles in measurements of vibration, temperature and relative humidity based on this system configuration and interrogation

attached, with a control voltage. It is clear that the Bragg wavelength shift of the reference FBG linearly depends on the TEC temperature and resultantly on the control voltage of the TEC. By measuring this control voltage, one can actually obtain the magnitude of wavelength shift of corresponding sensor, which is directly related to the required measurand [10, 13]. The TEC was driven by an IC chip and its surface temperature was set through a feedback control driving with an error signal related to a wavelength difference between the sensor and the reference FBGs.

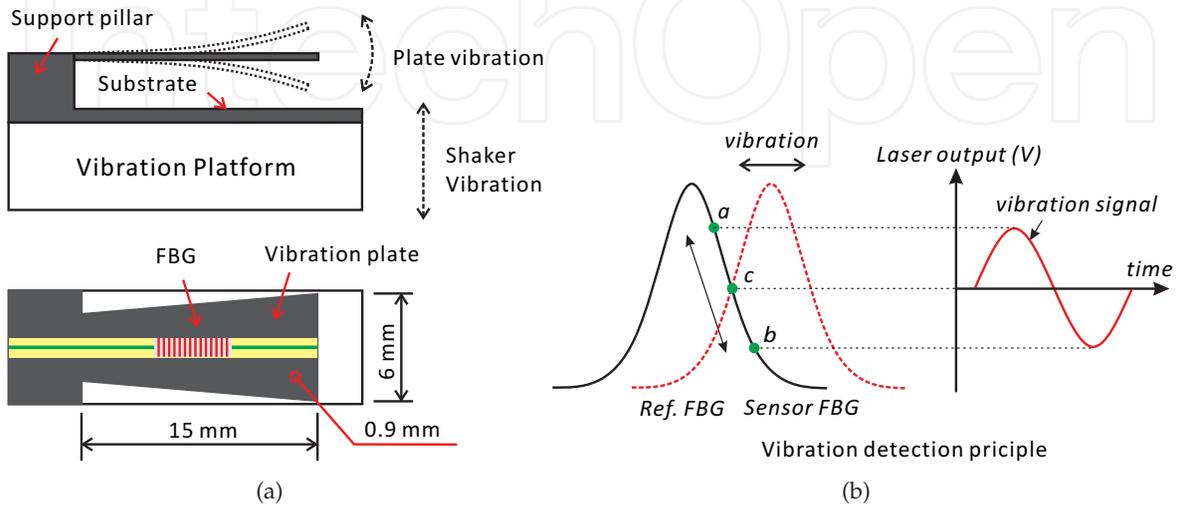


Figure 11. (a) Structure of FBG-based vibration/temperature sensor and (b) operation principle for vibration measurements

For vibration measurements, a vibration/temperature sensor was fabricated with FBG₁, as shown in Figure 11(a), which was constructed based on a mechanical amplifier structure, including a vibration plate mounted on a support pillar, and a substrate. The FBG sensor was adhered on the vibration plate with the epoxy glue. In this way the FBG sensor can be insulated from the effects of surrounding moisture. In sensing principle, when the sensor is mounted on the surface of a vibrating object, such as a shaker, a periodically up-down moving of the vibrating object will induce a periodical deformation of the vibration plate, as shown in Figure 11(a), which in turn generates a time-varying strain on the FBG₁ to periodically alter its Bragg wavelength. The magnitude of the wavelength variation of the sensor is proportional to its mechanical vibration amplitude. In sensor interrogations, when the Bragg wavelength of a reference FBG, such as FBG₄, is offset a little bit cross at the center point of the spectral profile of the sensor, marked as "C" in Figure 11(b), the periodical change in FBG₁'s Bragg wavelength can be easily converted into an intensity change in the fiber laser output. Based on this sensing principle, a vibration signal will be directly obtained from the PD₂ detection output as an AC signal.

For temperature measurements with the FBG-based vibration/temperature sensor during the simultaneous measurement of vibration, when the Bragg wavelength of FBG₁ slowly shifts due to an ambient temperature change, the Bragg wavelength of FBG₄ will be automatically adjusted by TEC₂ controller to match it with that of FBG₁. Since the magnitude of control signal voltage to TEC₂ is proportional to the magnitude of Bragg wavelength shift, in turn to temperature changes surrounding FBG₁, it can be utilized directly for temperature measurements.

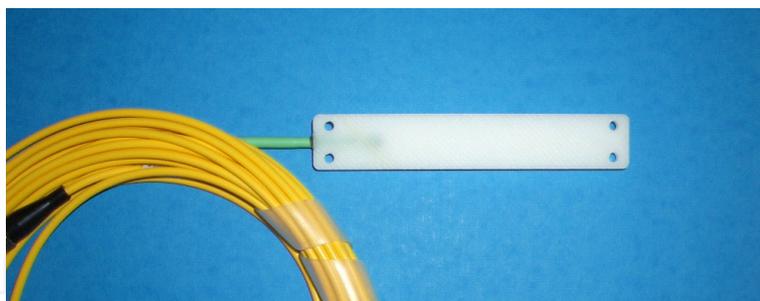


Figure 12. A photograph of packaged FBG humidity sensor

For humidity measurements, a packaged, ten-layer polyimide-coated FBG humidity sensor was used, as illustrated in Figure 12. The fundamental experimental investigations on performances of this sensor in measurements of relative humidity and water contents in oil had been carried out previously. The sensor was packaged in a specific plastic box formed with a 3-D printer, which was air permeable and allowed the moisture easily to penetrate the cover and arrived at the sensor.

The principle used for humidity sensing is similar to that employed for temperature sensing. The change of the relative humidity level surrounding FBG₂ will induce a Bragg wavelength shift of the sensor. As a direct reaction, the Bragg wavelength of FBG₃ will be automatically adjusted by TEC₁ controller to trace and finally match with the Bragg wavelength of the sensor. So the control voltage to TEC₁ can be taken directly as the measurement result of the humidity sensing.

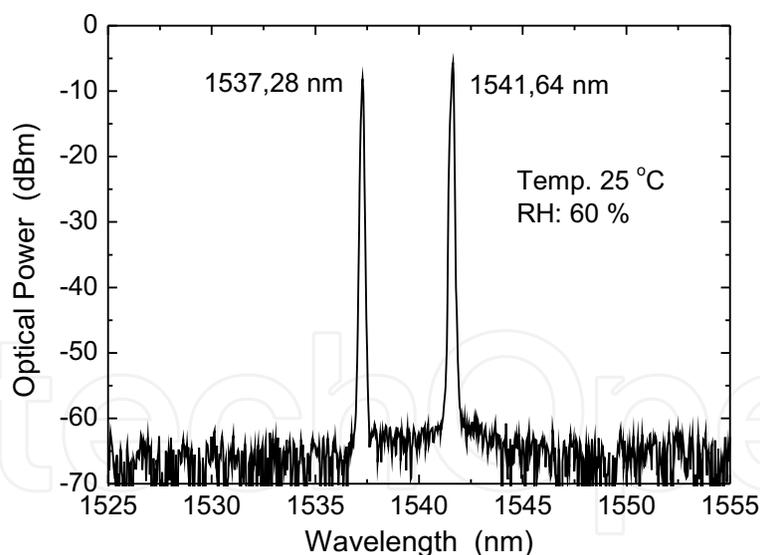


Figure 13. Output spectrum of SOA-based fiber laser sensor system

It should be noted that since the FBG-based humidity sensor has a humidity-temperature cross sensitivity, for a pure humidity measurement, however the temperature effects on the sensor should be taken into account and the temperature compensation should be taken with suitable techniques. Our system was intended to be used in a relatively closed environment for multiple parameters monitoring, for example, in a cabinet of high-voltage equipment, in which the temperature distribution is regarded to be uniform. Therefore the temperature

compensation can be real-time completed by using a measured value on the temperature change provided by the FBG-based vibration/temperature sensor.

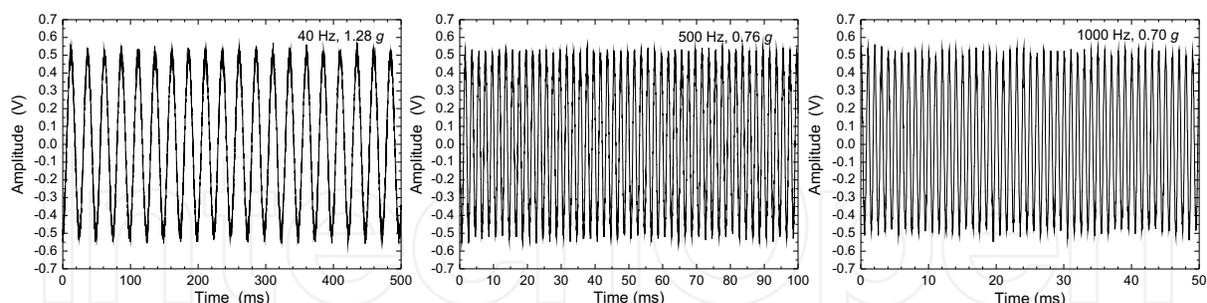


Figure 14. Three measured vibration waveforms at frequency, 40 Hz, 500 Hz and 1000 Hz, respectively

3.3. Experimental results

Several sets of experimental data for demonstrating the performances of proposed fiber laser sensor system on simultaneous measurements of vibration, temperature and humidity are presented here. Figure 13 is the output spectrum of the fiber laser sensor, measured at port "A" of a 3-dB optical coupler, OC₁. From this result, it is clear that this sensor system actually worked in a dual-wavelength lasing mode with two oscillating wavelengths at 1537,28 nm and 1541,64 nm, respectively. Figure 14 is a group of vibration waveforms measured at frequency, 40 Hz, 500 Hz and 1000 Hz, respectively, with the FBG-based vibration/temperature sensor. In this experiment, a shaker (Gilchrist TX Technology, Inc.) was used to generate the required mechanical vibrations with controlled frequency and acceleration values. The shaker had been calibrated at 100 Hz with 1 g acceleration. The sensor was placed on the vibration platform of the shaker and the output waveforms at PD₂ were monitored and recorded with a digital oscilloscope. From these waveforms measured at different frequency points, one can clearly observe that this sensor system possesses fair good performances in vibration measurements within a very wide frequency range from 40 Hz to 1000 Hz. We also investigated the frequency response of the sensor by tuning the mechanical vibration frequency of the shaker from 10 Hz to 2000 Hz and measured the average amplitude of each vibration signal at corresponding frequency point. The measured results are plotted in Figure 15, in which the red line with solid markers represents the frequency response curve of the sensor and the black line with circle markers is the acceleration profile of the shaker used. From this result, we further confirm that this FBG-based vibration/temperature sensor has a fairly flattening frequency response property from 40 Hz to 1,1 kHz and its resonance peak appears at near 1,3 kHz.

This sensor system not only can be used for continues vibration measurements, but also can be utilized for impact detections. Figure 16(Left) is a measured shock signal waveform when an impact force was applied on the table where the sensor was mounted on. Figure 16(Right) is the corresponding FFT spectrum of the shock signal. It is seen that the sensor and the designed interrogator have the ability for large-scale dynamic strain measurements within a wide frequency range up to 120 kHz.

We also investigated the system performances in tracing temperature changes. For a comparison, Figure 17 shows a group of measured vibration signal waveforms at 300 Hz with (b) and without (a) TEC₂ temperature control. It is clear that without TEC₂ temperature control, the amplitude of the vibration signal varied along with ambient temperature

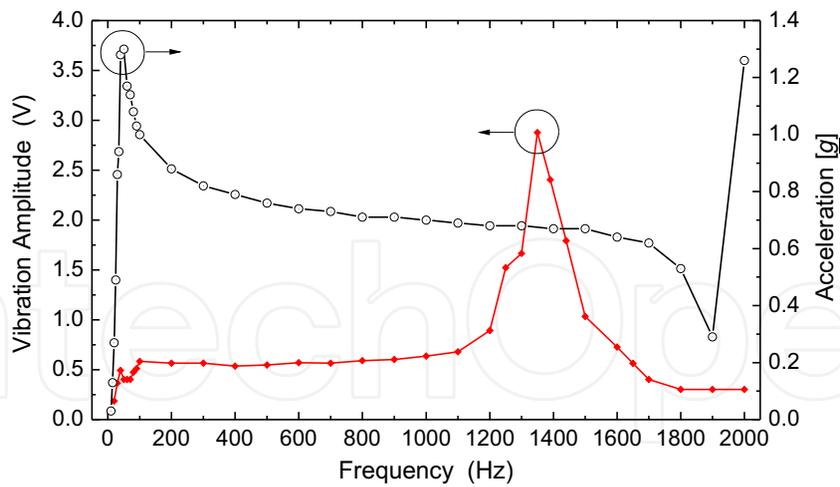


Figure 15. Measured frequency response of FBG vibration/temperature sensor and acceleration profile of shaker used in experiment. Resonance peak of sensor appears at near 1300 Hz

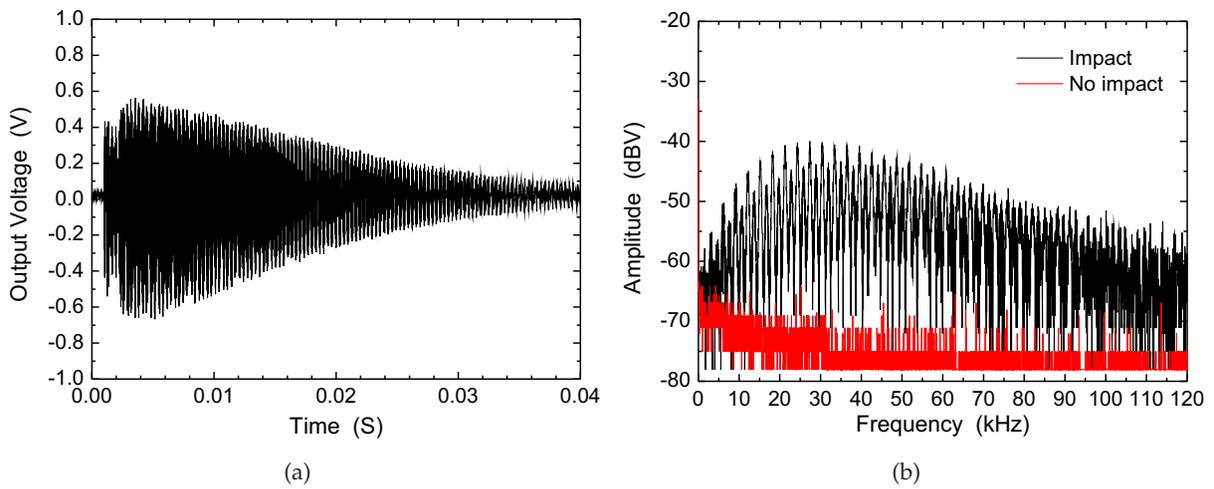


Figure 16. Measured results, (a) detected shock signal waveform, (b) corresponding FFT spectrum

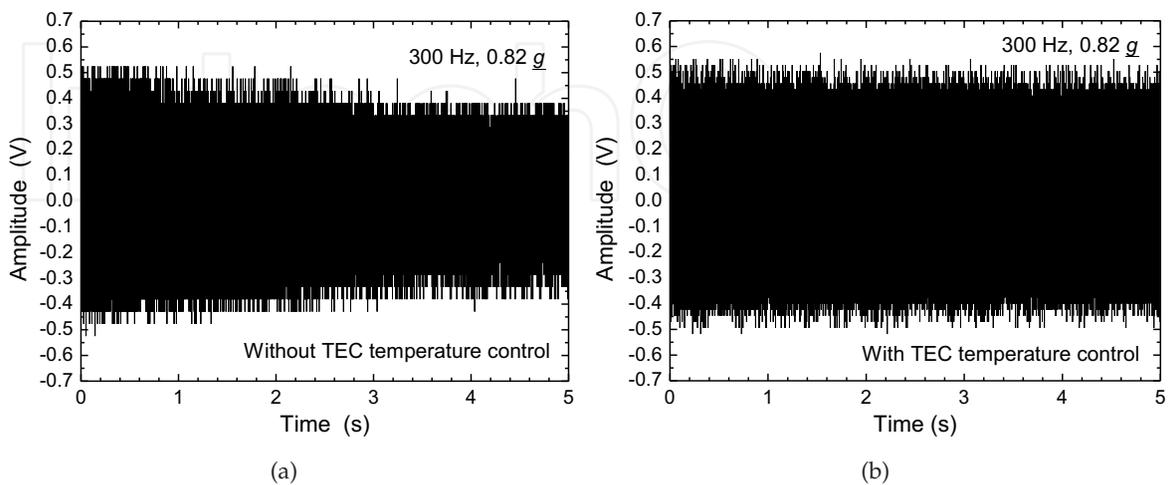


Figure 17. Measured vibration waveforms without (a) and with (b) TEC control

fluctuations. It should be noted that the TEC temperature actually is reversely proportional to its control voltage. Figure 18 is a profile of TEC₂ control voltage. From this we can obtain the information on the temperature variations. Figure 19 is a group of measured results on the amplitude variations of the vibration signal measured with the TEC temperature control. In this experiment, we placed the sensor inside a small size, thermal-insulation box with internal temperature controlled. This box then was mounted on the vibration platform of the shaker, vibrating at 500 Hz and the temperature inside this box was changed from 30 °C to 110 °C within 5 minutes. It is clear that the fluctuations in the vibration amplitude induced by temperature changes can be greatly suppressed into a small region of lower than 10 % with a suitable TEC temperature control process.

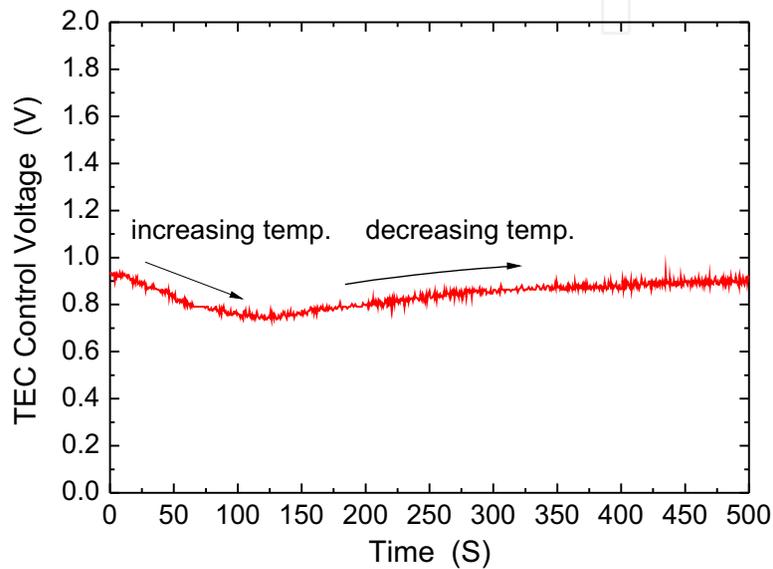


Figure 18. A profile of TEC₂ control voltage when temperature was changed

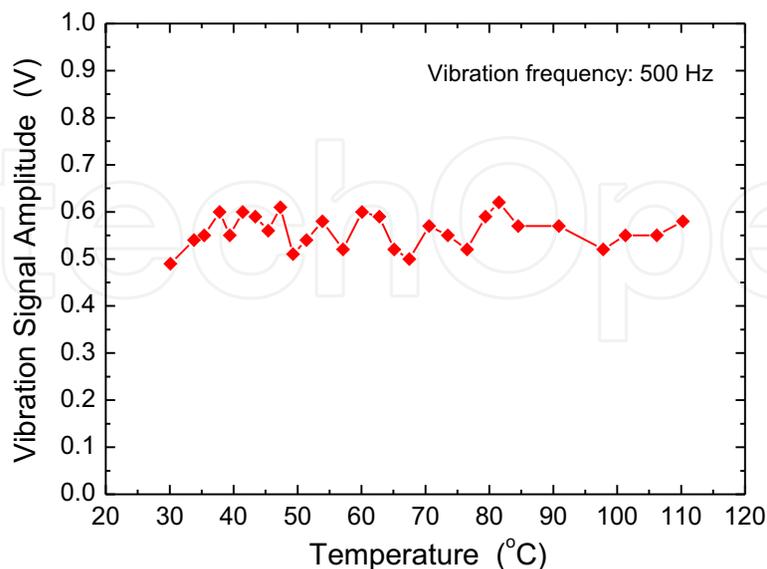


Figure 19. Amplitude fluctuation versus temperature change in a vibration measurement with TEC temperature control

Figure 20 shows an experimental result on temperature measurements with the FBG-based vibration/temperature sensor by reading TEC₂ control voltage. In this experiment, the sensor was placed into the temperature control box as mentioned above. The temperature inside the box was changed gradually from 25 °C to 110 °C within 30 minutes. During this period, the vibration and temperature were simultaneously measured. With this measured result through a linear fitting operation, we obtained a slope value of 0,00914 V/°C as the temperature sensitivity of the sensor.

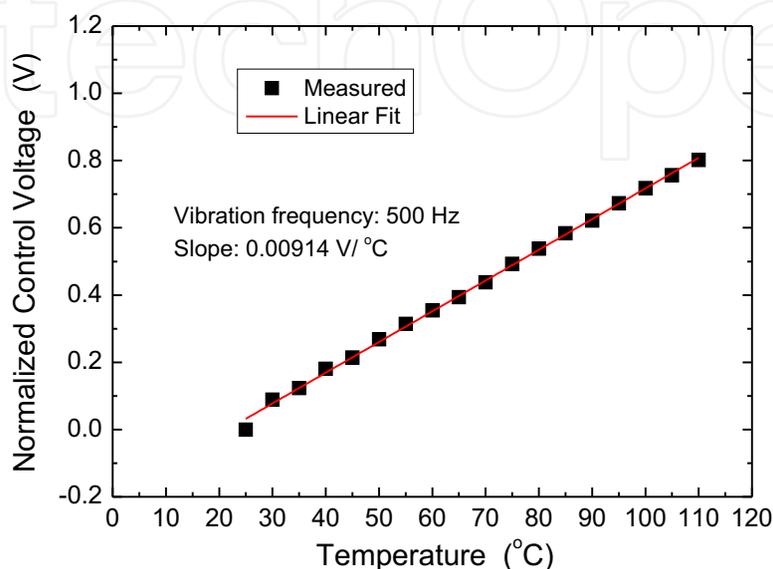


Figure 20. Measured normalized TEC control voltage versus temperature. A slope of 0.00914 V/°C was obtained

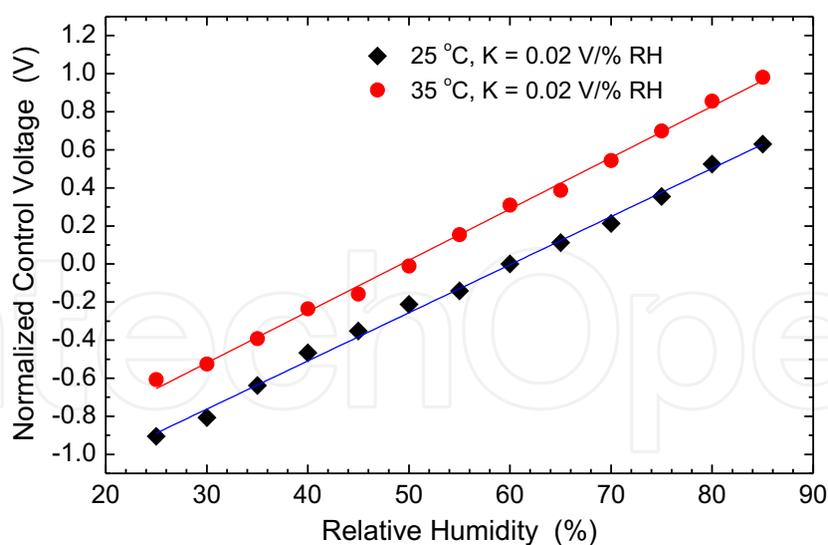


Figure 21. Measured normalized TEC control voltages versus different relative humidity levels at two environmental temperatures, 25 °C and 35 °C, respectively

Figure 21 is two sets of measured results on relative humidity measurements with the polyimide-coated FBG humidity sensor. In this experiment, the sensor was placed inside the environmental chamber, and the relative humidity level in the chamber was changed from 25 %RH to 85 %RH in a step of 5 %RH at two chamber temperatures, 25 °C and 35 °C,

respectively. In these results, the linear relationships at different temperatures between the control voltages of TEC₃ and the actual RH values in the chamber can be confirmed. Also it is clear that when the temperature in the chamber is changed the whole measured RH curve will move proportionally to the amount of the temperature change. In addition, the sensitivities of the sensor at 25 °C and 35 °C are almost same, equal to $K = 0.02 \text{ V}/\%RH$.

4. Conclusion

In this chapter, the sensing principle of polyimide-coated FBG humidity sensors has been introduced. Also some primary experimental results for investigations of sensor properties in respect of humidity sensing have been presented. The polyimide resin is an ideal coating material for fabricating the FBG-based humidity sensor. The polyimide coating swelling due to moisture absorption generates a strain imposed on the FBG, which in turn directly results in a linear and reversible Bragg wavelength shift with the relative humidity level over a wide range. This is a basis by using FBG sensors with polyimide coating for humidity sensing. The sensitivity of the sensor is dependent on the thickness of polyimide coating [21]. A thicker polyimide layer may effectively induce larger strains imposed on the FBG to increase the magnitude of Bragg wavelength shift. However this in turn inevitably degrades the time response property of the sensor and increases its susceptibility to surrounding temperature changes. The cross sensitivity of the polyimide-coated FBG humidity sensor to temperature as well as to humidity is an important influence factor in an actual sensing application for humidity measurements, which should be taken into account. Considering the importance of moisture detection and water content monitoring in industrial measurement fields, we tried to use the polyimide-coated FBG humidity sensor to measure the water contents in two types of industrial oils, including the engine oil and the insulation oil. The measured data showed that the fabricated humidity sensor has enough high sensitivity to detect the low-density moisture (< 2 %) in both industrial oils.

A prototype of SOA-based, dual-wavelength fiber laser system capable of simultaneous measurements of multiple physical parameters has been demonstrated. In this system configuration, a one-layer polyimide-coated FBG was used as the vibration/temperature sensor, and another ten-layer polyimide-coated FBG sensor was used for humidity sensing. The system performances have been investigated experimentally in various aspects, showing that this system has an ability of simultaneously sensing vibration, temperature and relative humidity in a relatively closed environment. Further work is to explore the polyimide-coated FBG sensor for other physical parameters sensing [17], and to develop the smart interrogation techniques as well as self-adapting systems [20, 40], which includes to employ the fiber laser system configuration together with wavelength multiplexing and de-multiplexing technology to form a sensor array for large scale, multiple point and multiple parameter measurements.

Acknowledgements

The authors would like to acknowledge the support and guidance provided by Key Laboratory of Specialty Fiber Optics and Optical Access Networks, School of Communication and Information Engineering, Shanghai University, China, Thanks to Prof. Ting-Yun Wang for his continuous support and encouragement during this work.

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