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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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ANALYSIS OF THE SENSOR OF TEMPERATURE AND HUMIDITY MEASUREMENT BASED ON THE OPTICAL FIBER

Abstract. The intracavity sensitivity to humidity based on the optical fibers of the Fabry-Perot interferometer (FPI) was demonstrated by means of experiment. There was described the mechanism of tactile sensitivity of lasers and their parameters of sensitivity. There was also performed an analysis of fibers deformation depending on the temperature of the reverse reflection effect of fiber Bragg grating (FBG). Based on results of these analyses, there was offered the operational principle of optical fiber sensor, which measures the humidity and temperature.

Keywords: temperature and humidity sensor, Fabry-Perot interferometer, Fiber Bragg Grating, relative humidity, Single mode fiber.

Introduction. Humidity and temperature monitoring play a very important role in many technical and scientific fields such as chemistry, biology, meteorology, electronics, cars, plants, and production of microelectronics.

Nowadays, there are many digital sensors that use physical principles.

At the present time, there are sensors that measure the humidity and temperature in the unit [1-4]. The humidity and temperature sensor based on optical fibers have such qualities as high sensitivity, fast response, small in volume and electro-magnetic interference.

Different types of sensors based on crystal fiber used to determine humidity [5-8]. Methods for measuring the temperature of optical fibers were shown [10]. Measuring system based on sensitivity of optic fiber Bragg grating (OFBG) [10-13], Fabry-Perot interferometers (FPI) [14, 15], homogeneous optical fibers [16] were discussed in publications.

The consumption of Agarose gel is low and has good results in preparation and calculation. Therefore, it is often used for comparative humidity [17]. To improve the sensitivity of optical fibers, they are made of hygroscopic materials. For example, agarose gel, graphene oxide, polyvinyl alcohol, SiO₂, WS₂, and so on. In recent years, fiber-optic sensors based on intracavity sensing of optical fiber have been investigated extensively because they can enhance the visibility of the resonant peak in the spectrum and narrow the 3 dB bandwidth [18-20].

In this article, given are experimental results of humidity that are based on fiber – optical analysis (FPI) with the range of 25 to 90 % as well as methods to determine temperature by reverse reflection of spectra on the basis of temperature dependence and optical fiber (Bragg grating).

1. Principle of the sensor's operation. Principle of the sensor's operation is based on two main sensitivities. First, it is determined by humidity sensitivity which is based on Fabry-Perot interferometer method. Second, determined optical fiber Bragg grating reflection effect of the strain change by temperature.

1.1. Spectrum reverses reflection effect of the optical Fiber Bragg Grating. It is called the Bragg wavelength (λ_B), and located in the middle of the waves which is the lumen of the filter to achieve the light spectrum that can satisfy the requirements of Bragg [3].

The value (λ_B) of these gratings in the most sensing temperature applications can be expressed as

$$\lambda_e = 2 \cdot \Lambda \cdot \eta_{eff} \quad (1)$$

where Λ is the spatial period of the Bragg grating, and η_{eff} is the effective refractive index of the optical single mode fiber. These two parameters are the function of strain and temperature. Optical Fiber Bragg Grating sensors (sensors shown in figure 2) are popular for detecting temperature strains. The Bragg wavelength shift ($\Delta\lambda_B$) induced by either a strain (ε) or temperature change (ΔT) is expressed by the following equation:

$$\frac{\Delta\lambda_e}{\lambda_e} = (1 - P_e) \cdot \varepsilon + [(1 - P_e) \cdot \alpha + \xi] \cdot \Delta T \quad (2)$$

Where respectively, P_e is the photoelastic constant, α is the thermal expansion coefficient, and ξ is the thermo optic coefficient of the optical single mode fiber.

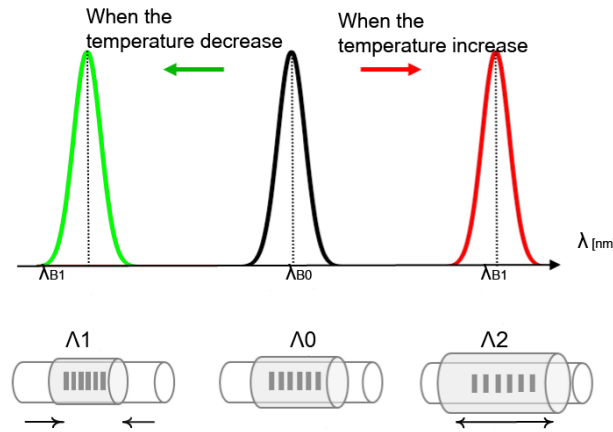


Figure 1 – The image shows the lengths and the spatial periods of the gratings as well as the Bragg wavelengths at three different temperature values

Regarding the temperature monitoring, it is performed by using a commercial FBG sensor coated by acrylate, which is sensitive to this parameter as shown in Equations (1) and (2).

1.2. Based on the Fabry-Perot, interferometer is sensitive to humidity. The scheme of the humidity-sensitive FPI diagram is shown in figure 2. Bragg Grating is placed on Optic single mode fiber and its cross-section covered with a half-reflective film, which continues with vacuum cavity of the FPI. A silicone diaphragm covers the vacuum cavity of the FPI. In figure 2 the silicon diaphragm deposited with Agarose. There are two reflective surfaces which are front and back of the vacuum cavity, whose length defined as h . Due to occurrence of interference between these two surfaces, light reflects. Because of the thickness of the silicon diaphragm on the Agarose gel, both are much less than the length of the vacuum cavity. Agarose gel has been seen as one reflective surface in the theoretical model. Therefore, the total reflected electric fields E_r of the FPI. The FPI can have the reflected electric field of two pages as follows.

$$E_r = E_0 [\sqrt{R_1} + (1 - \alpha)(1 - R_1)] \quad (3)$$

where E_0 is the input electric field, α is the transmission loss factors. R_1 and R_2 are the reflection coefficients of the two reflective surfaces. φ_{FPI} is the round-trip propagation phase shift, which can be given by

$$\varphi_{FP} = \frac{4\pi h}{\lambda} \quad (4)$$

Therefore, the peak wavelength of the m th order is given by

$$\lambda_m = \frac{2h}{m} \quad (5)$$

where m is an integer. We can derive the free spectral range, and the wavelength spacing between the two adjacent dips can be expressed as

$$\Delta\lambda_s = \frac{\lambda^2}{2h} \tag{6}$$

Total reflection spectra $I(\lambda)$ of the FPI is sensitive to humidity can be described as

$$f(\lambda) = \left| \frac{E_r}{E_0} \right|^2 = A + B \cos(2\varphi_{FR}) \tag{7}$$

Where

$$A = R_1 + (1 - a)^2(1 - R_1)^2R_2, B = 2\sqrt{R_1R_2}(1 - a)(1 - R_1) \tag{8}$$

According to Frenel formula, the reflection coefficient of the agarose gel can be written as

$$R_2 = \left(\frac{n_A - 1}{n_A + 1} \right)^2 \tag{9}$$

where n_A is the refractive index of the Agarose. When the refractive index of Agarose changes, the reflectance at the second surface will change. Because the refractive index of agarose is sensitive to ambient humidity [15]. FPI can be used to determine the humidity content of the wavelength $I(\lambda)$ below.

$$f(\lambda) = R_1 + (1 - a)^2(1 - R_1)^2 \left(\frac{n_A - 1}{n_A + 1} \right)^2 + 2\sqrt{R_1}(1 - a)(1 - R_1) \left(\frac{n_A - 1}{n_A + 1} \right) \cos(2\varphi_{FP}) \tag{10}$$

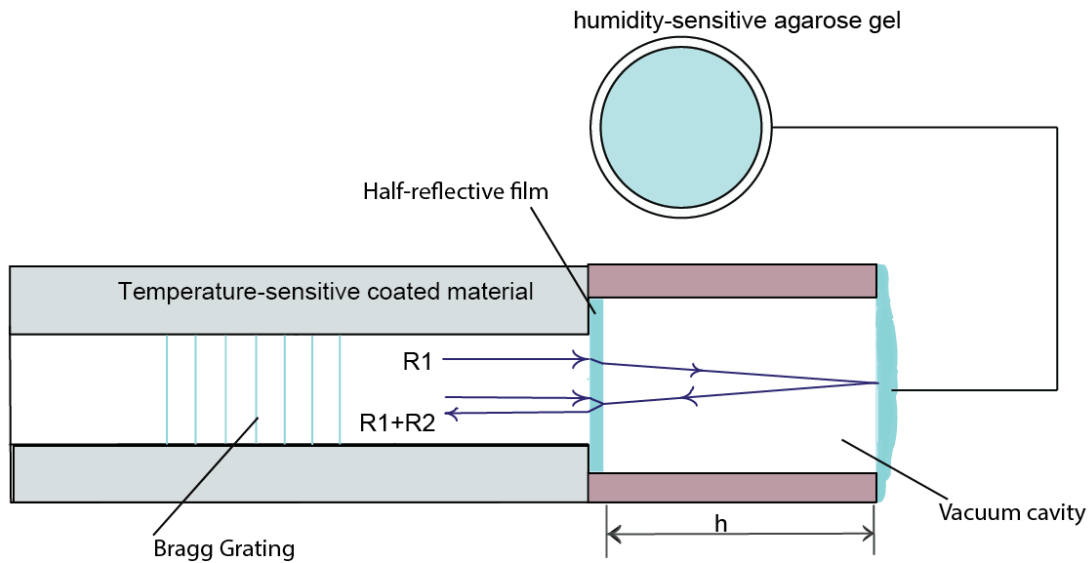


Figure 2 – The scheme of fiber-optic sensor for measuring the temperature and humidity

2. Preparation of experimental equipment and analysis of results. The experimental setup of the sensitive humidity based on FPI defines the fiber Bragg grating sensitivity that depends on the temperature. Spectrum wavelength from optical fibrous source of the laser is 1500 nm. The gain medium of the fiber laser is the Erbium-doped fiber with the length of 3 meters. In the fiber ring cavity, there is an isolator, which controls unidirectional flow. The sensors are inserted in the fiber laser by a circulator and the transmission optical fiber (TOF, Thorlabs,). Vacuum cavity of FPI serves as a wavelength selective filter and is used as the sensing head for humidity detection. Optical spectrum analyzer (OSA, YOKOGAWA, AQ6370, spectral resolution 0.02 nm) connects the three output spectrum. There are two spectrum values alternately analyzed, where first spectrum reverses reflection effect of the optical Fiber Bragg Grating and second when the ambient humidity of the sensing head changes the power reflection of the FPI.

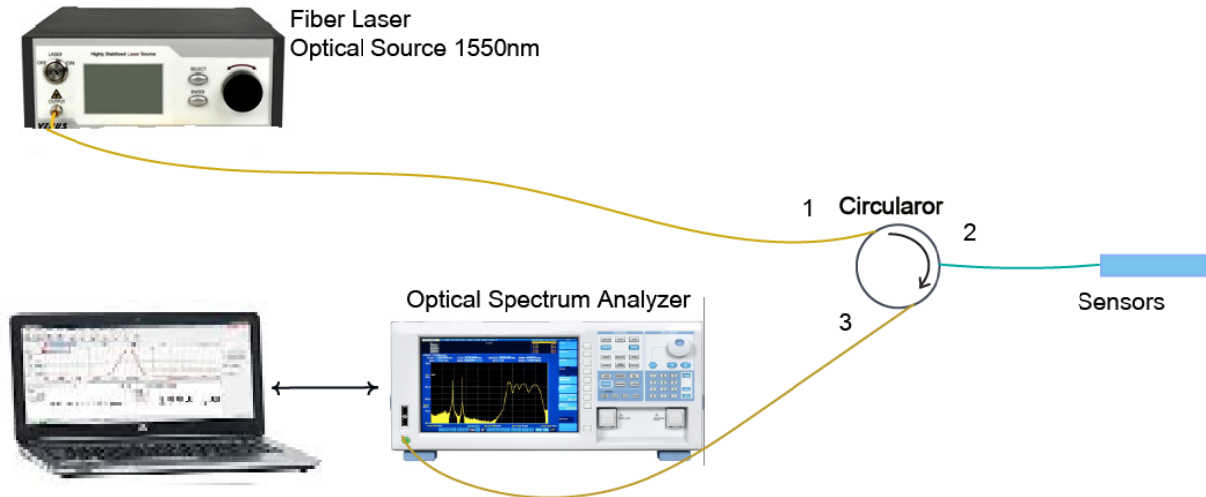


Figure 3 – Experimental setup;
Fiber optic laser light source, optical circulator, sensor, computer for results analysis, optical spectrometer analyzer

In the fabrication of the Fabry-Perot interferometer, the production of the silicon diaphragm employs mature micro-electromechanical system fabrication techniques, which provide capability of batch-production and we have reported that in [24]. The thickness of the silicon diaphragm is about 10 μm with dimension 2.5 \times 2.5 mm. The two reflecting surfaces are at the center in a vacuum environment. Then, the 2% Agarose gel deposited on the silicon diaphragm by a pipette. Agarose gel is prepared by dissolving the agarose powder in distilled water in the beaker. In the deposition process, the thickness of the Agarose is about 1 μm .

In order to obtain the optimized SNR of the proposed humidity sensor, the sensor fabrication should ensure the spectral overlap between the peak in the spectrum of the FPI. In the experiments, the gain peak at about 1500 nm is selected for the intracavity sensing. The peak wavelength and the wavelength spacing of the FPI can be designed by changing the h length of the FP cavity. When the ambient humidity is 35 %RH, the reflection spectrum of the FPI is measured as in Fig. 4. In the reflection spectrum of the Fabry-Perot interferometer, the peak with maximum intensity is at about 1530 nm and the reflection loss is -12.2 dB. The wavelength of the FPI is 15.5 nm.

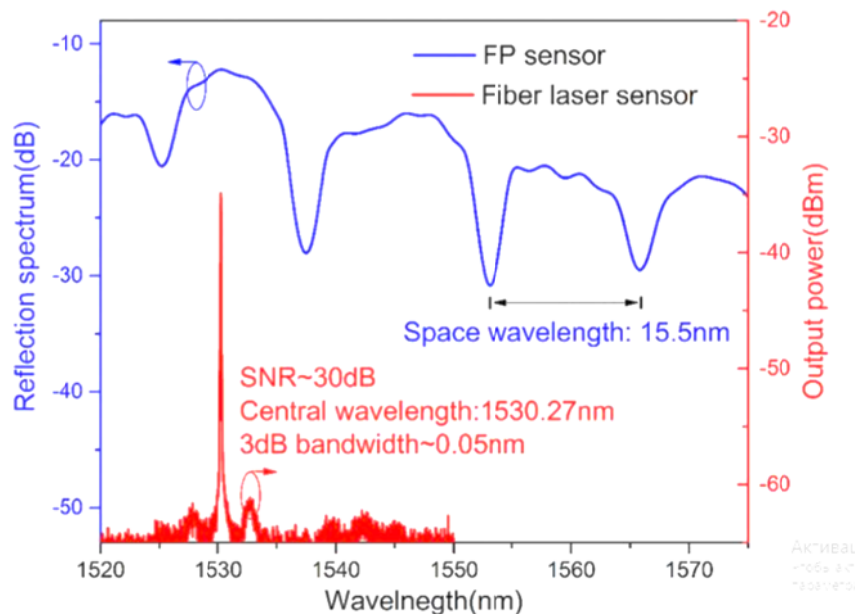


Figure 4 – The spectra of the Fabry-Perot interferometers and corresponding optical fiber when the ambient relative humidity is 35 %

Based on the FPI method, the relative humidity range is 20-98% RH. As the ambient humidity changes, the output spectra of the optical fiber laser is measured as shown in figure 5(a). Output power of the optical fiber laser increases from -36.78 to -22.61 dBm as the ambient humidity changes from 25 to 95 %RH with the resolution of 10 %RH. Accordingly, the signal-to-noise ratio increased from 30 to 45 dB and the transmittance was 3 dB, which was lower by 0.5 nm. The humidity sensitivity is measured to be 0.202 dB/%RH. It shows the sensor has a good linear response. The practice showed a good outline of the sensor. So, as the relative humidity of the environment has changed from 20 to 90%, The agglomerate breakdown index is measured from 1.45 to 1.48 [23].

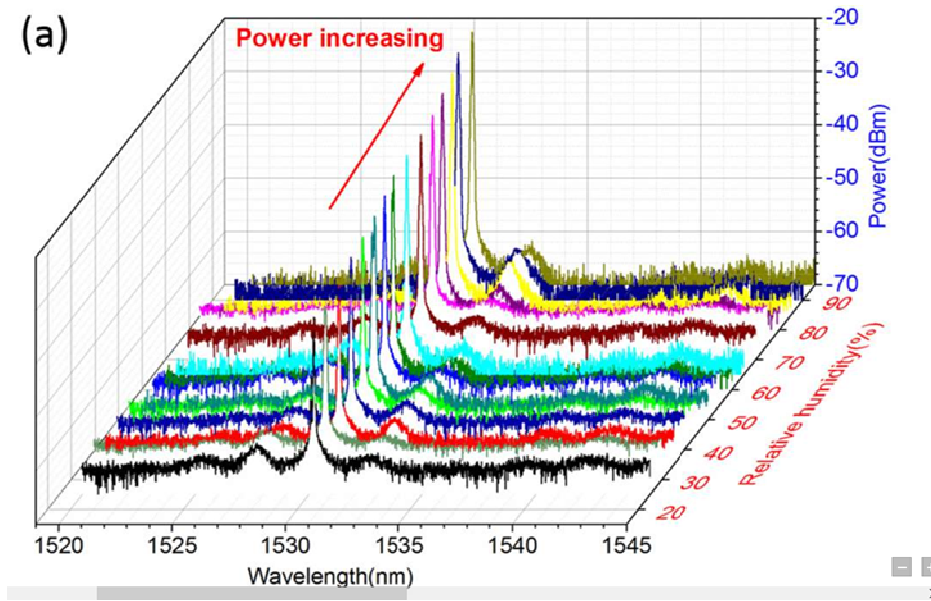


Figure 5 – The change in the optical fiber laser output spectrum when the ambient humidity varies from 20 to 90 %RH

Approximate response time of the sensor is as fast as of 72 ms. The recovery time is about 357 ms, which depends on the time of the humid air removed from the sensor. Input and remove time taken into consideration, the real response time and recovery time are shorter than the measured time.

Cross-sensitivity of the sensor is the laser spectrum of the fiber at any temperature. As the temperature increases from 25 to 45 °C, the release wavelength of the optical fiber laser sensor has a red shift from 1530.19 to 1530.64 nm and the output power decreases from -36.64 to -37.12 dBm. A low temperature cross sensitivity is receive as -0.025 dB/°C and 0.024 nm/°C.

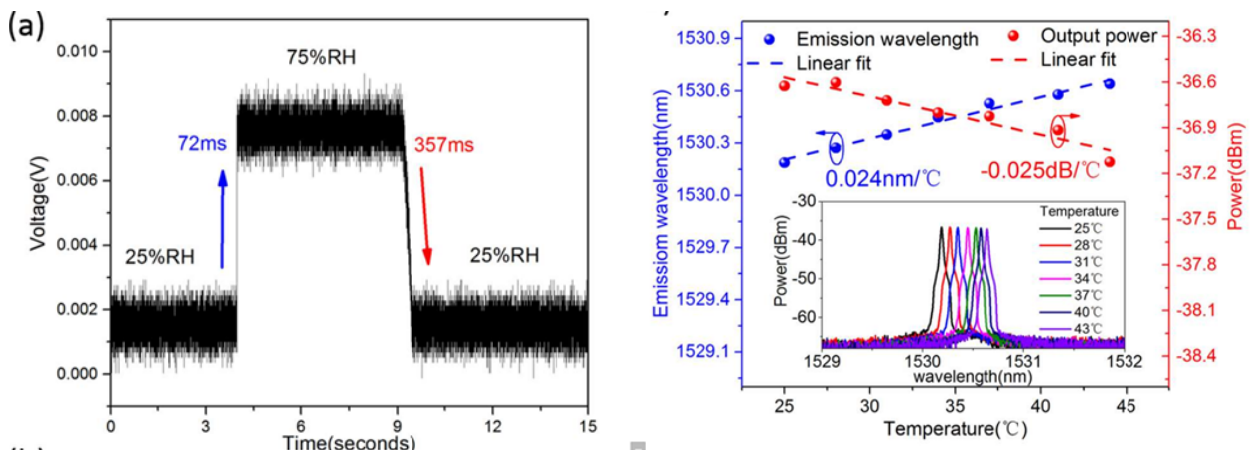


Figure 6 – (a) Sensor response time of the sensor (b) Temperature cross-sensitivity of the fiber sensor, output spectra of the fiber laser as the ambient temperature increases from 25 to 44 °C

Output stability is an important parameter for internal fiber laser sensors, which limits their applications [14]. For the stability analysis of the fiber sensor, emission wavelength and output power has been measured over 180 minutes by fixed the humidity at 65 and 95 %RH, respectively. The optical fiber laser output spectrum is perspective shown in figure 7 (a) and 7 (b). Wavelength and power stability are analyzed in figure 7 (c). The standard diversions of wavelength and power fluctuation are 0.101 nm and 0.129 dBm respectively at 65 %RH, and the standard deviations are 0.046 nm and 0.137 dBm respectively at 95 %RH. It demonstrates that the sensor shows a good repeatability for its humidity response and the fluctuation of measured humidity value which is less than ± 2 percentage RH.

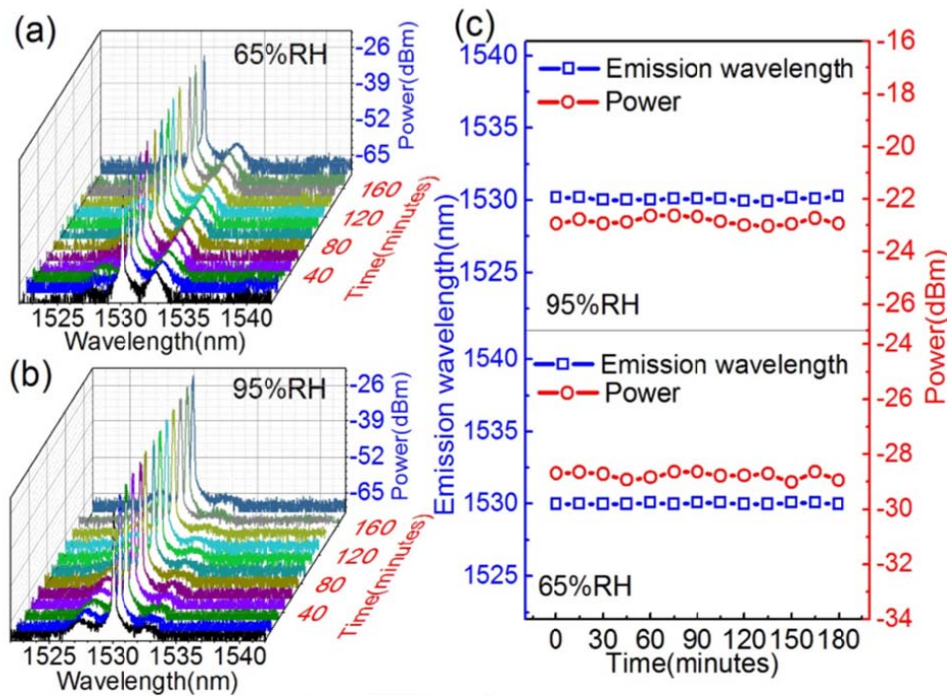


Figure 7 – The output spectrum of the optical fiber laser sensor by fixing the ambient relative humidity at (a) 65 %RH and (b) 95 %RH of the measured values measured in 180 minutes, and (c) the wavelength and power stability.

In response to the above results, we can control the temperature changes by determining the wavelengths of the fibrous fluid from wire mesh lattice sensitive to the temperature stages

Conclusion. In summary, based on the FPI method, theoretical substantiations were made and the results of the experiment on the sensitivity to humidity of agarose reflections were summed up. Also, a mathematical equation of optical fiber Bragg grating reflection effect of the strain change by temperature was created. We have suggested that the temperature can be determined on the basis of the reverse reflection spectrum according to the results, mentioned in the articles [10-13].

A compact humidity-sensitive optical fiber FPI was developed and inserted in a fiber laser for intracavity humidity sensing. We analyzed the sensing mechanism of the fiber laser sensor and characterized its sensing performance. The relative output power of the fiber laser had a good linear response to ambient humidity in a wide range from 25 to 90 %RH. In addition, the stability of the sensor was discussed.

The humidity and temperature sensor based on optical fibers have such qualities as high sensitivity, fast response, small in volume and electro-magnetic interference.

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ОПТИКАЛЫҚ ТАЛШЫҚ НЕГІЗІНДЕ ТЕМПЕРАТУРА МЕН ЫЛҒАЛДЫЛЫҚТЫ ӨЛШЕЙТІН ДАТЧИКТИ ТАЛДАУ

Аннотация. Ылғалдылыққа байланысты Фабри-Перот интерферометрлері (ФПИ) негізінде оптикалық талшықтың ішкі сезімталдығы ұсынылып, эксперименталды түрде көрсетілді. Лазерлік сенсорлық сезімтал механизмі және оның сезімталдық көрсеткіштері сипатталды. Оптикалық талшықты брэгг торларының (ТБТ) белгілі бір спектрлік кері шағылысту эффектісіне негізделіп температураға талшықтың деформациялық өзге-

рісін талдау. Осы талдаулар негізінде температурамен ылғалдылықты бірлікте өлшейтін оптикалық талшықты датчиктің жұмысын ұсыну.

Түйін сөздер: температура мен ылғалдылық өлшейтін датчик, Фабри-Перот интерферометрлері, Оптикалық талшықты брэгг торларыны, салыстырмалы ылғалдылық, Бір бағтты талшық.

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АНАЛИЗ ДАТЧИКА ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ И ВЛАЖНОСТИ НА ОСНОВЕ ОПТИЧЕСКОГО ВОЛОКНА

Аннотация. Экспериментально продемонстрирована внутррезонаторная чувствительность к влажности на основе оптических волокон интерферометров Фабри-Перо(ИФП). Описан механизм сенсорной чувствительности лазеров и их параметры чувствительности. Проведен анализ изменения деформации волокон в зависимости от температуры на обратном отражательном эффекте волоконной брэгговской решетки (ВБР). На основе этих анализов предложены принцип работы оптического волоконного датчика, который измеряет влажность и температуру.

Ключевые слова: датчик температуры и влажности, интерферометр Фабри-Перо, Брэгговская волоконная решетка, относительная влажность, однородное волокно.

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