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Simulation and Investigation of Humidity Sensor based on Fiber Grating Fabry-Perot

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Abstract

In this article we have discussed the relative humidity sensor based on fiber grating Fabry-Perot (FBG-FP) coated with polyimide (PI) as a moisture sensitive film in theory. The moisture expansion coefficient of PI film as moisture strain on the FBG-FP sensor, which will result the change of the fiber core effective refractive index, the length of the F-P cavity and the period and effective refractive index of FBG. For that reason, the interference fringes of the reflection spectrum will be changed also. The shift of peak wavelength of the spectrum is traced by the simulation of Matlab. We discuss three situations: the coating on the FBG, FP cavity and the both, and regardless of the temperature changes, the simulation results show that the RH sensitivity can reach to 3.77pm/%RH, 2.12 pm/%RH, 4.05 pm/%RH, respectively.

Keywords: *fiber Bragg grating Fabry-Perot (FBG-FP); Relative humidity (RH); polyimide (PI); moisture sensitive*

1. Introduction

Relative humidity (RH) is an important representation parameter of human environment, which is relate to the aerospace, civil engineering, medical science, military and meteorological fields. So the environment Relative humidity monitoring is very important. Currently, the monitoring humidity sensors available on the market are mostly based on the electronic and mechanical hygrometer, the electronic hygrometer makes up the most market because of the measurement accuracy, fast response speed and easy to handle and control signal. But it can't work under severe environmental pollution and strong electromagnetic interference, because of the bad long-term stability and interchangeability, besides the single point measurement of these are the obstacles for its applications [1]. Since 1993, Hill [2] put forward a method to fabricate fiber Bragg grating (FBG) using ultraviolet irradiate phase mask, the manufacturing of FBG toward the functionization and industrialization. As a new type of sensing element, FBG has been reported for its advantages of simple fabrication, wavelength coding, miniature size, non-conductive strong anti-jamming, low cost, and ease of multiplexing, what's more the center wavelength of which is sensitive to temperature and strain, so it is suitable to use FBG as a sensor [3]. But the production technology of fiber optic hygrometer is not yet mature, there are some defects, FBG has a small response to humidity, the shift of the wavelength is about 100pm during the range of 0-100%RH [4], and the humidity sensitive film on the surface of the fiber is not stable, and easy to fall off.

Compared to traditional FBG sensors, fiber Bragg grating Fabry-Perot (FBG-FP) has a higher sensitivity and resolution. The sensor is constituted by two FBGs which have same center wavelength are separated by a certain distance, the FBGs can work as a reflector in FP cavity for its reflectivity, and the fiber between the two FBGs has form a resonant cavity. The reflective spectrums of this kind of cavity structure are narrower than FBG;

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therefore, FBG-FP has wider application during the measurement of temperature and strain. In addition, FBG-FP sensors have the advantages of FBG and the advantages of FP at the same time, so it attracts extensive attentions of researchers [5].

In this article, we adopt FBG-FP to measure RH by coating the FBG with moisture sensitive polymer [6]. In the simulation, we chose the polyimide to work as moisture sensitive film. Polyimide (PI), that refers to a kind of polymer material, and which is famous for its heat resistance, low temperature resistance, excellent mechanical properties, chemical stability and easy to modify. We use the good humidity expansion linearity of PI in the humidity measurement. In this paper, we discuss the following three situations: the coating on the FBG, FP cavity and the both, respectively. And then we analyzed the humidity characteristics of FBG-FP under the different film thickness detially.

2. Principle of FBG-FP Sensor

The schematic of grating F-P cavity coated with polyimide is shown in Figure1. Two FBGs with the same Bragg wavelength are separated by a distance of d to form F-P cavity. In the simulation, the FBG used in this paper is carved in standard single-mode fiber, and the length of which is L. The diameter of fiber core and cladding are 8um and 125um, respectively. And the thickness of PI film coated on the FBG is t_{pf} and on the F-P cavity is t_{pc}.

As shows in the Figure1, Fabry–Perot interferometer formed by two identical FBGs, as the single mode fiber, the reflectivity coefficient can be expressed as the following [7]

$$r_g(\lambda) = \frac{-k\sinh(SL)}{\Delta\beta\sinh(SL) + iS\cosh(SL)} \tag{1}$$

In the equation, where $S^2 = k^2 - \beta^2, k = \frac{\pi\Delta n}{\lambda}$ is the coupling coefficient, and $\beta = \frac{2\pi n_{eff}}{\lambda}$ is the propagation coefficient, $\Delta\beta = \beta - \beta_0 = \frac{2\pi n_{eff}}{\lambda} - \frac{\pi}{\Lambda}$ is the detuning of β, Δn is the refractive index modulation depth, λ is the wavelength of incident light, n_{eff} is the core effective refractive index, Λ is the grating period.

According to coupled-mode theory and transmission matrix of FBG-FP, the reflectivity of FBG-FP can be deduced, shown in following

$$R_{F-P} = \frac{F\sin^2(\beta d - \phi_r)}{1 + F\sin^2(\beta d - \phi_r)} \tag{2}$$

In which, $F = \frac{4R_g}{(1-R_g)^2}$ $R_g = r_g^{\ 2}$ is the reflectivity of FBG, ϕ_r is the phase delay within the fiber cavity as defined by

$$\phi_r = \pi + \arctan\frac{S\cosh(SL)}{\Delta\beta\sinh(SL)} \tag{3}$$

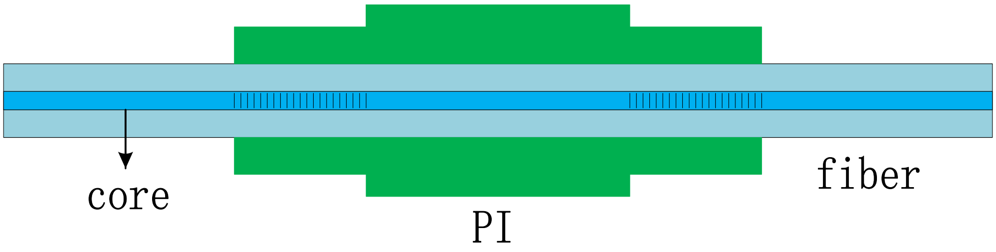

Figure 1.Schematic of Grating F–P Cavity Coated with Polyimide

Because the PI film is sensitive to humidity, when the FBG-FP is coated with PI film, the strain on the FBG and the cavity induced by an expansion of the polyimide coating due to the RH change. The grating period, cavity length and the effective refractive index will all be affected by the strain. As a result, the spectrum of the FBG-FP will be changed also.

According to the Bragg conditions $\lambda_B = 2n_{eff}\Lambda$, when the volume of PI is expansion, the stress is induced along the axial direction of Bragg granting area, so the change of RH is converted to the shift of Bragg center wavelength. The shift of the Bragg wavelength of the coated FBG due to strain change is determined by [8]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\varepsilon_{RH} + (1-P_e)\varepsilon_T + \xi\Delta T \tag{4}$$

Where ξ and P_e is the thermo-optic coefficient and elastic coefficient of the fiber, respectively; and ε_{RH} is the strain on the fiber core induced by an expansion of the polyimide coating, similarly ε_T is the strain on the fiber core due to temperature change moisture, can be written as [9]

$$\varepsilon_{RH} = \left[\frac{A_P E_P}{A_P E_P + A_f E_f}\right](\beta_P - \beta_f)\Delta RH \tag{5}$$

$$\varepsilon_T = \left[\frac{A_P E_P}{A_P E_P + A_f E_f}\right](\alpha_P - \alpha_f)\Delta T + \alpha_f \Delta T \tag{6}$$

In the equations, A_f and A_P are the cross-sectional area of fiber and PI film, respectively. E_f And E_P are the Young's modulus of fiber and polyimide, respectively. β_P And α_P are the wet expansion coefficient and thermal expansion coefficient of polyimide, respectively. Similarly, β_f and α_f are the wet coefficient and thermal expansion coefficient of the fiber, respectively. For bare optical fiber is not sensitive to the humidity, the coefficient of wet expansion is zero. By the equations above, the change of reflection spectrum of the FBG-FP due to RH and temperature can be calculated.

3. Simulation of the coated FBG-FP humidity Sensor

3.1 Only the F-P Cavity Coated with PI

The wet strains induced on the cavity due to a volume expansion of the polyimide coating when the RH changes. And the change of the FBG-FP's reflectivity depend on the following factors: the change of the fiber core effective refractive index based on the elastic light effect and the length of the F-P cavity will also change which is caused by the wet strains, the relationship can be given by [10]

$$d' = d(1+\varepsilon_{RH}) \tag{7}$$

$$n'_{eff} = n_{eff}(1-P_e\varepsilon_{RH}) \tag{8}$$

Where d' and n'_{eff} are length of F-P cavity and the fiber core effective refractive index after the change of the RH, respectively. The reflection spectrum of FBG-FP under different RH is shown in Figure2.

The sensor performance was simulated with the value of E_f was set to 73 Gpa while E_p was set to 2.5 Gpa. Similarly, β_p was set to 7×10^{-5} (%RH^{-1}), α_f, α_p were $5.5\times10^{-7}, 4\times10^{-5}(K^{-1})$, respectively, and P_e was set to 0.213 [11]. Two uniform FBGs with Δn of 9×10^{-5}, L of 3mm and of 1550nm separated by a distance d of 6 mm were used to form FP cavity. The value of t_{pc} was varied for three values, namely 10um, 15um, and 20 um.

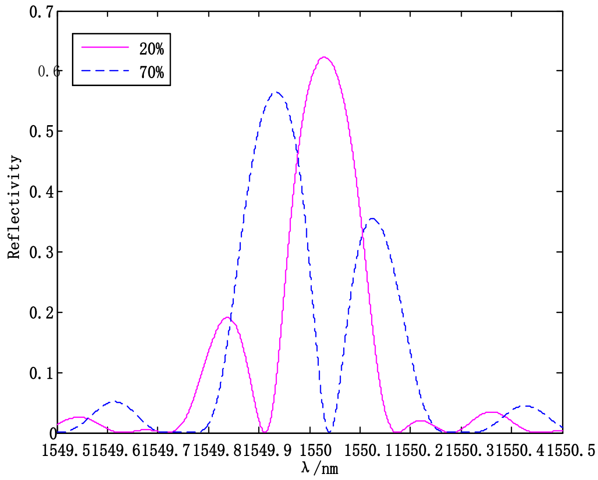

Figure 2. Reflection Spectra of FBG-FP at Different RH

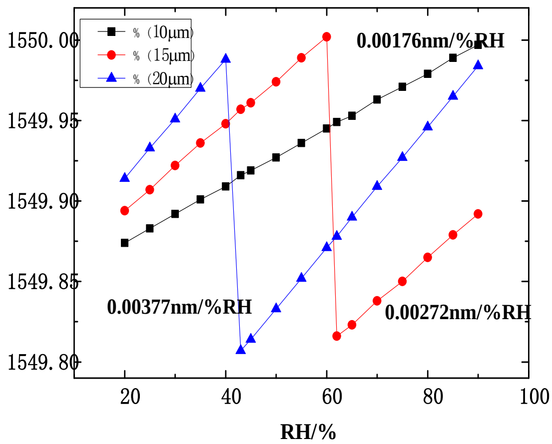

Figure 3. Humidity Response under Different Thickness

There are two peaks in the reflection spectra, as described in the Figure2 and Figure3. In order to calculate simply, we choose one of the peaks to detect the shifts of the wavelength when the RH changes. Keeping the room temperature unchanged, with the thickness of the coating increase, and the RH is increased from 20% to 90%, we can obtain the wavelength shift with the RH change and the coating thickness, and then fitting the data. It is shown that the sensor sensitivity increases as the t_{pc} increases, the RH sensitivity for t_{pc} of 10um, 15um, and 20 um are 1.76pm/%RH、2.72pm/%RH and 3.77pm/%RH, respectively. However, with the thickness increase, a discontinuity exhibits in the RH response. The discontinuity is a result of a shift of the Bragg wavelength to a value that coincides with a maximum of the interference function of the FBG-FP [12]. Obviously, although the RH sensitivity has increased, but the discontinuity limits the working range of the sensor with the thickness increased.

3.2 The F-P Cavity and FBG are Coated with same Thickness PI

The wet strains induced on the cavity and FBG due to the volume expansion of the polyimide coating when the RH change, not only the change of fiber core effective refractive index, but also the change of period and effective refractive index of FBG (For the refractive index difference between core and cladding is small, so we assume that both are equal in the simulations), which can be expressed as

$$n_{eff}^{'} = n_{eff}(1-\varepsilon P_e) \tag{8}$$

$$\Lambda^{'} = \Lambda(1+\varepsilon_{RH}) \tag{9}$$

$$d^{'} = d(1+\varepsilon_{RH}) \tag{10}$$

We can found from the Figure 4, when the coating thickness on the FP cavity and FBG are the same, the reflection spectra of the FBG-FP shift with the RH change, but the intensity of peaks stays stably. This can be explained the strains on the FBG-FP cavity and FBG are the same because of the same coating thickness, so the intensity of peaks is unchanged. The humidity response under different PI film thickness is shown in Figure 5.

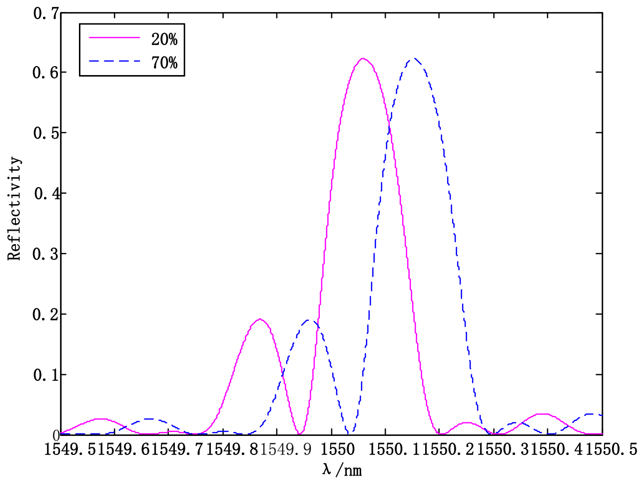

Figure 4. Reflection Spectra of FP Cavity at Different RH

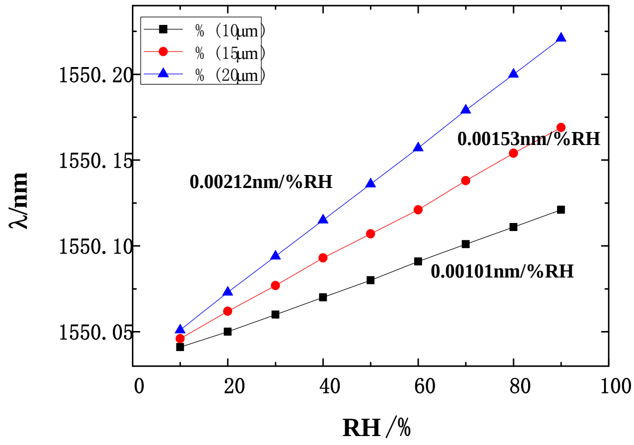

Figure 5. Humidity Response under Different Thickness

From the simulation, we can obtain that the RH sensitivity for t_{pc} of 10um, 15um, and 20 um are 1.01pm/%RH, 1.53 pm/%RH and 2.12 pm/%RH, respectively. It can be seen that, if the intensity demodulation is not considered, the RH sensitivity increases with the thickness, and the relationship between RH and the FBG-FP reflection spectrum wavelength is linear. So we should choose the thicker coating to obtain the higher RH sensitivity.

3.3 The F-P Cavity and FBG are Coated with Different Thickness PI

For the different coating thickness, the wet strains induced on the cavity and FBG caused by the volume expansion of the polyimide coating are different due to the RH change. With the RH change, the reflection spectra of the FBG-FP shift as well as the intensity of peaks change, so the sensors can be used as intensity demodulation device. The humidity response under the thickness of 15um, 20um and 25um are shown in Figure 7.

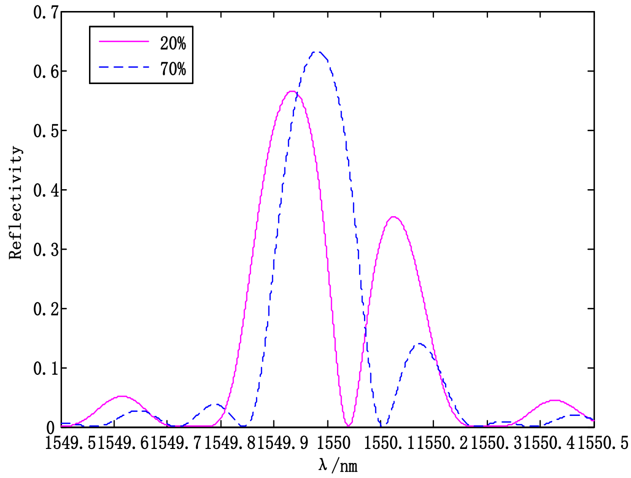

Figure 6. Reflection Spectra of FP Cavity at Different RH

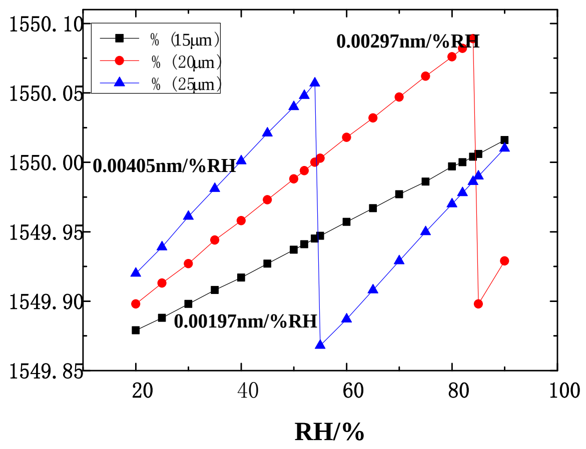

Figure 7. Humidity Response under Different Thickness

After fitting the data points, we get the RH sensitivities are 1.97 pm/%RH, 2.97pm/%RH and 4.05 pm/%RH, respectively. But the situation result is the same as the first simulation, with the thickness increase, there appears a discontinuity in the RH responses, which also limits the work range of the sensors.

4. Conclusions

We can obtain the following conclusions through the simulations of the FBG-FP coated with PI:

1. For the first situation we discussed above, the RH sensitivity rise with the thickness of PI coating increase. If the intensity demodulation isn't considered, we can choose the thicker PI coating to apply to accurate measurement of humidity in a small range. While for the large range of the humidity measurement, we'd better choose the thinner PI coating.

2. For the second situation, the interference intensity of the spectral remains the same with the thickness of PI coating increase, which cannot be used as the intensity demodulation. So in order to get higher RH sensitivity, we can increase the thickness of PI coating.

3. For the last situation, the RH sensitivity rise obviously with the thickness of PI coating increase, which can be apply to accurate measurement of humidity in a small range.

Acknowledgements

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