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Cascaded Fabry–Pérot Interferometers with Vernier Effect for Gas Pressure Measurement

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ABSTRACT

A sensitivity enhanced gas pressure sensor with Vernier effect is proposed in this paper. The sensor is a cascade configuration which includes two Fabry–Pérot interferometers (FPIs) with different free spectrum range (FSR). Each Fabry–Pérot interferometer is fabricated by inserting a piece of hollow core fiber (HCF) in between two sections of single mode fiber (SMF). Femtosecond laser is applied for drilling an opening on the HCF of sensing FPI to make the air hole interact with outside environment, while the air hole of the reference FPI is kept closed. Gas pressure response is measured by monitoring the wavelength shift of the envelope extracted from the superimposed spectrum of the cascaded FPIs. Experimental results show that the sensitivity of the cascade configuration can attain -65.482nm/MPa, which is -13 times of single sensing FPI.

Keywords: *Fabry–Pérot interferometer, Vernier effect, gas pressure*

1. INTRODUCTION

Vernier effect is an effective method to improve the sensitivity of fiber interferometers/resonators and has been widely applied in fiber optic sensing field, including temperature sensing [1], airflow monitoring [2], refractive index measurement [3] and so on. In terms of gas pressure measurement, a cascade Fabry–Pérot interferometers (FPIs) structure [4] proposed by Quan et. al can improve the sensitivity by an order of magnitude compared with general interferometers without Vernier effect. However, temperature crosstalk is a concern as the two FPIs with different configuration show very different response to temperature fluctuation, which leads us to design temperature compensated gas pressure sensors with Vernier effect [5-7].

In this paper, we present a gas pressure sensor that fabricated by cascading two hollow core fiber (HCF) based FPIs. Each of the cascaded FPI is constructed by splicing a short piece of HCF in between two sections of single mode fiber (SMF). Two FPIs with different length of HCF result in differences between their FSRs, which creates an envelope superimposed on the peaks of reflection spectrum. Femtosecond laser is applied for drilling an opening on the HCF of the sensing FPI to make the air hole interact with outside environment, while the air hole of the reference FPI is closed. Once the sensing FPI influenced by the gas pressure variation, sensitivity of the cascade configuration can be enhanced by an order of magnitude through tracing the wavelength shift of the envelope. Compared with our previous works [5-7], the cascade FPIs structure exhibits a simple configuration, thus leading to easiness in fabrication. Experimental results show that the sensitivity of this cascade structure is far away improved than that of single sensing FPI.

2. WORKING PRINCIPLE

The proposed gas pressure sensor is shown in Fig. 1, which consists of two cascaded FPIs with different FSR to generate superimposed reflection spectrum with Vernier effect. Both of the FPIs are fabricated by inserting a short section of HCF in between two sections of SMF. The FPI with an opening drilled on the HCF section can be used to detect gas pressure variation and serves as the sensing element, while another FPI whose air hole is closed serves as the reference element.

For single FPI, the reflectivity is very low according to the theory of Fresnel reflection, which means multiple reflections can be neglected. The FPI can be treated as a two-beam interferometer [8]. And the reflection intensity can be written as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{4\pi n_1 L}{\lambda}\right) \tag{1}$$

I_1, I_2 refer to the light intensity that reflected from M_1 and M_2, L refers to the length of HCF, and λ is the working wavelength of the light source.

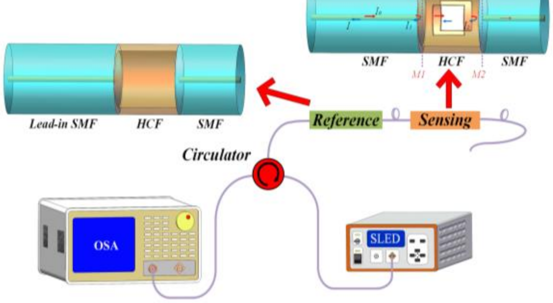

Fig. 1. Experimental setup for the measurement of gas pressure

FSR of the reflection spectrum can be written as:

$$FSR = \frac{\lambda_1 \lambda_2}{2n_1 L} \qquad (2)$$

λ_1, λ_2 refer to the resonant wavelength of two adjacent dips. And wavelength of each resonant dip in the reflection spectrum satisfies the condition as following:

$$\lambda_m = \frac{2n_1 L}{m} \qquad (3)$$

where λ_m is the central wavelength of *mth* order resonant dip. The sensing FPI is sensitive to gas pressure as the fabricated opening allows the air hole to interact with the environment directly. Gas pressure variation not only changes the cavity length, but also results in the change of the reflective index of the air hole. Both the two effects lead to the reflection spectrum shift, which can be written as:

$$\delta\lambda = \lambda_m \left(\frac{\Delta n_1}{n_1} + \frac{\Delta L}{L} \right) \qquad (4)$$

Δn_1 and ΔL respectively refer to the changes of the reflective index and length of the air hole with gas pressure changing.

For the cascade structure, due to the FSR of the sensing and reference FPIs is close but not equal, consequently, an envelope will be arisen on the superimposed spectrum. The period of the envelope is given by [4]:

$$FSR_{envelope} = \frac{FSR_r \bullet FSR_s}{|FSR_r - FSR_s|} \qquad (5)$$

where FSRs, FSRr are the free spectral ranges of the sensing and reference FPIs. The envelope of the cascade structure experiences a much larger amount of shift than that of single sensing FPI. And the amplification factor can be written as [4]:

$$M = \frac{FSR_r}{|FSR_r - FSR_s|} \qquad (6)$$

3. FABRICATION OF THE CASCADED FPIS

3.1 Fabrication of the reference FPI

To fabricate the reference FPI, a piece of HCF was connected to the SMF firstly, and then cut off at the position that 213 μm away from the splicing junction between the HCF and the SMF with the aid of microscope. The diameter of the air hole and the cladding for the HCF are 62.5 μm and 125 μm respectively. The photograph of the cross-section of the HCF is shown in Fig. 2(a). At last, the HCF was spiced to another SMF. Then a reference FPI with a closed microcavity was fabricated as shown in Fig. 2(b).

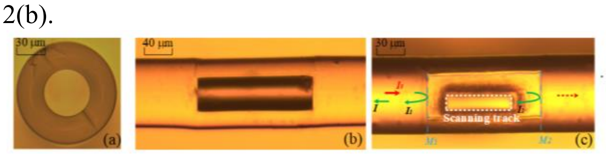

Fig. 2. (a) Cross-section image of HCF, (b)Image of reference FPI, (c) Image of sensing FPI

3.2 Fabrication of the sensing FPI

The sensing FPI with the same structure of reference FPI, but in order to generate Vernier effect, the length of HCF should be a little different from reference element, and an opening should be fabricated on the HCF section of the sensing FPI to make it sensitive to gas pressure. Here, the length of HCF was selected to be 197 μm. And femtosecond laser was applied to remove part of the cladding of the HCF to make the air hole contact with outside environment directly. The opening with a rectangle shapes whose size includes length of 100 μm and width of 30 μm. The laser power was set to be 200 mw during the whole fabrication process which was monitored by a high-resolution CCD camera in real time. The fabricated sensing FPI structure is shown in Fig. 2(c). In the experiment, the FSR of sensing FPI and reference FPI were observed to be 6.07 nm and 5.65 nm respectively by OSA. Through substituting the values into Eq. 6, we can get the theoretical sensitivity amplification factor of the cascade structure is -13.4 times to single sensing FPI.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Firstly, we measured the gas pressure response of single sensing FPI as a comparison. The sample was put into a closed gas pressure chamber whose gas pressure was increased from 0.1 MPa to 0.7 MPa gradually. Each gas pressure was maintained for 2 mins to get a stable reflection spectrum. A high precision barometer (ConST 211) was used to monitor the gas pressure in the chamber in real time.

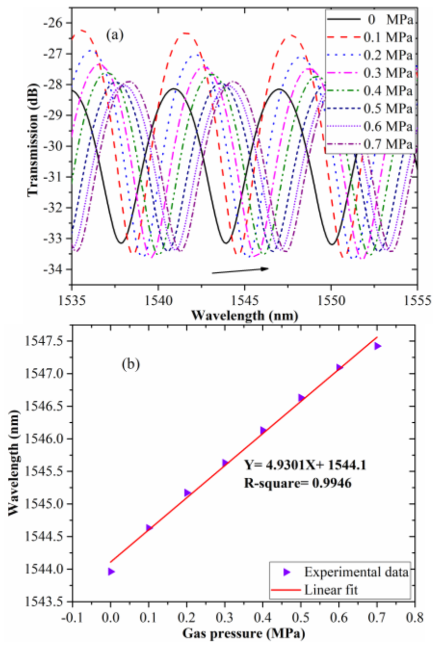

Fig. 3. (a) Reflection spectrum of single sensing FPI with different gas pressure, (b) Dip wavelength versus gas pressure and the fitted line

Fig. 3(a) shows the reflection spectrum of sensing FPI with different gas pressure. From the figure, we can find a red shift of the spectrum with gas pressure increasing. A

resonant dip near 1545 nm was traced, the sensitivity is 4.9301nm/MPa and linearity attains 99.46%. According to reported reference [5], the calculated theoretical sensitivity of the dip is 4.353nm/MPa which closes to the measured result.

Then we cascaded the reference FPI to the sensing element to measure gas pressure response of the cascade configuration. The measured results are shown in Fig. 4, from which we can find the envelope shifts to shorter wavelength with a sensitivity of –65.482 nm/MPa. Therefore, a sensitivity amplification factor of -13 times compared with single sensing FPI is attained, which is consistent well with the theoretical value. Besides, similar to our previous work [6], temperature compensation can also be realized by such a configuration if both the sensing and reference elements are working in the same temperature field, which is due to the same temperature response of each cascaded FPI.

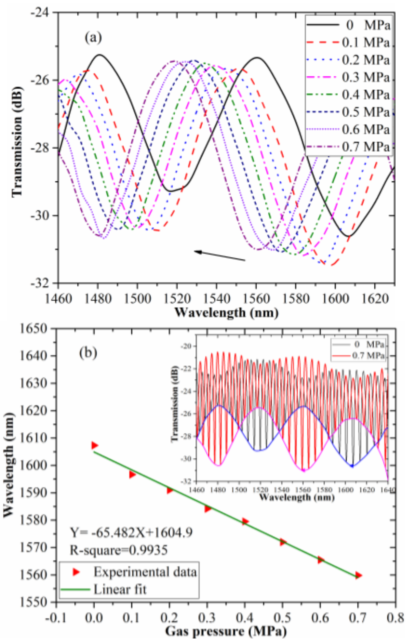

Fig. 4. (a) Extracted envelopes under different gas pressure, (b) Dip wavelength of envelope versus gas pressure and the fitted line

5. CONCLUSION

A cascaded FPIs configuration for gas pressure sensing is proposed in this paper. Experimental results show that the sensitivity of the sensor can attain -65.482 nm/MPa with Vernier effect, which is far away improved than that of single sensing FPI (-4.9 nm/MPa). Ultra-high sensitivity can ensure the sensor applied in gas pressure measurement and gas concentration monitoring practically.

6. ACKNOWLEDGMENTS

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