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New Optical Fiber Micro-Bend Pressure Sensors Based on Fiber-Loop Ringdown

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Abstract

A new optical fiber micro-bend pressure sensor using fiber loop ringdown is studied in this paper. It consists of a pulse microchip laser, two 2×1optical fiber couplers, a photodetector, and a section of fused-silica single-mode fiber, which makes the sensing element with a micro-bend structure. Pressure can be measured by measuring the ringdown time of fiber loop due to the monotone relation of fiber transmission loss and the micro-bend of the single mode fiber. A test setup is constructed, then the ringdown time corresponding to different pressure, which is simulated by putting different heavy masses on the micro-bend panel. The experimental results show that the pressure has good linear relation with the reciprocal of the ringdown time, which is well in agreement with the theoretical results. This new fiber sensor is free from the fluctuation of the light power, which badly affects the performances of traditional fiber micro-bend sensors. Furthermore, it has the advantages of simple structure, fast response, highly sensitivity, convenience for multi-parameter sensing, etc., which makes it have wide applications.

Keywords: fiber pressure sensors; fiber-loop ringdown; micro-bend structure

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1. Introduction

Optical fiber pressure sensors are widely applied due to its advantages of low cost, light weight, flexible structure design and not being affected by electromagnetism. According to sensing principle,

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optical fiber pressure sensors can be divided into intensity-based ones, interferometric sensors, polarization sensors, grating sensors and so on [1-2]. Among them, intensity-based sensors enjoy the most simply structure and thus were widely studied in the past. However, its application is with limitation due to its low sensitivity and poor performance towards the source light power fluctuations. Currently, the world put most attention on the study of interferometric and grating sensors with better performances.

Booming since late 1980s, Spectroscopy is a highly sensitive detection technology on the absorption spectra with the advantage of fast response and not being affected by light intensity fluctuations. However, in order to maintain optical collimation CRD technology is rather demanding on mirrors' reflectivity and position adjustment accuracy, which severely limits its engineering applications. Optical fiber Loop Ringdown (FLRD), originating from the traditional CRD technology, was first put forward by Stewart in 2001 to measure gas concentration [3]. FLRD connects two optical couplers into an optical ring and probes external influence on the transmission loss by measuring the eigentime of fiber loop ringdown. Because the measurand is time, no optical amplification is needed and no ASE noise will be introduced11. That's why FLRD manages to be highly accurate, sensitive, fast-responding and free from light power fluctuations at the same time. Apart from that, FLRD presents pleasing flexibility in application: By equipping with different sensors, it can sense various parameters such as pressure, temperature, strain, refractivity and etc [4-8]. Currently the studies of optical fiber sensors based on FLRD mainly focuses on chemical sensing. FLRD is also playing a promising role to develop new generations of intensity-based optical fiber pressure sensors and sensing systems.

In this paper we set up an optical fiber micro-bend pressure sensor based on FLRD, and measures the ringdown time corresponding to different pressures. It shows that when the tested pressure varies within a certain range, it maintains a good linear relation with the reciprocal of the ringdown time, which is well in agreement with the theoretical results.

2. Theory

All As shown in Figure 1(a), FLRD system acts in such a way: typically optical cavity consists of two connected optical fiber couplers with high splitting ratio. When a beam of pulsed light (the width of pulse is less than the time light requires to travel around the cavity) enters fiber loop through the input coupler, most of the light continues running in the cavity while the rest of them enters into a detector to monitor the intensity of light. The intensity of light observed decreases exponentially due to the transmission loss in the cavity, as shown in Figure 1(b). Hence, the decaying time changes in accordance with variation of the transmission loss.

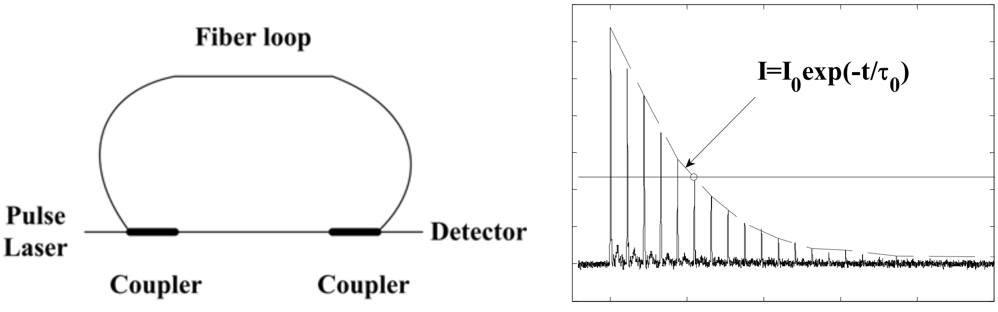

Fig. 1. (a) Setup of fiber loop ringdown system; (b) Typical output signal in time-domain of fiber loop ringdown system

The change process of light intensity in FLRD can be described by the differential equations below [5]

$$\frac{dI}{dt} = -\frac{IAc}{nL} \tag{1}$$

I denotes light intensity at the time of t; L denotes the length of optical fiber; c stands for the speed of light in vacuum; n is the average refractive index of fiber loop and A represents the total transmission loss within a single ring. The total fiber transmission loss includes that in fiber absorption, the connection of optical fiber coupler and optical fiber bend: A=αL+E+γ, α denotes optical fiber absorption index per unit length; E is optical fiber coupler insertion loss and γ is optical fiber bend loss. The solution to equation (1) shows that light intensity detected decays exponentially with the time.

$$I = I_0 \exp(-\frac{c}{nL}At) \tag{2}$$

Define the time that light intensity takes to decay to the 1/e of initial intensity as the ringdown time, τ_0

$$\tau_0 = \frac{nL}{cA} \tag{3}$$

With the change of the pressure on the sensor, the optical fiber transmission loss will change by B. Then the fiber loop ringdown time changes to

$$\tau = \frac{nL}{c(A+B)} \tag{4}$$

Among which *B=βlSP* when the variation of optical fiber transmission loss is within certain range. *β* is the pressure-induced loss coefficient in units of, e.g., $Pa^{-1}m^{-3}$, S is the interaction area, and *l* is the length of optical fiber which directly affected by the pressure,From equation (3) and (4) we obtain

$$\frac{1}{\tau} - \frac{1}{\tau_0} = \frac{c}{nL}B = \frac{c\beta lS}{nL}P = kP \tag{5}$$

Among which k=cβlS/(nL). Equation (5) indicates that the pressure tested has a good linear relation to the reciprocal of ringdown time 1/τ.

3. Experimenty

3.1. Experimental design

The system, as shown in Figure 2, consists of two 2x1 1064nm single-mode couplers with the splitting rate of 99:1. Suppose end 3 of the output coupler is connected to that of the input coupler; end 2 of the output coupler connects photoelectric detector and end 1 of both couplers connect with each other. The impulse light emitted from the source enters optical fiber cavity through input coupler. After reaching the output coupler and split by that, 99% of the light will remain in the cavity while only 1% of the energy will be detected as the change of light intensity. The light source in this paper is pulse laser (SNP-08E-000，produced by Teem Photonics Co.) with its center wavelength 1064nm, pulse width less than 1ns, repetition frequency about 8.5kHz and average output power less than 100mw. The OSC is TDS7154 from Tech Co, USA with its band width as much as 1.5GHz, and sampling rate 25GS/s at most. The detector we use is InGaAs (DC400FC) produced by Thorlabs with its responding speed about 0.1ns and band width 2.0GHz. As it can be seen, both the OSC and the photoelectric detector satisfy test demand. In the optical fiber cavity we use 1064nm singer-mode optical fiber as long as 4.5m. Its transmission loss is 0.3dB/km and optical fiber core refractive index n=1.45. It takes the impulse about 21.8ns to travel around the cavity, much more than the impulse width, which meets the basic requirements of FLRD.

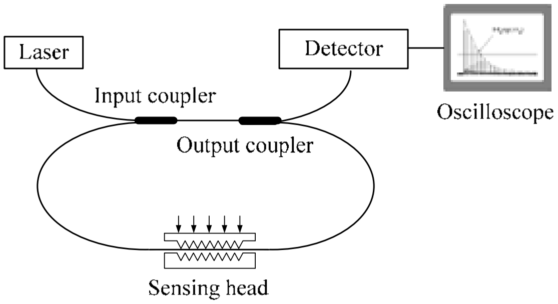

Fig. 2. Experimental setup of optical fiber micro-bend sensing system based on fiber-loop ringdown, a micro-bend structure is inserted into the fiber loop

3.2. Results and analysis

Figure 3(a) shows the wave pattern of light intensity without load. From it we can calculate the exact time for the impulse to travel around the cavity is 22ns which is fairly close to the theoretical time 21.8ns. By data fit the peak value of each impulse we obtain the exponential ringdown curve, shown as the dotted line in Figure 4. We can then work out the ringdown time of the cavity itself is about 68ns. Substitute all the variables into Eq. (3), the actual transmission rate after the light circles around is about 3.9dB, among which the transmission loss of the optical fiber itself is small enough to ignore and the insertion loss of the 2 couplers is 0.3dB and rest of them comes from the 3 welding points. From Eq. (3) to Eq. (5) we can come to a conclusion that by improving the welding skills and reduce welding point loss we can increase the ringdown time and thus result in the improvement of sensitivity.

In this experiment we simulate the external pressure by adding weight to the board. Hence, we can test the corresponding ringdown time by changing the weight on the board, as indicated in the dot marked by square. The horizontal coordinate denotes weight M with its unit kg while the Y-axis stands for the reciprocal of time $1/\tau$ with its unit 1/s. From Figure 3(b) we see that the curve is shaped as S which indicates that the ringdown time changes very slowly when the weight is small. At this moment the sensor is not sensitive to the pressure. That is to say, the optical fiber bend loss is quite small. With the increase of the weight, the radius of fiber bend curvature reduces and more light leaks from the layer, which add to the bend loss and thus reduces the ringdown time. When the weight is over 0.8kg, the reciprocal of the ringdown time remains good relation to the weight, shown as the real line in Figure 3(b) (obtained from Matlab), which matches the theoretical analysis above. When the weight is over 2.7kg, the sensitivity drops and the fitting expression is

$$\frac{1}{\tau} = 1.9515\times10^{7}\times M - 3.3198\times10^{6} \tag{6}$$

And the range of M is from 0.8 kg to 2.7 kg. Eq. (6) shows that when the weight is between 0.8 and 2.7kg, the fiber bend loss has a good linear relation to the pressure.

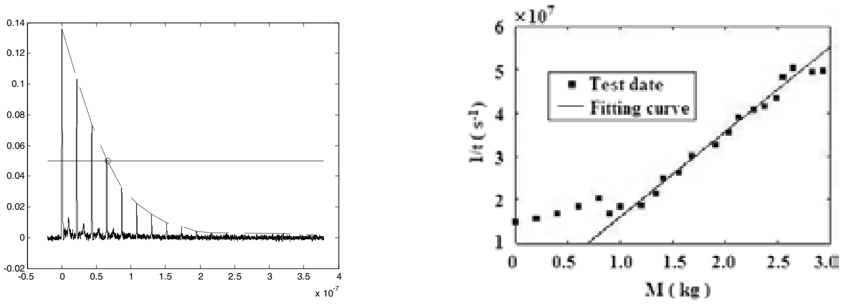

Fig. 3. (a) Output signal in time-domain of fiber loop ringdown micro- bend sensing system without load; (b) The relation between the reciprocal of ringdown time and the mass putting on the micro-bend structure

4. Conclusions

In this paper we combine the FLRD technology with the traditional optical fiber micro-bend pressure sensor into a new-type optical fiber sensor. It is a time-domain pressure sensor which measures the loop ringdown time. Its nature of low requirement to the light source and fast respond makes it competent in the real-time sensing. Besides, the multiple transmissions within the cavity accumulate the loss and thus greatly improve the detection sensitivity. By designing different sensor tops we can easily realize the measurement of multiple variables. We also design and set up an optical fiber micro-bend pressure sensor based on FLRD. The result of experiment indicates that when the pressure is within certain range, the pressure remains good relation to the reciprocal of ringdown time, which goes in line with the theoretical analysis and verify the feasibility of applying FLRD technology into micro-bend pressure sensing.

Acknowledgements

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