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Novel fibre sensor using etalon multi-reflection and pulsed interference

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Abstract

Recently, fibre sensors have been widely used for monitoring large structures (e.g., bridges, aircrafts, and accelerators) and monitoring in hard environment such as high temperature. In these fields, both accuracy and simplicity of measurement system are required. In this research, a new method to measure etalon absolute length is proposed, which harmonically synchronizes etalon multi-reflection and optical comb pulsed interference. Repetition frequency scanning comb is adopted for light source and interference between etalon multi-reflected pulses is detected while scanning repetition frequency. When frequency of etalon is integer multiple of repetition frequency of comb, interference fringe appears. From repetition frequency of comb at this point, etalon frequency and absolute length is calculated. Using this method, several nm accuracy for 200 mm etalon is expected. Advantages of this method are accuracy improvement by multiple reflection of etalon, high sensitivity with relatively long etalon length, simple measurement system, easy multiple etalon setups. In this paper, measurement system including repetition frequency scanning comb and length adjusted fibre etalon was made. The etalon is constituted of two kinds of fibre, anomalous dispersion and normal dispersion fibre, for dispersion compensation. With scanning repetition frequency of comb, interference fringe was obtained, and etalon absolute length is calculated from repetition frequency. 217 mm optical length fibre etalon was measured by proposed method and repeatability was 4.5 nm. If it is used for temperature measurement, sensitivity is $5.8\text{x}10^{-6}$ /K and resolution is 0.003 K. It is better than conventional fibre sensors.

optical comb, pulsed interference, etalon, sensor

1. Introduction

Recently, fibre sensors have been widely used for monitoring large structures (e.g., bridges, aircrafts, and accelerators) and monitoring in hard environment such as high temperature. Fiber Brag Grating (FBG) sensor [1] and extrinsic Fabry-Perot interferometric (EFPI) sensor [2] are mainly used for conventional measurement. Both methods measure fibre length stretched by external environment. However, measurement length is relatively short; in FBG sensor measurement length is wavelength order and in EFPI sensor it is several-hundreds μm. Therefore, measurement sensitivity and resolution are limited.

In these fields, both measurement accuracy and simplicity of measurement system are required. In this research, a new method to measure etalon absolute length is proposed, which harmonically synchronizes etalon multi-reflection and optical comb pulsed interference. In this method, measurement length is several-hundreds mm leading to high sensitivity and measurement resolution is enhanced by multiple reflection of etalon. In this paper, we experimentally show the characteristics of this measurement method and evaluate it by repeatability of measurement.

2. Principle of measurement

The principles of measurement are divided into two parts; optical comb pulsed interference and pulsed interference with etalon multiple reflection. Both are described below.

2.1. Pulsed interference using comb

Optical comb is ultra-short pulse laser with its repetition frequency is traceable and it is used for standard of length. Fig.1 shows optical comb pulsed interferometer based on Michelson interferometer. Optical pulse is emitted from optical comb with pulse interval which is inverse proportion to repetition frequency of optical comb. In pulsed interferometer, interference fringes are generated when optical path difference of two arms is equal to integer multiple of half pulse interval [3] as Eq. (1),

$$OPD = \frac{ml_c}{2} = \frac{mc}{2f_{rep}} \quad (1)$$

where OPD is optical path difference between two arms, m is integer, l_c is pulse interval of optical comb, c is speed of light and f_{rep} is repetition frequency of optical comb. Each interference fringe is localized to several-tens μm and generated by one arm scanning or repetition frequency scanning. Utilizing equally spaced localized interference fringes, pulsed interference is used for length measurement.

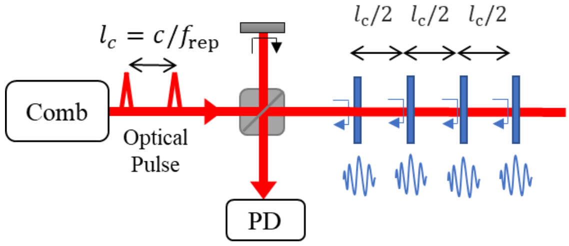

Fig.1 Principle of optical comb pulsed interference

2.2. Pulsed interference with etalon multiple reflection

Etalon is composed of two reflectors and medium sandwiched by them. In this research, fibre etalon which is constituted of fibre medium and two reflection coated end-face is used. When beam is introduced to etalon, beam is multiple-reflected and have multiple delays equal to etalon length. Fig.2 shows the case optical comb is introduced to etalon. Optical pulse is multiplied by etalon reflection. In this case, interference fringes are generated as Eq. (2),

$$\frac{l_c}{2} = m l_e \tag{2}$$

$$l_e = \frac{l_c}{2m} = \frac{c}{2m f_{rep}} \tag{3}$$

where l_e is etalon length. Because of m, measurement accuracy of l_e is improved. Since peak decision repeatability of pulsed interference is approximately 100 nm, l_e repeatability leads to 5 nm with m=20. Moreover, measurement length is only limited by pulse interval of optical comb and reflectivity of etalon so that measurement length of >100 mm is allowed. This leads to high sensitivity. These characteristics are realized by simple system as Fig. 2. This system is easy to implement with multiple etalon sensors whose length is a little different.

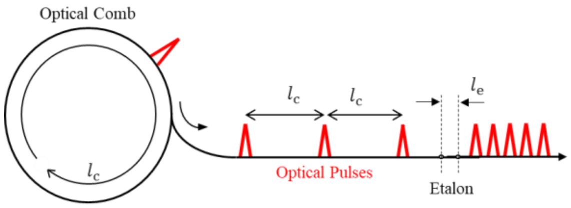

Fig.2 Principle of Pulsed interference with etalon multiple reflection

3. Measurement experiment

To evaluate the characteristics of proposed system, measurement system including optical comb and etalon is constructed in stable environment and is evaluated through repeatability of measurement.

Measurement system diagram is shown in Fig.3. Optical comb is developed in the lab, whose repetition frequency is approximately 34.5 MHz and scanned by PZT stage. The light from comb is split into two paths by a fibre coupler. On one path, the light is detected by PD1 and its repetition frequency is measured by frequency counter (Iwatsu, sc-7215a). On the other path, the light is introduced to fibre etalon. Fiber etalon as shown in Fig.4 is constituted of two kinds of fused fibre; normal dispersion one and anomalous dispersion one. With adjusting the length of two fibers, its dispersion is designed to be zero dispersion for sharp fringe and better accuracy. Two end-face of fibre etalon are contacted to high reflectivity coating fibre (99%) in fibre connector. Length of etalon is made to be specified fraction of comb length. Its optical length is approximately 217 mm and 1/40 of comb length. The output of etalon is amplified by Erbium Doped Fiber Amplifier (EDFA) and detected by PD2. The signal from two PDs is digitized by DAQ.

With scanning PZT of comb, interference fringe is detected on PD2 and repetition frequency on interference fringe peak is measured. Scanning frequency is 1 Hz and repetition frequency scanning range is approximately 3 kHz around 34.5 MHz. Fiber etalon is located in ice water so that its temperature is stable to evaluate its original characteristics. From repetition frequency at the peak of fringe, etalon length is calculated by Eq. (3), and its repeatability is evaluated.

Firstly, etalon is cooled from 20 ℃ to 0 ℃. Difference between repetition frequency of fringe peak at each temperature is approximately 80 kHz. Calculated temperature coefficient is 5.8x10^{-6} /K and it follows the theoretical value.

Measurement result is shown in Fig. 5. The Result is obtained every one second. Ten data do not show temperature drifting. Repeatability of measurement is 4.5 nm, and it is reasonable when compared to discussion in section 2.2.

The sensitivity of sensor is calculated from the fibre characteristics. If fibre etalon is used for temperature sensor, it is 5.8x10^{-6} /K and the sensitivity is approximately 1.3 μm/K with 217 mm etalon. The resolution is calculated from the sensitivity and repeatability of measurement and is 0.003 K. From these results, this system shows better characteristics than conventional FBG sensor that has several pm/K sensitivity and 0.1 K resolution.

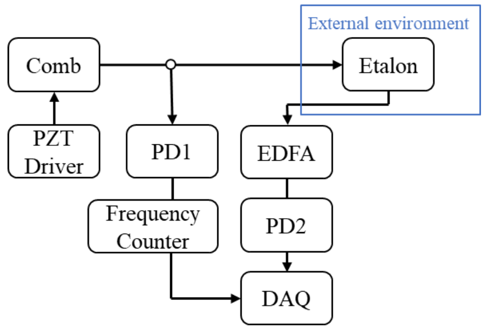

Fig.3 System of measurement experiment

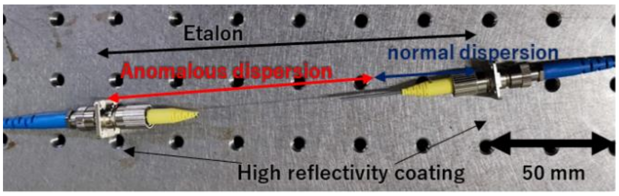

Fig. 4 Picture of fibre etalon in this experiment

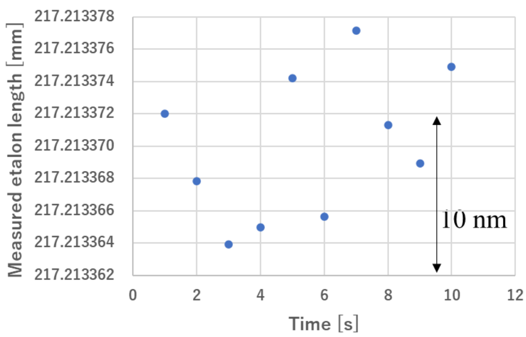

Fig. 5 Measurement result of etalon length

4. Conclusions

In this research, a new method to measure etalon absolute length with repetition frequency scanning comb is proposed. Optical comb and zero-dispersion fibre etalon is developed in the lab and etalon length is measured and evaluated. From experiments, measurement repeatability of 217 mm etalon is 4.5 nm and it has 5.8x10^{-6} /K sensitivity and 0.003 K resolution for temperature measurement. It exceeds the conventional method like FBG or EFPI. This method can be applied for other sensors such as distortion, pressure, etc. In the future, we will improve the measurement performance with longer optical comb and new etalon structure. And other characteristics such as linearity to external environment will be evaluated.

Acknowledgement

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