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A Novel, High-Resolution, High-Speed Fiber-Optic Temperature Sensor for Oceanographic Applications

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***Abstract*— A novel fiber-optic thermometer based on a thick silicon Fabry-Pérot interferometer (FPI) realized on the tip of a cleaved single-mode fiber has been designed and implemented, in order to achieve high resolution and high sampling rate necessary for studying underwater turbulent microstructures. The choice of silicon for its large thermal-optic coefficient and thermal expansion coefficient enables a high sensitivity of 84 pm/°C. A new data processing method, using average wavelength tracking, is proposed to reduce the wavelength noise. The high sensitivity along with the low wavelength noise results in a temperature resolution as high as 0.0009 °C. Furthermore, the good thermal conductivity of silicon endows the proposed sensor with a response time ~ 2 ms, which allows a sampling frequency of 500 Hz. By further optimizing the sensor structure, e.g. size of the silicon FPI, a better temperature resolution and quicker response can be expected. This novel temperature sensor significantly augments underwater sensing capabilities, especially those related to microstructure turbulence mixing process in the ocean. A preliminary experimental demonstration is presented, where the sensor was used to measure the highly dynamic temperature variations induced by a sharp thermo-gradient underwater.**

Keywords—* *Fiber-optic thermometer; Fabry-Pérot interferometer; ocean microstructure; turbulence

I. INTRODUCTION

Accurate measurement of temperature at high spatial, and temporal resolution is necessary in quantifying thermal structures in the ocean, especially those on small scales where mixing happens rapidly. Such data is critical in understanding the physical processes associated in such mixing events in terms of energy as well as material transfer. In addition, it has been shown by recent research that such processes also affect underwater signal transmission, which impact performance of various underwater imaging and communication systems through fluctuations of index of refractions [1]. Current high speed temperature probes, such as the most commonly used FP07, are prone to breakage under dynamic conditions, and lacks the expandability as well as necessary spatial resolution within the microstructures. An alternative sensor that is capable of addressing these elements, with potential higher sampling rate and dynamic range, is much needed. Our ultimate goal is to develop a robust thermometer for the oceanic applications that is able to measure the temperature fluctuation up to 1kHz rate, with an accuracy of 0.001°C or better.

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Compared to electric thermocouplers, fiber-optic sensors possess many advantages such as small size, immunity to electromagnetic interference (EMI), and remote sensing capability. Among them, those based on fiber-optic Fabry-Pérot (FP) interferometer have been widely investigated and shown great promise [2]. The sensor presented in this paper is based on a FP cavity formed by thin crystalline silicon film attached to the end face of a single-mode fiber. Due to the thermo-optic effect, temperature variations will change the optical thickness of the FP cavity and consequently cause spectral shifts in its reflection spectrum. The silicon material has a large thermal diffusivity (0.8 cm^2/s), comparable to many metals (e.g. aluminum and gold). As a result, the sensor is able to offer a very high sampling speed. To date, there is few previous work that used silicon as the sensing elements for temperature measurements [3-6]. Also, the reported temperature resolution and slow response of these sensors are far from meeting the requirements for the oceanographic applications. In fact, the broad reflection peaks/dips obtained from the ultra-thin silicon film (less than 1 μm in [3, 6]) is disadvantageous in terms of achieving high temperature resolution (only 3°C in [6]). By increasing the thickness of silicon, a thermometer realized by mounting an optical fiber against a silicon waveguide which was fabricated on a micro-electro-mechanical system (MEMS) device showed a temperature resolution of 0.064 °C [4]. However, the integration of such sensor into a sensor tip is challenging and the bulky silicon will limit its response time. In Ref. [5], the temperature resolution of ±0.12℃ and a response time of 1 s were demonstrated by taking advantage of the temperature-dependent absorption of silicon. Despite the low temperature resolution, the structure of one lead-in fiber and one read-out fiber is inferior for integration and the relative large silicon element reduces its response time.

In this paper, the proposed fiber-optic temperature sensor uses a thick silicon film directly attached to the endface of a cleaved single-mode fiber using UV curable glue. A novel signal processing method has also been developed for the proposed sensor, which significantly improves the spectral resolution therefore the temperature resolution. The small footprint of silicon material facilitates fast response of the sensor. Our experimental results indicate that the fiber-optic temperature sensor can achieve a measurement resolution no-less than 0.001°C, at a sampling frequency up to 500 Hz. Compared to the previous work, our sensor features high temperature resolution and fast response time, paving the way towards wide application in oceanography, and the preliminary experiments on measuring turbulence in water has been experimentally demonstrated.

II. System and Principle

The sensor system is schematically described in Fig. 1(a). Light from a broadband source goes through a circulator and reaches the sensor head, then the reflected spectrum is acquired by a high-speed spectrometer (Ibsen Photonics, I-MON 256

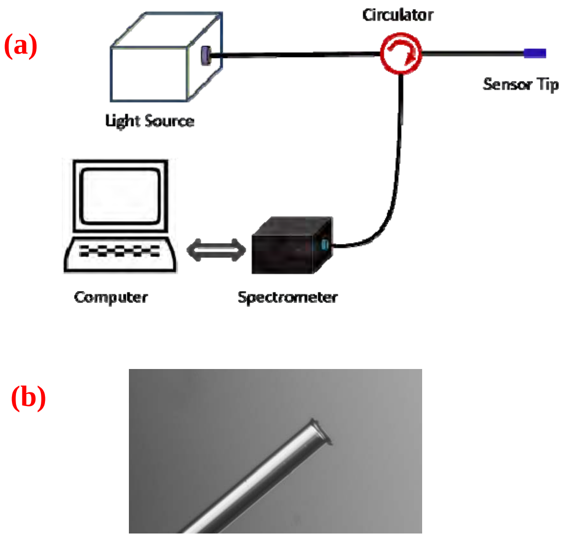

Fig. 1. (a) Sensor system. (b) Optical microscope image of a sensor tip with 10-μm-thick silicon film attached to the cleaved single-mode fiber.

USB) which is connected to a control computer. The spectrometer has a maximum sampling frequency of 6 kHz, which facilitates collection of spectrum that changes rapidly. Fig. 1(b) is a microscope picture of the fabricated sensor, in which a small piece of 10 μm thick Si wafer was bonded onto the tip of a single mode optical fiber using UV-curable glue. In addition to the sensor shown in Fig. 1(b), sensor probes with difference sizes of silicon film have also been fabricated.

In principle, the silicon film on the fiber tip forms a FP interferometer (FPI) which produces an interferometric reflection spectrum with the N^{th} valley wavelength λ_N expressed as

$$N\lambda_N = 2nL \,, \tag{1}$$

where n and L are, respectively, the refractive index (RI) and cavity length of the silicon FPI. If the temperature changes, the n an L will also change due to the thermal-optic effect and thermal expansion effect, which in turn shifts the valley wavelength λ_N. The large thermal-optic coefficient and thermal expansion coefficient of silicon is advantageous for obtaining a high sensitivity to temperature change.

III. Experiments and Results

Instead of forming an ultrathin silicon film (in the order of hundreds of nanometers) by deposition [6] or radio-frequency sputtering [3], we developed a process to introduce much thicker silicon pieces onto the optical fiber tip. UV curable glue was first attached to the endface of a cleaved optical fiber, then the silicon piece was connected to the fiber end through the UV glue after curing. Two thicknesses of the silicon film used were 10 and 200 μm, respectively. Compared to the thin silicon film reported [3, 6], our thicker silicon film forms a longer FP cavity and contributes to a shorter free spectrum range and more peaks/dips within a certain wavelength range. Instead of monitoring one peak wavelength, the average peak wavelength of several peaks will be applied to reduce the noise, which will be demonstrated later.

Experiments were carried out to examine the performance of this thermometer. Firstly, the sensitivity to temperature change was determined. Then, the wavelength noise was measured by keeping the environment temperature constant and thus temperature resolution was calculated according to the sensitivity and noise. Thirdly, the response time was obtained by fast inserting the sensor into a cup of hot water and tracking the wavelength evolution. Finally, a quick test to measure the dynamic temperature variations associated with a strong microstructure thermo-gradient is demonstrated.

A. Sensitivity

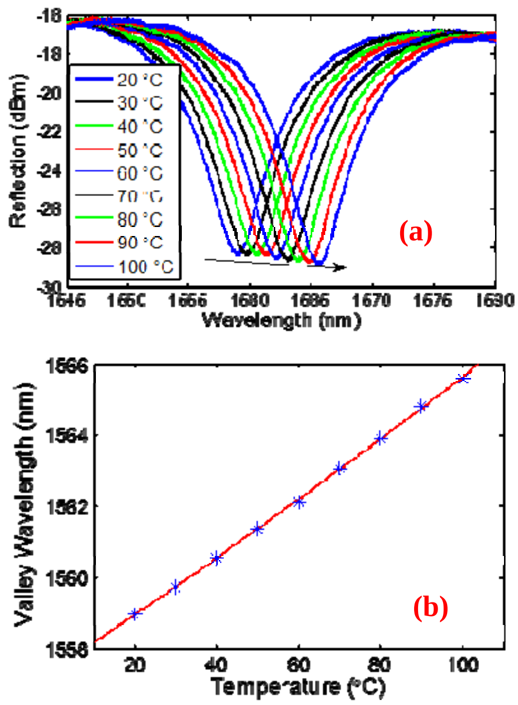

Fig. 2. (a) Spectra of a fringe valley at different temperatures. (b) Wavelength position of the fringe valley vs. temperature

Sensitivity to temperature change was performed on a sensor tip with a 10 µm thick silicon. The sensor was placed in an environment chamber in which the temperature was increased from 20 °C to 100 °C by step increment of 10 °C. The reflected spectrum was recorded by SM125 and the results are shown in Fig. 2. Apparently, Fig. 2(a) shows that the dip wavelength redshifts as the temperature increases. Fig. 2(b) tracks the dip wavelength as a function of temperature and suggests a good linear response. The measured sensitivity was ~84 pm/°C.

B. *Wavelength noise and temperature resolution*

To obtain the temperature resolution, the wavelength noise should be measured first using the system shown in Fig. 1(a). In this experiment, a sensor with 200-µm-thick silicon film was tested, so that denser fringes in the spectrum appeared. By placing the sensor under room temperature (a constant room temperature was assumed), the spectrum was recorded for 1 second at a sampling frequency of 6 kHz, which means around 6000 frames of spectrum were measured. One sample frame is shown in Fig. 3(a). It can be seen that dozens of fringes appear within the spectrum and the free spectrum range is ~1.5 nm. By taking advantage of the dense peaks, we calculate the average wavelength of multiple peaks (denoted by the red circles in Fig. 3(a)), i.e., the arithmetic mean value of the 22 peak wavelengths of a spectrum is calculated as the average wavelength, to reduce the random noise by averaging effects.

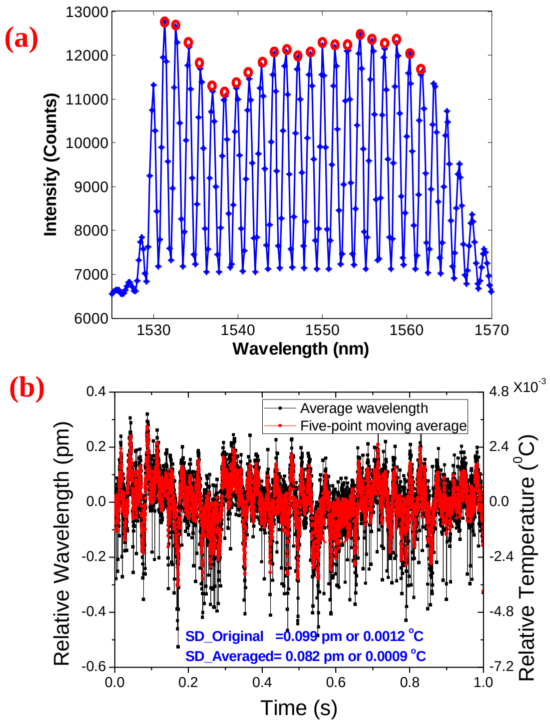

Fig. 3. (a) Reflection spectrum of a 200-µm-thick silicon FPI. (b) Sensor spectral and temperature measurement resolution test.

The achieved relative average wavelength versus time within 1 second is illustrated by the black curve in Fig. 3(b). If the wavelength noise is defined as the standard deviation (SD) of the relative spectral shift, then a noise of 0.099 pm is reached. If the temperature measurement resolution is defined as the ratio of noise to sensitivity, then a resolution of 0.0012 °C is measured for the average wavelength. To further reduce the noise, five-point moving average is applied to the average wavelength, as shown by the red curve in Fig. 3(b), and then the SD value is reduced to 0.082 pm which suggests a temperature resolution as high as 0.0009 °C.

C. *Response time*

In addition to the high temperature resolution, the fast response of the proposed thermometer is experimentally demonstrated. To test the response time, the sensor tip was first held in air (~22 °C) and then swiftly dipped into a cup of hot water (~80 °C) by hand. The temperature of the silicon film went up quickly and the spectrum red-shifted accordingly.

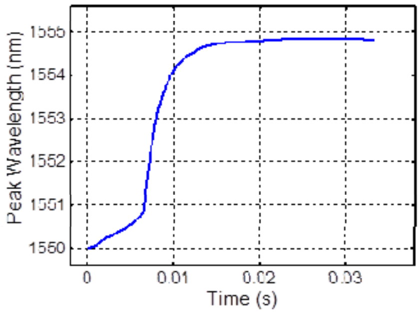

Fig. 4. Sensor response with the sensor rapidly dipped into hot water.

Figure 4 shows the peak wavelength position as a function of time. It is seen that the spectrum shifts toward longer wavelength as it was dipped into the hot water. The spectral shift at the first 7 ms showed a relative small slope, which we believe was the response from the sensor when it approached the hot water surface but before it was immersed in the water. Once the sensor was immersed into the water, the sensor quickly reached the equilibrium following a curve described by the Gaussian error function. The rising time (from 10% -90%) was approximately 2 ms, suggesting a temperature measurement speed of 500 Hz, which is sufficient for most applications associated with temperature fluctuations of oceanic microstructures. By optimizing the sensor tip, e.g. reducing the size of silicon film, a faster response could be expected due to the reduced mass for heat transfer.

D. *Turbulent microstructure measurement*

To demonstrate the capability of the newly developed sensor in quantifying highly dynamic temperature changes in the ocean, we set up an extreme case for our preliminary testing. A floating ice bag is added to a water container in room temperature, where the sensor has been submerged and then quickly moved to the vicinity of the ice bag. This setup produced a sharp themo-gradient and induced strong turbulent mixing. The temperature sensor was placed approximately 5 mm under the ice bag to record the temporal progression of the event. The results are shown in Fig. 5. It can be seen that the swift and large temperature variations has been successfully monitored. It is interesting to notice that the approaching low-temperature element can be seen on the sensor record, further demonstrate the short response time of this novel sensor.

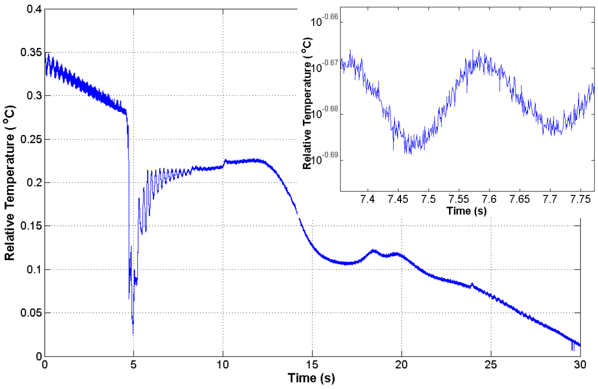

Fig. 5. Measured temperature variation due to turbulent mixing. Fine temperature variations are shown in the insert by zoomed-in section as marked by elapsed time period (7.4 to 7.8s).

IV. CONLUSION

In summary, the fiber-optic thermometer based on FPI realized by a thick silicon film has been investigated. The high TOC and TEC of silicon give rise to the high temperature sensitivity of the proposed sensor. Thick silicon film produces dense interferometric fringes within the spectrum, of which we take advantage to develop the novel wavelength tracking method, by calculating the average wavelength of multiple peaks, to reduce the noise. Using the new data processing method, a temperature resolution of 0.0009 °C was experimentally obtained. In addition, the experimental response time of approximately 2ms suggests a high sampling frequency of 500 Hz can be reached. Using the high sensitivity and fast response, the swift temperature variation within a water turbulence has been successfully discriminated, showing the great potential of the studied sensor in ocean applications.

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