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Demonstration of a Photonic-based Linear Temperature Sensor

Ji Fang TAO, Hong CAI, Yuan Dong GU, Jian WU, Ai Qun LIU

Abstract- A photonic thermal sensor has been demonstrated using photonic waveguide-based Michelson interferometer (MI), with a footprint of only $120\ \mu\text{m} \times 80\ \mu\text{m}$. Operating at the wavelength around $1550\ \text{nm}$, this ultra-compact MI configuration obtains a nearly linear temperature response with a sensitivity of $113.7\ \text{pm}/^\circ\text{C}$, which is around 20 times higher than that of traditional fiber-optic thermal sensors. It is fabricated by using standard CMOS processes. Benefitted from the advanced packaging technique, the proposed photonics sensor shows high thermal and mechanical stabilities, presenting a less than $0.1\ \text{dB}$ power variation over the temperature range of 13°C to 95°C , offering possibilities across a broad range of applications.

Index Terms—Integrated optics, temperature measurement, interferometers, nanofabrication, silicon photonics.

I. INTRODUCTION

Optical approach associated temperature sensors have demonstrated their high variety applications in important and expanding fields, such as turbines, combustors, nuclear reactors, oil-drills, health-monitoring systems for aerospace hot structures, owing to their intrinsic advantages of immunity to electromagnetic interference and possibility to operate in toxic, corrosive to potentially explosive environments [1-6]. However, most of today's optical temperature sensors are based on fiber-optics, so the limitation of compactness remains [1-4]. Moreover, its thermal sensitivity is also relative weak due to its relative low thermal modulation efficiency of silica material.

Recently, sensors constructed by use of silicon photonic waveguides are becoming more and more attractive due to their apparent advantages, including rapid response, high sensitivity, flexible integration with conventional electronic circuits [5, 7-9]. Sensors designs with both compactness and high sensitivity have been reported. For example, a micro-ring resonator with a radius of $4\ \mu\text{m}$ was used to monitor temperature [5], whose sensitivity is up to $83\ \text{pm}/^\circ\text{C}$. Although the micro-ring based sensor is very compact and highly

sensitive, its temperature detection range is limited as the range is inversely proportion to the radius of the micro-ring. Reducing the radius can improve the detection range, but the increased bending loss of small ring would impose a stringent limitation.

In this paper, we report a silicon photonic waveguide based temperature sensor, in an ultra-compact MI configuration. The sensing elements convert the temperature variation induced phase variation into wavelength shifts, which can be easily read-out via spectrometers. This low-cost CMOS-based sensor exhibits a linear temperature response, with the sensitivity of $113.72\ \text{pm}/^\circ\text{C}$. Taking advantages of reliable packaging technique, it provides substantial size and cost effective over traditional optical sensors solutions, with good linear response performance.

II. DESIGN AND FABRICATION

Fig. 1. Schematic of the photonic sensor device constructed as an ultra-compact Michelson interferometer.

The proposed photonic temperature sensor is schematically depicted in Fig. 1. It consists of a directional coupler (DC) structure and two waveguide arms with a mirror at each end. When a light beam is coupled into the chip from an lensed-optical fiber, it is equally splitted into two beams by the DC and guided into arm 1 and arm 2, respectively. Due to the end-mirror reflection, the reflected light beams are recombined through the DC. The phase difference between the two reflection beams would be determined by surrounding temperature (change) when the lengths of arm 1 and arm 2 are fixed. Such phase different can be readout by recording the MI destructive interference wavelengths shift at the output detection point. In this typical MI configuration, the structures acts as a typical MI, but the chip size is much compact comparing to traditional designs.

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Fig. 2. (a) Comparison of TOE and TEE effect. (b) Comparison of the space of adjacent destructive interference wavelengths of MI ($\Delta\lambda$) and adjacent peaks of micro-ring resonator (FSR).

In the MI configurations, its destructive interference wavelengths (λ_{dip}) depend on the effective length difference of two arms, and can be expressed as [10]

$$\lambda_{dip} = \frac{2n\Delta L}{k} \quad (1)$$

where k is an integer and n is the group index of the silicon waveguide, ΔL is the length difference of the two arms. Since both ΔL and n relate the temperature (T), the corresponding temperature sensitivity can be expressed as,

$$\frac{d\lambda_{dip}}{dT} = \frac{2\Delta L}{k} \frac{dn}{dT} + \frac{2n}{k} \frac{d(\Delta L)}{dT} \quad (2)$$

where the first term represents the group index changes induced by temperature variation, named as thermo-optic effect (TOE); the second term expresses the physical thermal expansion effect (TEE). Here, $dn/dT = 1.8 \times 10^{-4} + 3.47 \times 10^{-7}T - 1.98 \times 10^{-10}T^2$ is estimated based on single oscillator model in [11]. And, thermal expansion coefficient is readily known as $d(\Delta L)/dT = 3.725 \times 10^{-6} \{1 - \exp[-5.88 \times 10^{-3}(T - 124)]\} + 5.547 \times 10^{-10}T$ [12]. It should be mentioned that, the optical phase (wavelength) changes induced by the TEE can be neglected compared with the TOE, as plotted in Fig. 2(a). For instance, the ratio of two effects is up to 69 at 450 °C.

Temperature sensing range is determined by the space between the two adjacent destructive interference wavelengths (i.e. dip distance $\Delta\lambda$). Further derivation of Eq. (1), $\Delta\lambda$ can be expressed as $\Delta\lambda = \lambda_0^2/(2n\Delta L)$, where λ_0 is the center operation wavelength. A similar feature as in the micro-ring resonator based temperature sensor configuration, its sensing range was determined by the free spectral range (FSR), $FSR = \lambda_0^2/(2n\pi r)$, where r is the radius of the micro-ring. As comparing, temperature sensing range based on MI and micro-ring are simulated as shown in Fig. 2(b). Apparently, $\Delta\lambda$ and FSR are inversely proportional to the arms' difference and micro-ring radius, respectively, but sensing range of MI is always π times larger than micro-ring when ΔL is equal to r . On the other hand, small ΔL has nothing related to the optical power loss, hence, its ideal sensing range can be wider and more effective than that of the micro-ring based sensors.

III. EXPERIMENTAL RESULTS

Fabrication of the photonic chip started from an 8-inch SOI wafer with 220 nm-thick top silicon layer and 2.0 μm -thick

buried dioxide layer. A standard 248 nm deep-UV lithography defined the waveguide patterns with a resolution of 180 nm. The silicon waveguide was etched by the inductively coupled plasma (ICP) etcher. Subsequently, a 1.2 μm -thick undoped silicate glass (USG) layer was grown over the waveguide to reduce the scattering loss.

Fig. 3. SEM images of the fabricated photonic sensor chip. Inset shows a zoom-view of the DC with a length of 11 μm , a coupling gap of 300 nm.

SEM images of the fabricated photonic chip are shown in Fig. 3. The unequal arms of the MI are 20 μm and 30 μm , respectively. Optical waveguide loops are adopted as mirrors for the full-band reflection. All waveguide structures are fabricated as strip configurations with a width of 400 nm. A 2D inverted taper with a dimension of 200 $\mu\text{m} \times 180 \text{ nm} \times 220 \text{ nm}$ (Length $\times$ Width $\times$ Height) is integrated at the end of waveguide to improve coupling efficiency.

Fig. 4. (a) Experimental setup. ASE: amplified spontaneous emission; PC: polarization controller; OSA: optical spectrum analyzer; PM: powermeter, (b) packaged chip, (c) coupling between the lensed-fiber and the inverted taper.

The photonic sensor chip is mounted on a holder standing on a precision stage, whose temperature is controlled by a thermoelectric cooler (TEC) and monitored by a reference thermocouple. The responding optical signal can be injected and collected via the packaged fiber, and then observed by an optical spectrum analyzer. The experimental setup is schematically illustrated in Fig. 4(a). Since the input light and output light can share a common fiber, this passive photonics chip can be packaged as active photonic devices, such as laser diodes. It also simplifies the packaging process by single fiber packing instead of two ends waveguide-fiber coupling in passive silicon photonics chips [13]. Additionally, the photonic sensor chip was packaged by laser welding and

harming technology reported previously in [13-15], to offer it with stable performance even in harsh environment. The packaged sensor device is shown in Fig. 4(b) and the zoom view of the coupling part in Fig. 4(c). The lensed-fiber has a curvature radius of 10 μm with a 3.8 μm simulated focused-spot and 2.25 dB measured coupling loss to the inverted taper. The total loss, including the propagation loss and the coupling loss, is measured of 6.3 dB.

Fig. 5. (a) Comparison of the output responding spectra between the bare chip and packaged sensor prototype; (b) Power response at different temperature; (c) Transmission spectra response on temperature change, in terms of wavelength shift; (d) Almost linearly spectral response upon the temperature change, with a sensitivity of ~ 113.72 pm/ $^{\circ}\text{C}$.

The reflection spectra of the actively aligned chip and the prototype of the packaged sensor are compared, as depicted in Fig. 5(a). Over the spectrum range from 1510 nm to 1590 nm, the measurement results indicate the packaged sensor prototype has a small extra loss, characterized as of 2.1 dB, which is mainly due to the coupling loss associated with fiber/chip optical misalignment during packaging procedures. The output power at different environment temperature is measured (over the range from 13 $^{\circ}\text{C}$ to 95 $^{\circ}\text{C}$), as shown in Fig. 5(b). It can be seen that the optical power remains at ~ -10 dBm over the entire temperature range, although there is a small reduction at higher temperature. The optical spectral response to the temperature variation is investigated, as displayed in Fig. 5(c). It is noticed that as the temperature varies from 13 $^{\circ}\text{C}$ to 95 $^{\circ}\text{C}$, the destructive interference wavelength is red-shift from 1568.80 nm to 1578.12 nm, corresponding to a fitting linear sensitivity of 113.7 pm/ $^{\circ}\text{C}$ as shown in Fig. 5(d). The temperature resolution is around 0.04 $^{\circ}\text{C}$ when the optical spectrum analyzer with 5 pm resolution is used in experiment. According to the spectral analysis, the sensor has a potential to cover a temperature range of 246 $^{\circ}\text{C}$ (from $\sim 10^{\circ}\text{C}$ - $\sim 260^{\circ}\text{C}$) due to the big separation of two adjacent destructive interference wavelengths (~ 27.95 nm). While based on the current experiment set-up, we obtained a linear temperature range of temperature range of 82 $^{\circ}\text{C}$.

IV. CONCLUSIONS

We have experimentally demonstrated a photonic temperature sensor, with a small footprint of 120 $\mu\text{m} \times 80 \mu\text{m}$, by using an ultra-compact Michelson Interferometer configuration. Supported by the standard CMOS process, the photonic sensor offers attractive features in combination of compactness, high sensitivity and low cost. In particular, its spectra response to the temperature variation achieves a linear manner, with a sensitivity of 113.72 pm/ $^{\circ}\text{C}$ over the temperature range of 82 $^{\circ}\text{C}$. Meanwhile, it presents a relatively stable output power over the whole temperature range of 13 $^{\circ}\text{C}$ to 95 $^{\circ}\text{C}$ at the -10 dBm output power level.

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