PHOTONIC THERMOCOUPLER DESIGN BASED ON AN ULTRA-COMPACT MICHELSON INTERFEROMETER

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ABSTRACT

This paper reports a photonic thermocouple based on an ultra-compact Michelson Interferometer (MI) for on-chip temperature sensing. All components are fabricated by using standard CMOS process. Compared with the traditional temperature sensors based on electronics, this proposed photonics thermocouple has more compact size (40 μm × 70 μm), high sensitivity (113.72 pm/K), cost-effective, and immunity to the electromagnetic interference. The proposed photonic thermocouple has potential applications in harsh environments, such as nuclear power plants and oil-drills.

KEYWORDS

Photonic thermocouple, on-chip temperature sensing, integrated optics sensor, NEMS

INTRODUCTION

The research of reliable optical temperature sensors capable of operating in harsh environment is currently a topic that has attracted considerable interest by the sensor community [1-2]. Optical temperature sensors have applications in important and expanding fields such as turbines, combustors, nuclear reactors, oil-drills, health-monitoring systems for aerospace hot structures, et al., since the intrinsic advantages of immunity to electromagnetic interference and possibility to operate in toxic, corrosive to potentially explosive environments. Today, most of these kinds of optical temperature sensor are based on optical fibers, which are difficult to be integrated and not compatible with standard CMOS fabrication process.

Using silicon optical waveguide to sense the temperature is recently demonstrated based on the thermal modulation property [3-5]. It is regarded as a more effective way due to silicon is a common material and has mature fabrication technology. Meanwhile, it has the advantages of higher cost effective and more sensitivity than fiber-based sensors. For example, a micro-ring resonator with a 4-μm radius was used to sense the temperature with sensitivity of 83 pm/ºC is demonstrated that is much higher than fiber-based temperature sensor.

In this paper, silicon optical waveguide is used as the sensing element which is integrated into ultra-compact silicon MI. The MI is going to convert the phase variation into the wavelength shift, which is easier to be detected by optical spectrum analyzer. The sensing range can be potentially achieved up to 1000 ºC since the distance between two adjacent interference wavelengths can be very big in the transmission spectrum and not limited by the bending loss which exists in the micro-ring configurations. A simple packaging process is also developed for low cost and high reliability solution.

DESIGN AND THEORY

The proposed photonic thermocouple is shown in Fig. 1. It consists of a directional coupler (DC) and two waveguide arms with mirror at the ends. A light beam is coupled into the chip from an optical fiber, and then splitted into two light beams by DC and transmitted in the arm 1 and arm 2 separately. The reflective beams recombine at DC. The phase difference of two reflective beams is determined by the environmental temperature when the lengths of arm 1 and arm 2 are fixed, which can be readout by recording the interference wavelength shift.

The structures act as a typical MI, but the size is much smaller.

![Figure 1: Schematic of the photonic thermocouple based on an ultra-compact Michelson Interferometer. The phase difference of two reflective light beams is determined by environmental temperature.](image-url)
where $\Delta L$ is the length difference of the two arms, $n$ is the refractive index of the silicon waveguide. Since both $L$ and $n$ are the function of the temperature $T$, the temperature sensitivity can be expressed as

$$\frac{d\lambda_{dy}}{dT} = \frac{2\Delta L}{k} \frac{dn}{dT} + \frac{2n}{k} \frac{d\Delta L}{dT}$$

(2)

where the first term represents the refractive index changes induced by temperature, which is named as the thermo-optic effect (TOE). The second term expresses the thermal expansion, which is named as the thermal expansion effect (TEE). With reasonable agreements on various thermo-optic coefficient measurements, a useful model based on thermal expansion and temperature variation of the excitonic bandgap is proposed to physically account for the silicon TOE. By assuming a single dominant electronic oscillator with constant oscillator strength, the thermo-optic coefficient can be expressed as [6]

$$\frac{dn}{dT} = n^2 \left[-3k_{ex} - \frac{2}{E_g} \frac{dE_g}{dT} \frac{1}{E_g} \right]$$

(3)

where $E_g$ is the excitonic bandgap at a critical point where the aforementioned oscillator resides and $k_{ex}$ is the silicon thermal expansion coefficient. The expression of $k_{ex}$ over the range of 120 - 1500 K can be readily known as $k_{ex}(T) = 3.725 \times 10^{-6}(1 - \exp[-5.88 \times 10^{-3}(T - 124)]) + 5.548 \times 10^{-10}T$. $E_g(T) = 4.03 - 3.417T/(T + 439)$ [7]. Thus, the phase change induced by TOE can be expressed as

$$\frac{d\phi}{dT} = \frac{2\pi}{\lambda} \frac{dn}{dT} = 2\Delta L$$

(4)

While the phase change induced by TEE can be expressed as

$$\frac{d\phi}{dT} = \frac{2\pi}{\lambda} \frac{2\Delta L}{\alpha} = \frac{2\pi}{\lambda} \frac{2\Delta L}{\alpha}$$

(5)

where the term $\alpha = \partial \Delta L / (\Delta L \partial T)$ is the thermal expansion coefficient ($2.5 \times 10^{-6}$ K$^{-1}$ for silicon) [8]. The phase contribution for these two kinds of thermal modulation effect is plotted in Fig. 2. The ratio between the phase changes induced by thermo-optic effect and by thermal expansion effect is up to 25 when the temperature is 500 °C. Therefore, the phase change is mainly induced by TOE.

In [3], the authors used a silicon micro-ring to sense the temperature, a sensitivity of 88 pm/K is obtained, but the sensing range is limited by the free spectrum range (FSR), which varies inversely with the radius of the ring. The radius of the ring cannot be too small due to the increased bending loss. In this design, the optical loss does not increase when the arm changes. The distance between two adjacent interference wavelengths can be much larger than the micro-ring typed temperature sensor. Therefore, the sensing range is also much larger than the micro-ring typed configuration. Fig. 3 shows the comparison of the sensing range between the micro-ring configuration and the MI configuration. For instance, when the radius of the micro-ring is 5 μm while the beam difference of the MI is also 5 μm, the sensing range of the MI is four-fold larger than that on the micro-ring.

FABRICATION AND PACKAGING

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**Figure 2: Simulation of thermal modulation on the silicon waveguide by thermo-optic effect and expansion.**

**Figure 3: Simulation of the maximum temperature sensing range vs the length difference of two arms. Sensing range of MI configuration is much higher than the previous optical micro-ring figuration.**

**Figure 4: SEM of the fabricated photonic thermocouple. Two optical waveguide loops are used as full-band reflector at the end of arms, while two parallel...**
waveguides is properly designed to serve as an integrated optical beam splitter as shown in the inset.

The chip as shown in Fig. 4 is fabricated on a commercial 8-inch silicon-on-insulator wafer with a structure layer of 220 nm and a buried oxide layer of 2 μm. Deep UV lithography (248 nm) is used to define the device pattern. Then, inductively coupled plasma etching system was used to dry etch the silicon layer. The lengths of the unequal arms of the MI are 20 μm and 30 μm, respectively. For the reflector, although Bragg grating is a choice, its bandwidth is narrow and reflection spectrum is not temperature independent. Thus, an optical waveguide loop is adopted as a mirror for full-band reflection. The performance is demonstrated in previous works [9]. The waveguide loop circuit acts like a mirror for full-band reflection. The 3-dB DC is 11-μm long and the coupling gap is 300 nm. All of the waveguide structures have a width of 400 nm. A mode size converter is integrated on the input side to improve the coupling efficiency. The width and length of the converter are 180 nm and 200 μm, respectively. The expanded spot diameter is approximately 1.8 μm.

Figure 5: Optical power loss induced by misalignment between the lensed optical fiber and waveguide mode converter.

Figure 6: (a) Experimental setup in laser welding process. (b) Coupling part between lensed fiber and silicon nano-waveguide. (c) Packaged module based on laser welding technology.

The coupling loss between the lensed-fiber and inverted taper is 2.25 dB normalized fiber to fiber coupling. The optical power loss induced by misalignment is shown in Fig. 5. The 3-dB lateral tolerance (X-misalignment and Y-misalignment) is 1.25 μm while the 3-dB longitudinal tolerance is larger than 5 μm. The packaging process is processed on a laser welding station. The lensed-fiber is special design with a surrounded metal ferrule made of nickel. The metal ferrule is joined with a nickel-based fiber clip, and the fiber clip is joined with a KOVAR alloy substrate. The thickness of the fiber clip is approximately 150 μm. The main procedures include: 1) attaching the chip on KOVAR alloy substrate by using epoxy; 2) aligning the lensed-fiber on the laser welding station; 3) placing the fiber clip and weld it on KOVAR alloy substrate; 4) welding the metal ferrule and the fiber clip by YAG laser. In the packaging, the reflection light is detected to align the optical fiber. The Experimental setup in laser welding process is shown in Fig. 6(a). The packaged module is shown in Fig. 6(b) and the zoom view of the coupling part between the lensed-fiber and the mode size converter in Fig. 6(c). During welding, rapid solidification of the welded region and the associated material shrinkage causes the misalignment. This misalignment is ranging from 0 to 20 μm depending on the welding procedure [10]. To compensate the misalignment, the mechanical tuning has to be implemented via power monitoring. The design of the input and output light sharing a same lensed-fiber also reduces the difficulty in packaging.

RESULTS AND DISCUSSIONS

The optical power of the chip and packaged module has been compared as shown in Fig. 7. The distance between two adjacent interference wavelengths is approximately 27.9 nm. The chip measurement is performed on a waveguide testing stage. The total loss of the MI chip is approximately 6.9 dB. The optical loss of the module after the mechanical tuning process is measured as 2.1 dB. The output variation induced by temperature is within 1.7 dB when the temperature changed between 0 °C to 180 °C.

Figure 7: Module performance evaluation. Optical power loss comparison between chip and module. Dip distance ~ 27.95 nm.

The optical spectral response of the photonic thermocouple is observed as shown in Fig. 8. When the temperature varies from 13 °C to 95 °C, the interference wavelength is red-shifted from 1568.8 nm to 1579.9 nm. With the temperature changes, the quality of the interference dip of the MI has insignificant change. The
sensitivity is measured as 113.72 pm/°C, which is higher than 83 pm/°C in [3]. The estimated sensing range is approximately 246 °C (27.95 nm / 113.72 pm/°C).

CONCLUSIONS

In conclusion, a photonic thermocouple based on an ultra-compact Michelson Interferometer is experimentally demonstrated. The device is fabricated by using standard CMOS process, which provides a cost effective and highly integrated approach for optical temperature sensor. Good linear response characteristic and high output stability in temperature sensing is obtained. It provides an alternative approach for temperature sensing in harsh environment.

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