Demonstration of a Photonic-based Linear Temperature Sensor

Journal:	*Photonics Technology Letters*
Manuscript ID:	PTL-28848-2014
Manuscript Type:	Original Paper
Date Submitted by the Author:	14-Sep-2014
Complete List of Authors:	TAO, JIFANG; Institute of Microelectronics, Sensors & Actuators Microsystems Program
Key Words:	Waveguides, Optical waveguides, Optoelectronic devices, Microsensors, Micromachining

SCHOLARONE™
Manuscripts

For Review Only

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 μm × 80 μm. Operating at the wavelength around 1550 nm, this ultra-compact MI configuration obtains a nearly linear temperature response with a sensitivity of 113.72 pm/ºC, which is around 20 times higher than that of traditional fiber-optic thermal sensors. It is fabricated by standard CMOS process. Benefitted from the advanced packaging technique, the proposed photonics sensor shows high thermal and mechanical stabilities, presenting a less than 0.1 dB power variation over the temperaturer 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 the silica material.

Recently, sensors configured with 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 μm was used to monitor temperature [5], whose sensitivity is up to 83 pm/ºC. 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 incrseased bending loss of small ring would impose a stringent limiation.

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 pm/ºC. Taking advantages of reliable packaging technique, it provides substantial size and cost effective over traditional optical sensors solutions, with good linear response performance.

Manuscript received August 23, 2014. This work was supported by the Science and Engineering Research Council of Agency for Science, Technology and Research (A*STAR), under SERC Grant 1021650084

J. F. Tao, H. Cai, Y. D. Gu are with the Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), 117685, Singapore. (e-mail: taojf@ime.a-star.edu.sg; caih@ime.a-star.edu.sg).

J. Wu is with the Beijing University of Posts and Telecommunications, 100876, Beijing, P. R. China (e-mail: jianwu@bupt.edu.cn)

A. Q. Liu is with the Nanyang Technological University, 639798, Singapore. (e-mail: eaqliu@ntu.edu.sg)

II. DESIGN AND FABRICATION

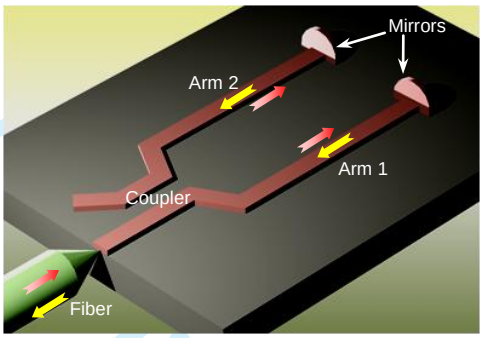
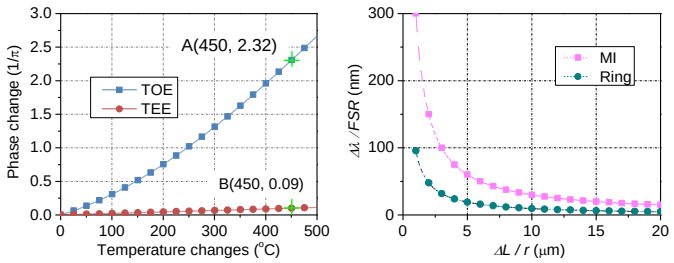


Fig. 1. Schematic of the photonic sensor chip constructed as an ultra-compact Michelson interferometer.

The proposed photonic temperature sensor is schematically depicted in Fig. 1. It consists of a coupler structure and two waveguide arms with a mirror at each end. When a light beam is coupled into the chip from an optical fiber, it is equally splitted into two beams and guided into arm 1 and arm 2, respectively. Due to the end-mirror reflection, the reflected light beams are recombined through the coupler. 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. And such phase different can be readout by recording the destructive interference wavelength 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.

For Review Only



(a) (b)

Fig. 2. (a) Simulation of the compared sensing range of micro-ring resonator and proposed MI configuration. (b) Simulation of the thermal modulation on silicon-waveguide.

The lengths of two arms of MI are unequal so that the destructive interference wavelength can be generated and to be estimated from reflection spectrum [10]. The destructive interference wavelength (λ_{dip}) of MI depends on the effective length difference of two arms, and can be expressed as

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

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 both are function related to the temperature (T), the corresponding temperature sensivity 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, $dn/dT = 1.8\times10^{-4} + 3.47\times10^{-7}T - 1.98\times10^{-10}T^2$ is estimated based on single oscillator model in [11]. And, thermal expansion coefficient is readily known as $d(\Delta L)/dT = 3.725\times10^{-6}\{1 - exp[-5.88\times10^{-3}(T - 124)]\} + 5.547\times10^{-10}T$ over the range of 120 – 1500K [12]. It should be mentioned that, the thermal expansion induced wavelength shift can be neglected compared with the more pronouced TOE induced one, as plotted in Fig. 2(a). For instance, the ratio of the TOE induced sensing range to the thermal expansion induced one can be up to 69 at 450 ºC.

Temperature sensing range of the proposed MI configuration is determinded by the distance between the two adjacent destructive interference wavelengths (i.e. dip distance $\Delta\lambda$). Futher 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 ring resonator based temperature sensor configration, its sensing range was determinded 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, dip distance and FSR are inversely proportional to the arm difference and ring radius, respectively, but sensing range of MI is always π times larger than micro-ring when ΔL equates 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

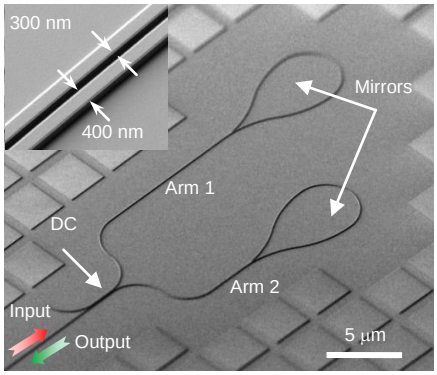


Fig. 3. SEM images of the fabricated photonic sensor chip. (a) Overview, and the inset is a zoom-view of the DC with a length of 11 μm, a coupling gap of 300 nm.

The photonic chip is fabricated on a commercial 8-inch silicon-on-insulator (SOI) wafer. Its structure layer and buried oxide layer are 220 nm and 2 μm, respectively. SEM pictures of the photonic temperature sensor chip are shown in Fig. 3. The unequal arms of the MI are 20 μm and 30 μm, respectively. Thus, we adopt an optical waveguide loop as a mirror for the full-band reflection, which is implemented through a silicon wire loop design [10]. In the DC design, the coupling length and coupling gap are 11 μm and 300 nm, respectively. All waveguide structures are with a width of 400 nm. A inverted taper with a dimension of 180 nm × 220 nm (W × H), is integrated at the end of waveguide to improve coupling efficiency.

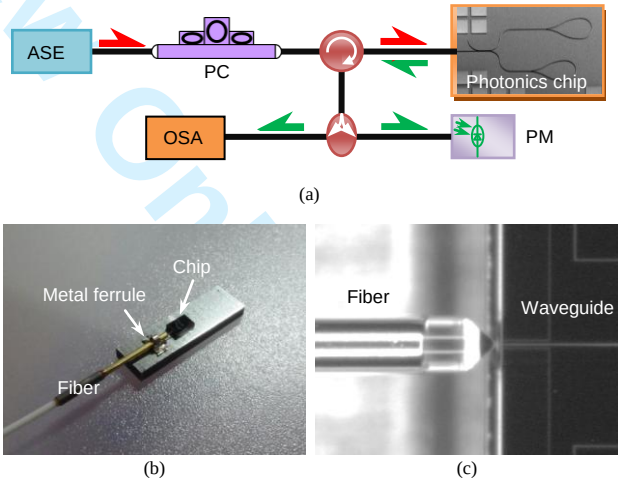


Fig. 4. (a) Experimental setup in temperature sensing. ASE: amplified spontaneous emission; PC: polarization controller; OSA: optical spectrum analyzer; PM: powermeter, (b) packaged chip in a small form factor, by laser welding technique, and (c) coupling part between the lensed-fiber and the inverted taper coupler.

The photonic sensor chip is characterized, with the experimental setup schematically illustrated in Fig. 4(a). Since the input light and output light can share a same fiber, this passive photonics chip can be packaged as active photonic devices, such as laser diodes (LDs) and semiconductor optical amplifiers (SOAs). It also simplifies the packaging process by single fiber packing instead of two ends waveguide-fiber

For Review Only

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 total loss, including the propagation loss and the coupling loss, is measured of 6.3 dB. Specifically, the coupling loss between the lensed-fiber and inverted taper coupler is around 2.25 dB.

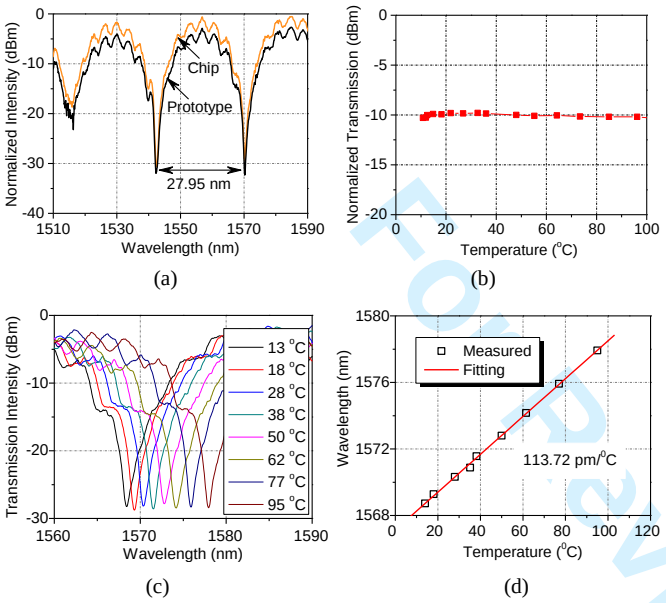


Fig. 4. (a) Comparison of the responded output spectra of the unpackaged chip and packaged sensor prototype. (b) Output power at different operating. (c) Transmission spectral response on temperature change, in terms of wavelength shift. (d) Almost linearly spectral shift response upon the temperature change, with a sensitivity of ~113.72 pm/ ºC.

The reflection spectra of the actively aligned chip and the prototype of the packaged sensor are compared, as depicted in Fig. 4(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 believed mainly due to the coupling loss associated with fiber/chip optical misalignment introduced during packaging procedure. The distance between two adjacent destructive interference wavelengths is around 27.95 nm, sufficient to cover a 245°C temperature change. The output power at different environment temperature is measured (over the range from 13 °C to 95°C), as shown in Fig. 4(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. 4(c). It is noticed that as the temperature varies from 13 ºC to 95 ºC, the destructive interference wavelength is red-shift from 1568.8 nm to 1579.9 nm, corresponding to a high sensitivity of 113.72 pm/ºC at the measured temperature range which provides a high temperature resolution potentially. It is observed that the wavelength shift is almost linearly with the temperature change, as in Fig. 4(d).

IV. CONCLUSIONS

We have experimentally demonstrated a photonic temperature sensor, with a small footpring of 120 μm × 80 μm, by using an ultra-compact Michelson Interferometer configuration. Supported by the standard CMOS process, the photonic sensors offer attractive features in combination of compactness, high sensitivity and low cost. In particulr, its spectra response to the temperature variation achieves a linear manner, with a sensitivity of 113.72 pm/ºC over the temperature range of 82 ºC. Meanwhile, it presents a relatively stable output power over the whole temperaturer range of 13 °C to 95 °C at the -10 dBm output power level.

REFERENCES

[1] J. M. Hsu, C. L. Lee, P. J. Huang, C. H. Hung, and P. Y. Tai, "Temperature sensor with enhanced sensitivity based on photonic crystal fiber interferometer with material overlay," *IEEE Photon. Technol. Lett*., vol. 24, no. 19, pp. 1761-1764, Oct. 1, 2012

[2] J. Zhang, X. Qiao, T. Guo, Y. Weng, R. Wang, Y. Ma, Q. Rong, M. Hu, and Z. Feng, "Highly sensitive temperature sensor using PANDA fiber sagnac interferometer," *J. Lightw. Technol.*, vol. 29, no. 24, pp. 3640-3644, Dec. 15, 2011

[3] A. K. Sang, M. E. Froggatt, D. K. Gifford, S. T. Kreger, and B. D. Dickerson, "One centimeter spatial resolution temperature measurement in a Nuclear reactor using rayleigh scatter in optical fiber," *IEEE Sensors J.*, vol. 8, no. 7, pp. 1375-1380, 2008

[4] D. Barrera, V. Finazzi, J. Villatoro, S. Sales, and V. Pruneri, "Packaged Optical Sensors Based on Regenerated Fiber Bragg Gratings for High Temperature Applications," *IEEE Sensors J*., vol. 12, no. 1, pp. 107-112, 2012

[5] G. D. Kim, H. S. Lee, C. H. Park, S. S. Lee, B. T. Lim, H. K. Bae, and W. G. Lee, "Silicon photonic temperature sensor employing a ring resonator manufactured using a standard CMOS process," *Opt. Express*, vol. 18, no. 21, pp. 22215-22221, 2010

[6] T. B. Andersen, S. I. Bozhevolnyi, L. Markey, and A. Dereux, "Fiber-pigtailed temperature sensors based on dielectric-loaded plasmonic waveguide-ring resonators," *Opt. Express*, vol. 19, no. 27, pp. 26423-26428, 2011

[7] S. L. Tsao, and P. C. Peng, "An SOI Michelson interferometer sensor with waveguide bragg reflective gratings for temperature monitoring," *Microw. Opt. Technol. Lett*., vol. 30, no. 5, pp. 321-322, 2001

[8] C. Qiu, T. Hu, P. Yu, A. Shen, F. Wang, X. Q. Jiang, and J. Y. Yang, "A Temperature Sensor Based on Silicon Eye-like Microring with Sharp Asymmetric Fano Resonance," *IEEE 9th International Conference on Group IV Photonics*, 2012, pp. 123-125, 2012

[9] H. S. Lee, G. D. Kim, W. J. Kim, S. S. Lee, and W. G. Lee, "Tunable-Resonator-Based Temperature Sensor Interrogated through Optical Power Detection," *Appl. Phys. Express*, vol. 4, 102201, 2011

[10] J. F. Song, Q. Fang, S. H. Tao, T. Y. Liow, M. B. Yu, G. Q. Lo, and D. L. Kwong, "Fast and low power Michelson interferometer thermo-optical switch on SOI," *Opt. Express*, vol. 16, no. 20, pp. 15304-15311, 2008.

[11] F. G. D. Corte, M. E. Montefusco, L. Moretti, I. Rendina, and G. Cocorullo, "Temperature dependence analysis of the thermo-optic effect in silicon by single and double oscillator models," *J. Appl. Phys.*, vol. 88, no. 12, pp. 7115-7117, 2000

[12] Y. Okada and Y. Tokumaru, "Precise determination of lattice parameter and thermal expansion coefficient of silicon between 300 and 1500 K," *J. Appl. Phys*., vol. 56, no. 2, pp. 314-320, 1984

[13] J. H. Song, J. Zhang, H. Zhang. C. Li, and G. Q. Lo, "Si-photonics based passive device packaging and module performance, " *Opt. Express*, vol. 19, no. 19, pp. 18020-18028, 2011

[14] J. H. Song, P. O'Brien, and F. H. Peters, "Optimal laser welding assembly sequences for butterfly laser module packages," *Opt. Express*, vol. 17, no. 19, pp. 16406-16414, 2009

[15] J. H. Song, H. N. J. Fernando, B. Roycroft, B. Corbett, and F. H. Peters, "Practical design of lensed fibers for semiconductor laser packaging using laser welding technique," *J. Lightw. Technol*., vol. 27, no. 11, pp. 1533-1539, 2009

For Review Only