Chip-Packaged Silicon Photonic Nanoscale Thermometers

Nikolai N. Klimov[1,2*], Thomas Purdy[3], and Zeeshan Ahmed[1]
[1]*Thermodynamic Metrology Group, Sensor Science Division, Physical Measurement Laboratory, NIST, Gaithersburg, MD 20899*
[2]*Joint Quantum Institute, University of Maryland, College Park, MD 20742*
[3]*Quantum Optics Group, Quantum Measurement Division, Physical Measurement Laboratory, NIST, Gaithersburg, MD 20899*
*nklimov@nist.gov

Abstract: We report on the development of on-chip integrated packaged nanoscale silicon photonic temperature sensors capable of detecting temperature differences as small as 70 µK, thus showing the potential to replace legacy resistance thermometers.
OSIC codes: (120.3940) Metrology; (280.6780) Temperature; (130.6010) Sensors.

1. Introduction

Resistance thermometry plays a crucial role in modern technology ranging from medicine and manufacturing process control, to environmental and oil-and-gas industry. Although today's resistance thermometers achieve temperature uncertainties of 10 mK, their performance is very sensitive to various environmental variables such as mechanical shock, thermal stress and humidity [1]. These limitations have encouraged the development of cost-effective alternative temperature measurement solutions such as photonics-based temperature sensors. A wide variety of photonic thermometers has been proposed recently ranging from macroscale photosensitive dyes [2], hydrogels [3], and fiber Bragg grating [4] to microscale on-chip integrated silicon photonic devices such as nanowaveguide Bragg grating [5] ring resonator [6,7] and Fabry-Perot type devices [8].

In this work we report on the development of packaged silicon photonic thermometers with ultra-small footprint and ultra-high temperature sensitivity. The sensors are photonic crystal nanobeam cavity type devices fabricated on a silicon-on-insulator (SOI) photonic chip. When the chip is packaged via bonding of an array of optical fibers, our integrated nanothermometers are capable of detecting temperature differences as small as 70 µK at 0.1 s integration time. Our photonic thermometers are on par if not better than legacy-based resistance thermometers.

2. Results and Discussion

The photonic chip with integrated silicon photonic thermometers described in this work was fabricated at the National Institute of Standards and Technology / Center for Nanoscale Science and Technology (NIST/CNST) NanoFab user facility using SOI CMOS-technology[a]. The integrated sensors were patterned on SOI wafers via electron beam lithography followed by inductive plasma reactive ion etch (ICP RIE) of unprotected topmost 220 nm-thick silicon layer. After the ICP RIE etch the devices were top-cladded with 800 nm of silicon dioxide. Each sensor has two on-surface focusing grating couplers [9] for coupling 1550 nm laser light from and into single mode optical fibers. After device fabrication, we packaged the photonic chip by bonding a v-groove fiber array to the input/output ports on the chip. For packaging we used a home-built fiber alignment/bonding setup, consisting of a sub micro-positioning stage with 10 degrees of freedom, a micro-dispensing unit for controlled application of epoxy adhesive and a UV light source for curing of adhesive. The packaged chip is shown on Fig.1a.

The integrated thermometers are silicon photonic crystal cavities (Si PhCC). These Fabry-Perot (F-P) type sensors operate in the telecom frequency range and have a very sharp resonance peak that shifts with temperature [8] due to the intrinsically high thermo-optic coefficient of silicon [10]. Each Si PhCC consists of an 800 nm wide silicon waveguide that has a F-P cavity in its center. On the either side of the cavity, the waveguide is patterned with a one dimensional array of subwavelength holes (holes' diameters range from 170 nm to 200 nm). Our design follows the deterministic approach of Ref. [11], in which the PhCC features a zero length F-P cavity and two adjacent photonic crystal Bragg mirrors with a Gaussian field attenuation that maximizes the Q of the cavity. For Si PhCC sensors we coupled the light into the F-P cavity via an evanescent coupling from a 510 nm wide bus waveguide placed within ≈ 200 nm to 300 nm from the PhCC active area (Fig.1a).

All temperature measurements were conducted in the temperature range from -40 °C to +80 °C in a dry bath that has a 1 mK temperature stability. In the first set of measurements at each set temperature we scan the wavelength across the resonance peak and record the peak center versus the set temperature. Inset to Fig. 1b shows a resonance peak corresponding to the fundamental mode of one of the sensors. The Q factor of the peak is 20 000. In the studied

[a]Disclaimer: Certain commercial fabrication facility, equipment, materials are identified in this paper in order to adequately specify device fabrication, the experimental procedure and data analysis. Such identification is not intended to imply endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the facility, equipment, material or software identified are necessarily the best available.

temperature range, the resonance wavelength λ_0 corresponding to the peak center can be described by a linear temperature dependence with a slope of $d\lambda_0/dT \approx 75.2$ pm/°C (Fig. 1b).

The second set of measurements was focused on the investigation the minimum detectable temperature difference and the noise floor. In these measurements, instead of sweeping the wavelength we parked the laser on a side of the resonance peak (both output laser intensity and wavelength were kept constant), and recorded the transmission laser power. In this configuration a subtle change in bath temperature δT is read out as a change in the transmission. By recording the transmission power variation, δP, we calculate the bath temperature change as follows:

$$\delta T = \delta P\ (d\lambda_0/dT)^{-1}(dP/d\lambda)^{-1},$$

where $d\lambda_0/dT = 75.2$ pm/°C is the first derivative of $\lambda_0(T)$ – dependence, and $dP/d\lambda = 35.5$ pW/pm is slope of the side of the resonance peak.

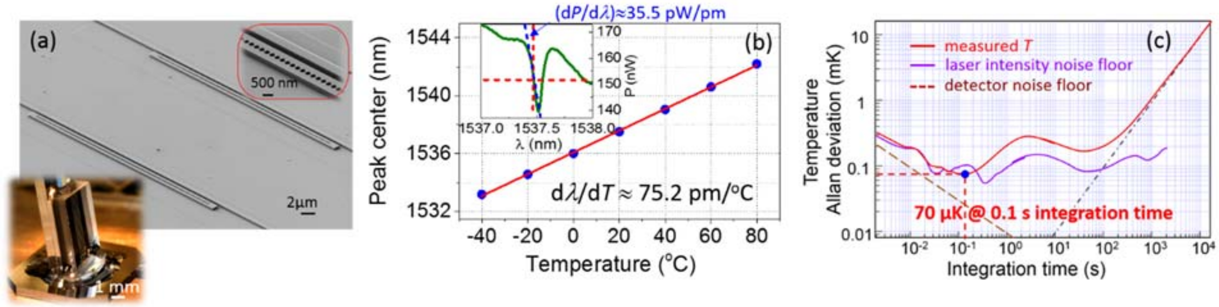

Fig. 1. (a) SEM image of two Si PhCC thermometers. The upper inset is a zoom-in region of the central part of the sensors; the lower inset is a packaged silicon photonic chip. (b) Temperature dependence of the resonance peak of the fundamental mode. Insert: resonance peak of the fundamental mode measure at $T = (19.969 \pm 0.001)$ °C . Dashed red lines indicated where the laser's wavelength and power were parked during the temperature noise floor measurements. (c) Temperature Allan deviation plot. Red and blue curves correspond to measured temperature and measured laser intensity variations, respectively.

3. Summary

We have developed and fabricated on-chip packaged nanoscale thermometers capable to detect a temperature difference as small as 70 μK. The temperature resolution can be further increased by increasing the Q of the photonic sensors. These sensors are on par, if not better, than state-of-the-art resistance thermometers.

Acknowledgement

The authors acknowledge the NIST/CNST NanoFab facility for providing the opportunity to fabricate silicon photonic temperature sensors.

References

[1] G.F. Strouse, Standard Platinum Resistance Thermometer Calibrations fromthe Ar TP to the Ag FP, NIST Spec. Publ. 250 (2008) 81.

[2] J.S. Donner, S.A. Thompson, M.P. Kreuzer, G. Baffou, R. Quidant, Mapping Intracellular Temperature Using Green Fluorescent Protein, Nano Lett. 12 (2012) 2107–2111. doi:10.1021/nl300389y.

[3] E.M. Ahmed, Hydrogel: Preparation, characterization, and applications: A review, J. Adv. Res. 6 (2015) 105–121. doi:10.1016/j.jare.2013.07.006.

[4] A. Kersey, T.A. Berkoff, Fiber-optic Bragg-grating differential-temperature sensor, IEEE Photonics Technol. Lett. 4 (1992) 1183–1185. doi:10.1109/68.163773.

[5] N.N. Klimov, S. Mittal, M. Berger, Z. Ahmed, On-chip silicon waveguide Bragg grating photonic temperature sensor, Opt. Lett. 40 (2015) 3934. doi:10.1364/OL.40.003934.

[6] M.-S. Kwon, W.H. Steier, Microring-resonator-based sensor measuring both the concentration and temperature of a solution, Opt. Express. 16 (2008) 9372–9377. doi:10.1364/OE.16.009372.

[7] H. Xu, M. Hafezi, J. Fan, J.M. Taylor, G.F. Strouse, Z. Ahmed, Ultra-sensitive chip-based photonic temperature sensor using ring resonator structures, Opt. Express. 22 (2014) 3098. doi:10.1364/OE.22.003098.

[8] N.N. Klimov, T. Purdy, Z. Ahmed, Fabry-Perot cavity-based silicon photonic thermometers with ultra-small footprint and high sensitivity, Conf. Proc. Adv. Photonic Congr. 2015 Boston MA.

[9] F. Van Laere, G. Roelkens, M. Ayre, J. Schrauwen, D. Taillaert, D. Van Thourhout, et al., Compact and Highly Efficient Grating Couplers Between Optical Fiber and Nanophotonic Waveguides, J. Light. Technol. 25 (2007) 151–156. doi:10.1109/JLT.2006.888164.

[10] G. Cocorullo, F.G.D. Corte, I. Rendina, Temperature dependence of the thermo-optic coefficient in crystalline silicon between room temperature and 550 K at the wavelength of 1523 nm, Appl. Phys. Lett. 74 (1999) 3338–3340. doi:10.1063/1.123337.

[11] Q. Quan, P.B. Deotare, M. Loncar, Photonic crystal nanobeam cavity strongly coupled to the feeding waveguide, Appl. Phys. Lett. 96 (2010) 203102. doi:10.1063/1.3429125.