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Integrated Nanophotonics for One-Step Traceability for Temperature Measurements

Nikolai N. Klimov[1], Kevin O. Douglass[1], Tobias Herman[1], Zeeshan Ahmed[1], Michal J. Chojnacky[1]
[1] National Institute of Standards and Technology, Gaithersburg, MD 20899, USA,
nklimov@nist.gov

Summary:
We report on the development of the next-generation photonics-based thermometry at National Institute of Standards and Technology (NIST). We provide details on design, fabrication, and performance of ultra-high resolution photonic thermometers. Our device shows a noise floor of sub-10 µK when measured at water triple point and gallium fixed-point cells, demonstrating the potential for photonic thermometry that is on-par or even better than the state-of-the-art resistance thermometry.

Keywords: temperature metrology, thermometry, photonics

Introduction

Temperature measurements play a crucial role in various aspects of modern technology. Among various temperature measurement solutions, resistance-based thermometry is a time-tested method of disseminating temperature standards [1]. Although industrial resistance thermometers can routinely measure temperatures with uncertainties of 10 mK, their resistances drift over time due to sensors' sensitivity to multiple environmental variables. These fundamental limitations of resistance thermometry, as well as the desire to reduce sensor ownership cost, have ignited a substantial interest in the development of alternative temperature measurement solutions such as photonics-based temperature sensors [2]–[4]. Here we present the results of our efforts at NIST in developing novel on-chip integrated silicon photonic temperature sensors with a nanoscale footprint and ultra-high resolution as an alternative solution to legacy resistance thermometers. These nanophotonic sensors operate in telecom frequency range and have a high-quality (high-*Q*) resonant frequency mode that is highly sensitive to even ultra-small temperature variations. We present a direct comparison of our photonic thermometers to Standard Platinum Resistance Thermometers (SPRT), the best-in-class resistance temperature sensors used to disseminate the International Temperature Scale of 1990. Our preliminary results indicate that our photonic thermometers are capable of detecting changes of temperature as small as sub-10 µK and can achieve measurement capabilities that are on-par or better than state-of-the-art resistance thermometry.

Device design, fabrication, and packaging

The integrated photonic thermometers described in this work are silicon photonic crystal cavity (Si PhCC) nanoresonators that have a very sharp resonance optical mode in their transmission spectra [3]. The mode frequency shifts with temperature due to high thermo-optic coefficient of silicon [5] and can be used to trace temperature variations with high precision. Our photonic thermometer features Fabry-Perot cavity that is shaped out of two symmetrical photonic crystals (Fig. 1). To design photonic crystal cavity we follow a deterministic approach of Ref. [6] with additional optimization.

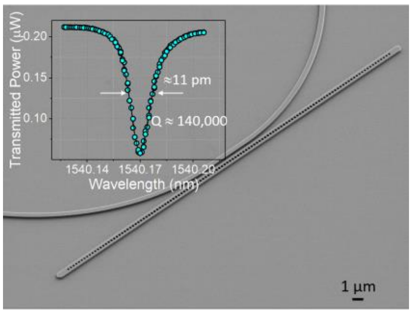

Fig 1: SEM image of silicon photonic thermometer. The insert shows the resonant absorption peak of the sensor.

The photonic chip with integrated silicon photonic thermometers was fabricated at the NIST NanoFab facility [7]. The integrated sensors were patterned on silicon-on-insulator substrate. The substrate consists of 220 nm-thick silicon, 3 µm-thick buried silicon dioxide, and 670 µm of silicon handle. The devices were patterned via electron-beam lithography followed by inductively coupled plasma reactive ion etch (ICP RIE) of the patterned topmost silicon layer. After the ICP RIE etch, devices were top-cladded with a silicon dioxide layer with a thickenss of 1500 nm . After device fabrication, we fiber-coupled the photonic chip on a custom-built photonic chip packaging station by bonding a v-groove fiber array to the input/output ports on the chip using ultraviolet light curable adhesive. The fiber-coupled device was then placed in a sheath tube and sealed under inert gas.

Results

The fabricated photonics thermometer has a resonance peak at ≈1540 nm wavelength at 300 K and a temperature sensitivity of ≈67 pm/K. The photonic thermometer is interrogated using a telecom tuneable laser and a laser dither locking technique. To realize a dither lock a laser frequency is modulated via a low-frequency laser current modulation. When the laser frequency is close to the photonic crystal cavity resonance, the frequency modulation produces an amplitude modulation of the photodiode signal. A transmission signal from the cavity is sent to a phase-sensitive detector, which transforms this modulation signal into a derivative signal. The produced "error" signal is used in a feedback loop to adjust the laser frequency to constantly track the PhCC resonance shift. Once a laser lock is realized, the laser frequency is locked to the top of the fringe of photonic crystal cavity resonance. Whenever the PhCC resonance frequency shifts due to external temperature variations, the laser frequency is automatically adjusted via a feedback loop.

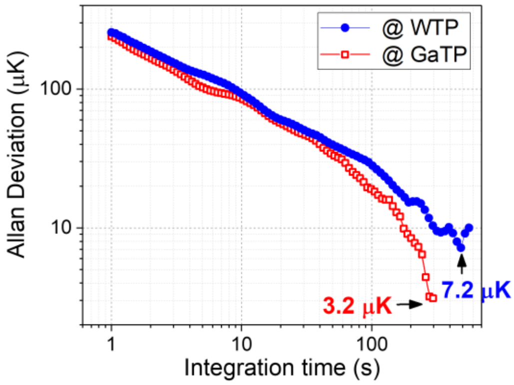

Fig. 2: Allan deviation plot of photonic thermometer TP-W and TP-Ga.

To access sensor's performance, we calibrated our photonic thermometer against two fixed-point cells with phase-transition temperatures defined within the International Temperature Scale of 1990 (ITS-90): the triple-point of water (TP-W, 273.16 K) and the triple-point of gallium (TP-Ga, 302.9166 K). These two temperatures bracket the most frequently used range of ITS-90 [9]. The resonance frequency of the photonic thermometer changes monotonically with temperature. Calibration of the resonance frequencies at the two fixed-point temperatures allows the thermometer to make absolute temperature measurements referenced to the ITS-90 temperature scale. The measured noise floor for TP-W and TP-Ga are at the 10 µK level (Fig. 2).

Conclusion

In conclusion, we fabricated an ultra-sensitive photonic temperature sensor and demonstrated its performance at TP-W and TP-Ga in water and gallium fixed-point cells. The photonic thermometer shows a noise floor below 10 µK and is comparable to the performance of SPRT. Moreover, the photonic thermometer is more robust against mechanical shock and temperature stress than SPRTs. The results from this study show the potential for photonic thermometers to serve as future standards for the dissemination of ITS-90 to commercial calibration laboratories and as transfer standards for international measurement comparisons between National Metrology Institutes.

References

[1] G. F. Strouse, "Standard Platinum Resistance Thermometer Calibrations fromthe Ar TP to the Ag FP," *NIST Spec. Publ.*, vol. 250, no. 250, p. 81, 2008.
[2] AD. Kersey and T. A. Berkoff, "Fiber-optic Bragg-grating differential-temperature sensor," *IEEE Photonics Technol. Lett.*, vol. 4, no. 10, pp. 1183–1185, Oct. 1992.
[3] N. N. Klimov *et. al*, "On-chip silicon photonic thermometers: from waveguide Bragg grating to ring resonators sensors," May 2015, p. 948609.
[4] N. N. Klimov *et. al*, "On-chip silicon waveguide Bragg grating photonic temperature sensor," *Opt. Lett.*, vol. 40, no. 17, p. 3934, Sep. 2015.
[5] G. Cocorullo *et. al*, "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.*, vol. 74, no. 22, pp. 3338–3340, May 1999.
[6] Q. Quan and M. Loncar, "Deterministic design of wavelength scale, ultra-high Q photonic crystal nanobeam cavities," *Opt. Express*, vol. 19, no. 19, pp. 18529–18542, Sep. 2011.
[7] "Disclaimer: Certain commercial fabrication facility, equipment, and materials are identified in this paper in order to specify device fabrication, and the experimental procedure adequately. 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, or materials identified are necessarily the best available."
[8] F. Van Laere *et al.*, "Compact and Highly Efficient Grating Couplers Between Optical Fiber and Nanophotonic Waveguides," *J. Light. Technol.*, vol. 25, no. 1, pp. 151–156, Jan. 2007.
[9] H. Preston-Thomas, "The International Temperature Scale of 1990 (ITS-90)," *Metrologia*, vol. 27, no. 1, pp. 3–10, Jan. 1990.