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Towards replacing resistance thermometry with photonic thermometry

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ABSTRACT

Resistance thermometry provides a time-tested method for taking temperature measurements that has been painstakingly developed over the last century. However, fundamental limits to resistance-based approaches along with a desire to reduce the cost of sensor ownership and increase sensor stability has produced considerable interest in developing photonic temperature sensors. Here we demonstrate that silicon photonic crystal cavity-based thermometers can measure temperature with uncertainities of 175 mK ($k = 1$), where uncertainties are dominated by ageing effects originating from the hysteresis in the device packaging materials. Our results, a ≈4-fold improvement over recent developments, clearly demonstate the rapid progress of silicon photonic sensors in replacing legacy devices.

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1. Introduction

Temperature measurements play a central role in all aspects of modern life ranging from process control in manufacturing [1], physiological monitoring [2,3] in medicine, to environmental engineering control in buildings [4] and automobiles [5]. Despite the ubiquity of thermometers, the underlying technology, resistance measurement of a thin metal film or wire, has only undergone incremental improvements over the last century [6,7]. Though resistance thermometers can routinely measure temperature with uncertainties as low as 10 mK, they are sensitive to environmental variables such as humidity, chemical oxidation and mechanical shock which causes the resistance to drift over time, requiring frequent off-line, expensive, and time consuming calibrations [6]. In recent years, there has been considerable interest in developing photonic devices as an alternative to resistance thermometers as a means of overcoming the shortfalls of resistance thermometry. Optical fiber and silicon photonic based technologies have received considerable interest as they have the potential to provide greater temperature sensitivity while being robust against mechanical shock and electromagnetic interference. Furthermore, the low weight, small form factor photonic devices may be multiplexed to provide low-cost sensing solutions [8–10].

Photonic temperature sensors exploit temperature dependent changes in a material's properties – typically, a combination of thermo-optic effect and thermal expansion [11,12]. For example, fiber Bragg gratings (FBG), exhibit temperature dependent shifts in resonant Bragg wavelength of ≈10 pm/K [8,13,14] which can be utilized to measure temperature over the range of 233 K–293 K with uncertainties of 500 mK ($k = 2$) when humidity and strain effects are minimized [14]. The impact of humidity on silicon photonic devices' performance is significantly reduced by depositing a passivating silicon dioxide layer on top of the silicon device [10]. Silicon Bragg thermometers have been demonstrated to measure temperature with uncertainties of 1.25 K ($k = 2$) over the range of 278 K–433 K [15]. The measurement uncertainty in silicon Bragg devices is dominated by the uncertainty in peak center measurement which could be significantly reduced by fabricating high quality-factor (Q-factor) devices such as photonic crystal cavity or ring resonators.

Numerous researchers have reported on silicon ring resonator and photonic crystal cavity (PhCC) based temperature sensors that were probed using fiber-to-chip evanescent coupling cumulatively demonstrating the superior temperature sensitivity, noise floor and temporal response of silicon photonic temperature sensors [10,16–20]. Recently, we undertook a systematic survey of ring resonator parameter space that aimed to optimize the device performance while achieving consistent results [21,22]. Our results suggest that consistently high performance temperature sensors are obtained from the zone of stability (waveguide width >600 nm,

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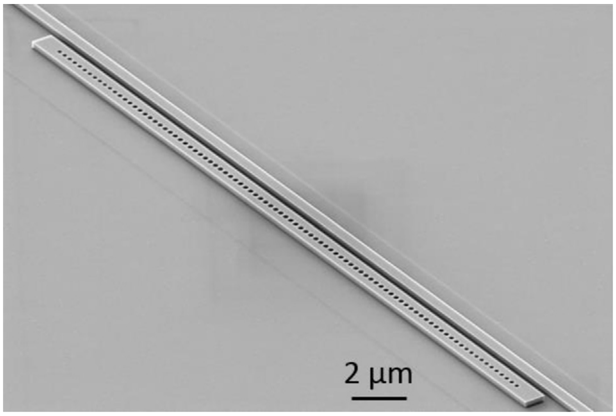

Fig. 1. SEM image of a silicon nanobeam photonic crystal cavity (Si PhCC) device.

air gap ≈130 nm and ring radius >10 μm) such that quality factors are consistently 10^4 and the temperature sensitivity is consistently in the 70 pm/K–85 pm/K range [22]. For evanescently coupled devices, over the temperature range of 293 K–418 K, the fit residual varies between 170 mK to 30 mK. Although comparison of the same device fabricated across different chips in the same batch reveals significant variation in temperature response, our results suggest that with better process control it is possible to achieve device interchangeability over a 200 mK tolerance band i.e. devices of the same design parameter, using nominal calibration coefficients will provide temperature readings that are within 200 mK of each other. Similar results can be reasonably expected of other resonant Si devices such as PhCCs.

Here we build upon our recent progress and characterize the temperature response of a packaged PhCC device over an extended temperature range. Our results indicate that these silicon photonic devices enable measurements of temperature with uncertainties of 175 mK ($k = 1$). The long-term stability of the thermometer is limited by hysteresis likely due to the epoxy used in pigtailing of fiber array to the chip. Nevertheless, this result represents a ≈4-fold improvement over the Si Bragg waveguide thermometer [15].

2. Experimental

2.1. Chip design and fabrication

The photonic chip with integrated temperature sensors was fabricated at the National Institute of Standards and Technology (NIST), Center for Nanoscience and Technology (CNST) using the CMOS process line on a silicon-on-insulator (SOI) wafer with a 220 nm thick layer of crystalline silicon on top of a 3 μm thick buried oxide layer that isolates the optical mode and prevents light leakage into the substrate. The device is initially patterned via electron beam lithography followed by an inductive coupled plasma reactive ion etch (ICP RIE) of 220 nm-thick silicon layer of the SOI substrate. After silicon etch an 800 nm-thick passivating layer of silicon dioxide was deposited via plasma enhanced chemical vapor deposition (PECVD).

The photonic thermometer described in this work is a Si PhCC device (Fig. 1), operating in the telecom frequency range. The PhCC, similar to a macroscopic Fabry-Perot cavity, is sensitive to changes in effective length. Linear expansion due to temperature or strain and local changes in refractive index due to temperature (thermo-optic effective), strain and/or environment (e.g. humidity or gas pressure) lead to mode frequency shift. For the case of a temperature sensor, the goal is to minimize the impact of other variables while leveraging the thermo-optic coefficient of silicon to realize highly sensitive thermometers. Silicon with a thermo-optic coefficient that is ≈100× larger than its linear expansion coefficient, is one of the best materials to build a photonic thermometer. The sensor consists of a silicon waveguide ($w = 800$ nm; $h = 220$ nm) that has a cavity at its center. The design of the cavity follows a deterministic approach of Quan and Loncar [23]. Two symmetrical Bragg mirrors made of one-dimensional array of holes etched in the nano-waveguide are placed on the opposite sides from the cavity. The diameters of the holes in the Bragg mirrors are monotonically tapered from 170 nm, at the edge, to 200 nm, at the center, to achieve a Gaussian field profile within the cavity, which minimizes radiation losses and maximizes the Q of the cavity [23]. The light was coupled into the cavity via an evanescent coupling from an adjacent 510 nm-wide bus waveguide placed within 250 nm of the PhCC (Fig. 1). Focusing grating couplers were utilized as a means for efficient coupling of light from an optical fiber in/out of the photonic device with coupling losses on the order of −4 dB per coupler.

The photonic chip with integrated PhCC temperature sensors was pigtailed using v-groove fiber array and low viscosity UV curable adhesive (Norland) i.e. transparent at 1550 nm. Following this step the photonic chip was lowered into a glass tube (with a diameter of approximately 12 mm). A small amount of dry magnesium oxide (MgO) is added to the glass tube to improve heat-exchange between the chip and the tube walls. Lastly, the tube was back filled with argon gas and sealed with epoxy.

2.2. Experimental setup

In our experiments, a tunable extended cavity diode laser (New Focus TLB-6700)[1] was used to probe the photonic devices. A small amount of laser power was immediately picked up from the laser output for wavelength monitoring (HighFinesse WS/7) while the rest, after passing through the photonic device via grating couplers was detected by a large sensing-area power meter (Newport, model 1936-R). The assembled photonic thermometer was placed in a cylindrical aluminum block (25 mm diameter, 170 mm length). The cylinder has two 150 mm deep blind holes for accommodating a calibrated thin film platinum resistance thermometer (PRT) and the sealed in a glass tube photonic thermometer, respectively. The metal block along with the sealed in glass tube photonic thermometer was placed inside the dry-well calibrator (Fluke 9170). The dry-well calibrator's temperature was controlled by an automated LabVIEW program, which thermally cycled the bath between measured temperatures. The program also added a 30 min settling delay for temperature equilibration between the bath and the photonic thermometer. Five consecutive scans were recorded at each temperature and the photonic sensor was thermally cycled three times and once in the follow-up cycles 800 h later. The recorded data was fitted using a piecewise polynomial fitting routine to extract peak center, peak height and peak width as a function of temperature. The peak temperature (343 K) is kept well below the glass transition temperature of the UV-curable epoxy (404 K) to ensure thermo-mechanical stability of the packaged device.

3. Results and discussion

Fig. 2A shows transmission spectra of PhCC measured in the wavelength range between 1520 nm and 1570 nm. In the measured wavelength range the PhCC has four different modes with Q-factors of ≈10^4 and a free spectral range of ≈9.4 nm. All four

[1] Disclaimer: Certain equipment or materials are identified in this paper in order to specify 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 materials or equipment identified are necessarily the best available.