Ring Resonator Thermometry

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***Abstract* – We report on our study of temperature response of ring resonator based sensors and their interchangeability over a wide temperature range. Our results suggest that with a proper fabrication process control the interchangeability in photonic thermometers can be on a 0.2 °C tolerance band.**

Keywords – ring resonator, photonic thermometer, temperature sensors

1. Introduction. Temperature measurements play a central role in all aspects of modern life including manufacturing, medicine and environmental engineering controls [1, 2]. Despite the ubiquity of thermometers, the underlying technology, resistance measurement of a thin metal film or wire, has been slow to advance [3, 4]. Though resistance thermometers can routinely measure temperature with uncertainties as low as 10 mK, they are sensitive to environmental variables, such as humidity and mechanical shock, which causes the resistance to drift over time requiring frequent off-line, expensive, and time consuming calibrations [3]. In recent years there has been considerable interest in developing photonic devices as an alternative to resistance thermometers [5-7]. Extending the concepts from Kim *et al.* [8], we demonstrated that silicon ring resonator devices show temperature sensitivity of ≈ 77 pm/K with a noise floor of ≈ 80 µK [9]. Recently, we undertook a systematic survey of ring resonator parameter space that aimed to optimize the device performance while achieving consistent results [10, 11]. Our results suggest that consistently high performance temperature sensors are obtained from the zone of stability (*ring waveguide width* > 600 nm, *air gap* ≈ 130 nm and *ring radius* > 10 µm) such that quality factors are consistent ≈ 10^4 and the temperature sensitivity is consistently in the range of 80 pm/K to 85 pm/K range [11].

In this work, we extend upon our previous work and examine the temperature dependent response of evanescently coupled ring resonator devices over the temperature range of 20 °C to 135 °C. Our results demonstrate that for an individually calibrated sensor the fit error varies from 0.02 °C to 0.11 °C. A comparison of the same device fabricate across different chips in the same batch reveals a significant variation in temperature response, though our results do suggest that with better device fabrication process control it may be possible to achieve device inter-changeability on a 0.2 °C wide band.

2. Experimental. The photonic device consists of a ring resonator coupled to a straight-probe waveguide, with 610 nm × 220 nm cross-section designed to assure a single-mode propagation of the transverse-electric (TE) light at 1550 nm. For the three devices examined, the structural parameters (ring waveguide width/air gap/ring radius) were centered in the zone of stability (Device A: 610 nm/130 nm/15 µm; Device B: 610 nm/130 nm/11 µm; Device C: 610 nm/140 nm/20 µm). The photonic chip was fabricated using standard CMOS (complementary metal oxide semiconductor) technology using a silicon-on-insulator (SOI) wafer with a 220 nm thick layer of silicon on top of a 2 µm thick buried oxide layer. The fabrication of silicon devices itself was performed at LeTI[1] (Laboratoire d'Electronique et de Technologie de l'Information, France) facility. Grating couplers where utilized as a means for efficient free space coupling of light in/out of the photonic device. Coupling losses were approximately 4 dB per coupler.

In our experiments, a tunable extended cavity laser (TLB-6700) was used to probe the ring resonator. A trace laser power was immediately detected 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 photonic chip was mounted on a 3-axis stage (Newport) in a temperature controlled enclosure.

3. Results and Discussion. Over the temperature range of 20 °C to 135 °C the photonic ring resonators show a mean linear slope of 83.6 pm/°C and quality factor of 10^4, indicating excellent temperature sensitivity. As shown in Figure 1, the sensor response when individually fitted to a quadratic equation effectively minimizes the fit residuals. This result is in agreement with our previous examination of silicon waveguide Bragg (Si WBG) thermometer [12]. The standard

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deviation of fit residual (σ_R) varies from 0.02 °C to 0.11 °C (Figures 1 and 2) showing an apparent bimodal distribution for σ_R. Bimodal distribution in σ_R would suggest a systematic defect or structural variance likely due to fabrication variations. We note that the fit error contains contributions from the error in peak center estimation as well as fitting the quadratic function to the overall data. Based on our previous work with Si WBG [12], we anticipate the total fit error will dominate the combined expanded uncertainty of any ring resonator based thermometer. Our results suggest that, currently, ring resonator devices could offer measurement uncertainties that may be competitive with a wide range of resistance thermometers including platinum resistance thermometers.

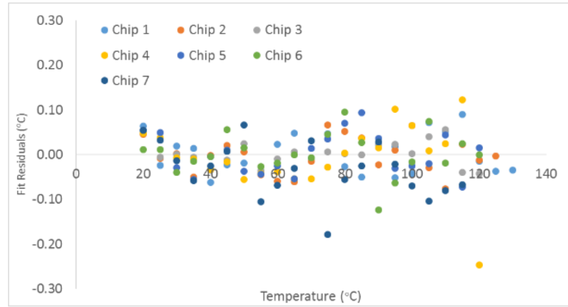

Figure 1: Residuals from quadratic fit to device C do not show any systematic structure suggesting a quadratic fit is sufficient to describe the temperature behavior of photonic ring resonators.

We have examined the feasibility of device inter-changeability in photonic thermometers. In this analysis, for each device, the fitted polynomial coefficients taken from one chip were used to fit the data for the same device from other chips that were randomly selected from the entire batch. The residuals thus calculated allow us to determine how closely different devices from the same batch perform. As shown in Figure 2, the residuals for device A and B show significant variance. On the other hand, for device C the residuals for 6 out of 7 chips are less than 0.1 °C. These results suggest that with a better fabrication process control, photonic thermometers could achieve the same level of inter-changeability that is available with resistance thermometers.

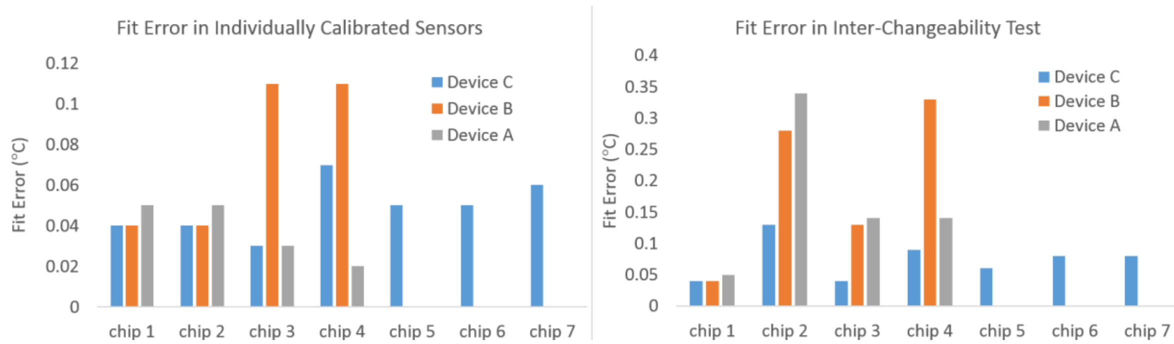

Figure 2: Fit errors in individually calibrated devices and inter-changeability test.

4. Summary. We examined the response of ring resonator devices over the temeprautre range of 20 °C to 135 °C. Our results indicate the temeprautre response of an individual device shows fit residuals of ≈0.05 °C. However, a cross-device comparison reveals significant variation between devices and chips that arises due to routine fabrication errors. Our results suggest that with proper device fabrication process control interchangeability in photonic thermometers can be winin a 0.2 °C tolerance band.

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