

Towards Reproducible Ring Resonator Based Temperature Sensors

Nikolai KLIMOV, Michaela BERGER, * Zeeshan AHMED

Thermodynamic Metrology Group, National Institute of Standards and Technology,
Gaithersburg, MD 20899, USA
E-mail: zeeshan.ahmed@nist.gov

Received: 24 June 2015 /Accepted: 30 July 2015 /Published: 31 August 2015

Abstract: In recent years photonic devices have emerged as a powerful tool for developing novel, high-sensitivity sensors. In particular, tremendous progress has been reported in developing photonic temperature sensors using a wide variety of materials including optical fiber and on-chip silicon photonic devices. We recently reported on ultra high sensitivity temperature sensor based on silicon ring resonator structure that has a noise floor of 80 μ K. Here we have systematically examined the impact of structural parameters on the performance of silicon ring resonator photonic thermometers. Our results suggest that consistently high performance temperature sensors are obtained from the zone of stability (*waveguide width* > 600 nm, *air gap* \approx 130 nm and *ring radius* > 10 μ m) such that quality factors are consistent $\approx 10^4$ and the temperature sensitivity is in the 70 pm/K to 80 pm/K range. The zone of stability identified in this work is a useful starting point for future testing of inter-changeability wafer-scale produced sensors.

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Keywords: Photonic sensors, Ring resonator, Temperature, Thermo-optic coefficient, CMOS compatible.

1. Introduction

In recent years there has been considerable interest in developing photonic sensors that leverage advances in frequency metrology in order to enable generational improvements in sensing capabilities while reducing the cost of sensor ownership. Considerable effort has been expended in developing novel photonic (bio) chemical sensors to enable reliable, cost-effective, pervasive monitoring of environmental and health specific variables including glucose [1], pH [2] and temperature [2-4].

In general, photonic sensors exploit changes in a material's properties, such as the thermo-optic effect to enable sensitive measurements. For example, synthetic sapphire's intrinsically high thermo-optic effect has been exploited to enable highly sensitive temperature measurement by measuring microwave frequency shifts of resonant whispering gallery

modes [5-6]. An optical analog of this, using infrared light to probe silicon ring resonator devices has demonstrated that such devices respond rapidly to small temperature variations [7] and can be used to detect temperature differences as small as 80 μ K while being insensitive to changes in humidity [4]. Alternative optical devices include fiber Bragg gratings (FBG) which have been demonstrated to exhibit temperature dependent shifts in resonant wavelength of 10 pm/K [8-11].

Development of mass producible, high performance thermometers requires that we identify a parameter space where devices can be reproducibly fabricated to produce high quality-factors (*Q*-factors) and high temperature response. This requires identifying structural parameters where the device is relatively insensitive to small fabrication errors that are likely to be encountered with CMOS (complementary metal-oxide semiconductor)

compatible manufacturing technology. Here we have carried out a systematic survey of structural parameters of a ring resonator device to optimize its performance. Our results point to a zone of stability [12] (waveguide width, $w > 600$ nm, air gap, $g \approx 130$ nm and ring radius, $r > 10$ μm) in the parameter space where we consistently obtain quality factors of $\approx 10^4$ and the temperature sensitivity is in the 70 pm/K to 80 pm/K range [13].

2. Experimental

The photonic device consists of a ring resonator coupled to a straight-probe waveguide. The cross-section is designed to ensure single-mode propagation of the transverse-electric (TE) light (the electric field in the slab plane) at the telecom wavelength (1550 nm) and air gap for evanescent coupling between the resonators and the probing waveguide. The photonic chip was fabricated using standard CMOS technology on silicon on insulator (SOI) wafer with a 220 nm thick layer of silicon on top of a 2 μm thick buried oxide layer to isolate the optical mode and prevents loss to the substrate. The fabrication of the silicon devices was performed in two batches by IMEC and LETI (Laboratoire d'Electronique et de Technologie de l'Information, France) facilities, respectively.

In our experiments, a tunable single-mode diode laser (New Focus, TLB-6700)^a was used to probe the ring resonator (Fig. 1).

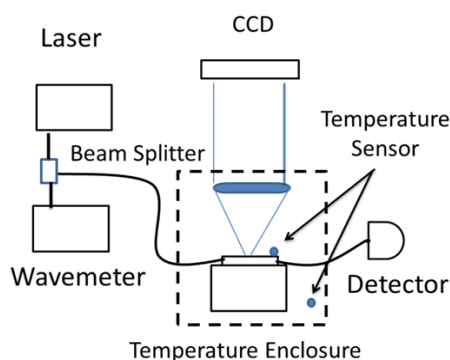


Fig. 1. Schematic of experimental setup.

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, was detected by a large sensing-area power meter (Newport, model 1936-R). The photonic chip itself is mounted on a

^a 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.

3-axis stage in a two-stage temperature controlled enclosure. Input from a platinum resistance thermometer from each stage is fed to its respective proportional-integral-derivative controller that drives a thermoelectric cooler (Laird Technologies) maintaining a fixed temperature to within 20 mK. In this study, temperature-dependent measurements were carried out at 22 °C, 24 °C, 27 °C and 29 °C. We have previously demonstrated that the 1 μm thick protective oxide layer deposited on the device makes it insensitive to changes in humidity.

3. Results and Discussion

We systematically varied the waveguide width ($w = 480$ nm, 600 nm, 610 nm), air gap ($g = 100$ nm, 115 nm, 130 nm, 145 nm, 165 nm) and ring radius ($r = 9$ μm , 10 μm , 11 μm and 12 μm) over 100 devices to examine the impact of structural parameters on device performance. Variation in waveguide width is expected to impact the effective refractive index of the mode and hence the temperature sensitivity of the device; air gap impacts the coupling losses (κ) which impacts the Q -factors of the resonant modes, meanwhile, the ring resonator radius (r) is expected to primarily impact the FSR. In our initial survey of the 100 devices, we identified 40 devices where at least one resonance was observed over the range of 1520 nm to 1565 nm. None of the devices with waveguide width of 480 nm show any resonances in this range indicating a failure to couple light between the waveguide and ring resonator. For the 40 viable devices at least one FSR was measured at three different temperatures.

As shown in Fig. 2, the FSR values vary inversely with r while Q -factors show an asymptotic dependence on g with highest Q values observed when $g \geq 115$ nm. Temperature sensitivity ($\Delta\lambda/\Delta T$) decreases linearly with r , and asymptotically with g . The largest temperature sensitivity is observed at $g = 100$ nm, however, the Q -factors are only 10^3 . The reduced mode Q -factors likely derive in part from slight fabrication errors e.g. the gap distance between waveguide and ring may deviate slightly from 100 nm or the walls of waveguide and ring may slope downwards, effectively narrowing the air gap. When air gaps > 100 nm the quality factor increases to 10^4 but $\Delta\lambda/\Delta T$ is limited to ≈ 60 pm/K to 80 pm/K. These results suggest device with $g > 115$ nm and radius ≥ 10 μm delivers consistent performance.

In the second batch (Fig. 3) we focused down on the zone of stability and systematically varied the waveguide width ($w = 450$ nm, 510 nm, 610 nm), air gap ($g = 120$ nm, 125 nm, 130 nm, 135 nm, 140 nm, and 150 nm) and ring radius ($r = 11$ μm , 13 μm , 15 μm and 20 μm) over 10 devices to further examine the impact of structural parameters on device performance. In agreement with theory and previous experiments we find that FSR decreases with increasing r . As expected, we find that

temperature sensitivity of these devices is nearly consistent regardless of g or r and varies by 8 % as w is increased from 450 nm to 610 nm. The dependence

of temperature sensitivity on w arises from more of the mode being confined inside the larger silicon waveguide.

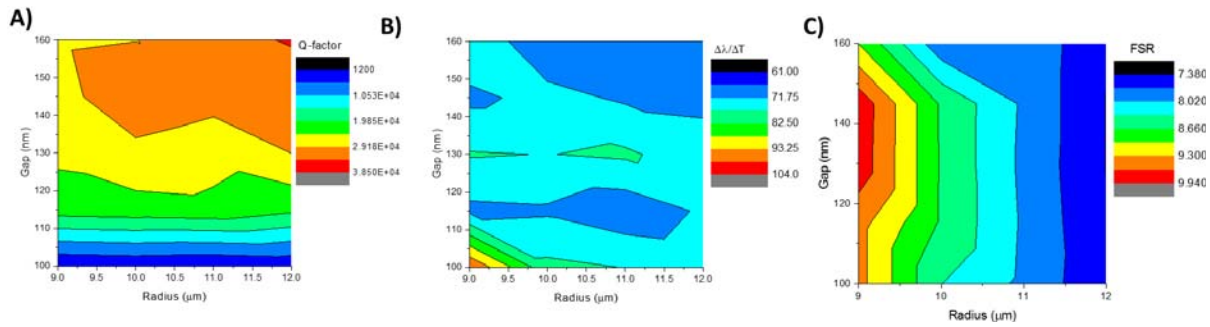


Fig. 2. Impact of structural parameters on (a) Q-factors (b) temperature sensitivity and (c) FSR indicate a zone of stability where consistently high Q-factors and temperature sensitivity is obtained.

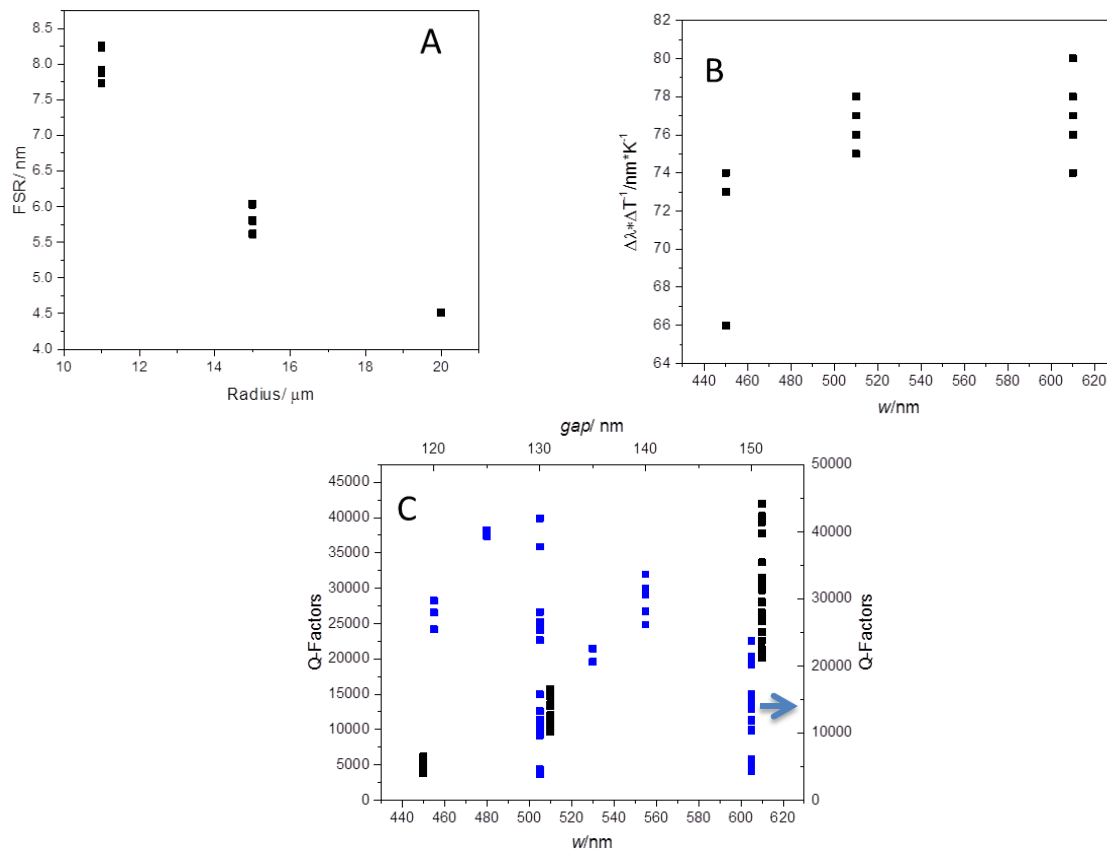


Fig. 3. (A) As expected, the measured FSR decreases linearly with increasing ring radius. (B) The temperature response shows an 8% increase with waveguide size. (C) Resonator Q-factors increase proportionally with waveguide width (black squares), but maximized for devices with air gap of centered around 130 nm.

In agreement with our previous survey of ring resonator structures, we find that devices with $g > 100$ nm and $w > 600$ nm show Q -factors $\approx 10^4$. An examination of the entire dataset however, reveals that Q -factors increase proportionally with w and r with Q -values being generally stable over the range examined. The positive correlation with increasing w and r suggests the Q -factors are being limited by scattering losses. As w gets smaller, less of the mode is confined within the core of the

waveguide thus exposing more of the mode to the waveguide surface. Surface roughness due to fabrication processes can lead to increased scattering losses. Similarly, increasing the ring radius reduces the bending losses which would increase observed Q -factors. Overall, our results indicate that the zone of stability allows us to fabricate consistently high performance devices. The size of the zone could be further expanded by limiting scattering losses at the surfaces and bending losses in the ring resonator.

4. Summary

We have systematically characterized the impact of structural parameters on ring resonator thermometer's performance. Our results indicate that consistently high performance temperature sensors may be obtained from the zone of stability ($w > 600$ nm, $g \approx 130$ nm and $r > 10$ μ m), where the surface scattering and bending losses are minimized.

The zone could be further expanded by developing fabrication procedures that minimize surface scattering losses. The zone of stability will serve as an ideal starting point for future studies of device inter-changeability in wafer scale production.

Acknowledgements

The authors would like to thank Wyatt Miller's assistance.

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