Systematic Examination of Ring Resonator Structures for Temperature Sensing Applications

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ABSTRACT

In recent years silicon photonic devices have emerged as a powerful tool for devleoping novel, high-sensitivity sensors. In a recent study we systematically examined the impact of structural parameters on silicon ring resonator's performance. In this study, we build upon our previous work and systematically optimize the ring resoantor parameters to consistently obtain high performace temperature sensors.

Keywords: photonics; ring resonator; temperature sensor

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. In general, photonic fiber optic or silicon sensors exploit changes in a material's properties, such as the thermo-optic effect to enable highly sensitive measurements. Recent studies have demonstrated that silicon ring resonator devices respond rapidly to small temperature variations [1] and can be used to detect temperature differences as small as 80 µK while being insensitive to changes in humidity [2]. In a recent study we systematically examined the impact of structural parameters on silicon ring resonator's performance [3]. Our results demonstrated that device optimization requires balancing between waveguide-resonator coupling (κ) and the effective refractive index (β) of the device. We found that for air gaps of 100 nm ($\kappa \approx 0.2$), the quality factors (Q-factors) drop to 10^3, while $\Delta\lambda/\Delta T$ rises to ≈100 pm/K. However, at air gaps of >100 nm the quality factor increases to 10^4 while $\Delta\lambda/\Delta T$ is limited to ≈60 pm/K to 80 pm/K. Development of mass producible, high performance thermometers require that we identify a zone of stability in the parameter space where devices can be reproducibly fabricated to produce high Q's and high temperature response. This requires identifying structural paramters where the deivce is relatively insensitive to small fabrication errors that are likely to be encountered with CMOS (complementary metal-oxide semiconductor) compatible manufacturing technologies. Here we have focused on the zone of stability as our starting point to optimize performance of photonic thermometers. Our results indicate that device performance in the zone of stability is least sensitive to fabricaiton error.

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 techniques on a 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 by the LETI (Laboratoire d'Electronique et de Technologie de l'Information, France) facility.

In our experiments, a tunable single-mode diode laser (New Focus, TLB-6700) was used to probe the ring resonator (see Fig 1). 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 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 □m thick protective oxide layer deposited on the device makes it insensitive to changes in humidity.

3 RESULTS AND DISCUSSION

We have 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 examine the impact of structural parameters on device performance. The variation in waveguide width is expected to impact the n_e of the mode, g impacts the coupling losses (κ), while ring resonator size is expected to primarily impact the free spectral range (FSR). In agreement with theory and previous experiments we find that FSR decreases with increasing r. As expected, we find that temperature response ($\Delta\lambda/\Delta T$) of these devices is more or less consistent regardless of g or r and varies by only 8% as w is increased from 450 nm to 610 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. Lastly, we note that previously observed dependence of *Q*-factors on the air gap could suggest that small gap values (100 nm) fabrication errors could dominate scattering losses. For example, in narrow gap devices, where obtaining consistently flat surfaces down a crevasse is a difficult challenge, the observed decrease in *Q*-factors may derive from slight irregularities in etched surfaces. Overall, our results indicate that the zone of stability, as previously, identified allows us to fabricate consistently high performance devices. The size of the zone could be further expanded by limiting scattering loses at the surfaces and bending loses in the ring resonator.

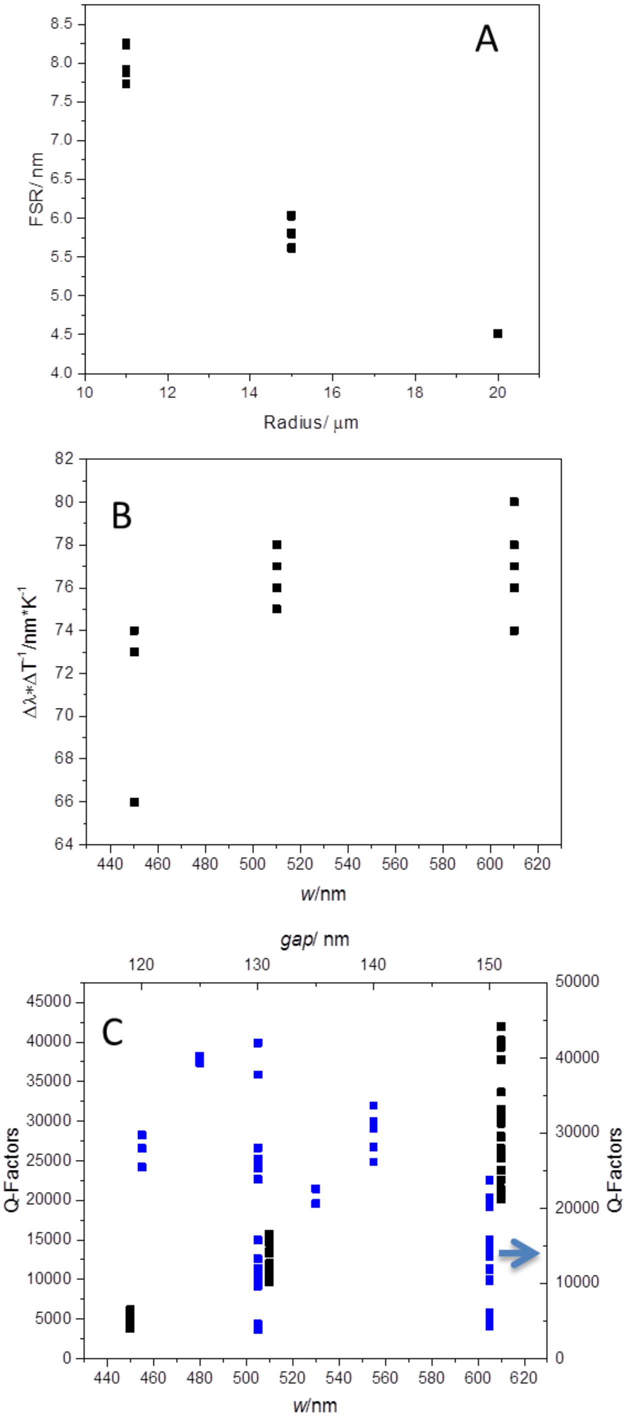

Figure 1: A) As expected, the measured FSR (free spectral range) decreases linearly with increasing ring radius. B) The temperature response shows an 8% increase with waveguide size. C) Resonator Q-factors increase proportionally with waveguide width (black squares), but maximized for devices with air gap of centered around 130 nm.

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 ≈130 nm and r >10 μm), because the surface scattering and bending loses are minimized. The zone could be further expanded by developing fabrication procedures that minimize surface scattering loses.

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