Characterization of Ring Resonator Structures for Applications in Photonic Thermometry

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Abstract: We have systematically examined the impact of structural parameters on silicon ring resonator-based photonic temperature sensor's performance by systematically varying the ring radius, waveguide width and gap separating the ring and waveguide.

1. Introduction

In recent years there has been considerable interest in developing photonic sensors that leverage advances in frequency metrology to enable generational improvements in sensing capabilities. 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]. Given the wide application landscape, a wide variety of photonic temperature measurement solutions have been proposed and developed including functionalized dyes, hydrogels, fiber optic-based sensors and silicon photonic devices.

In general photonic fiber optic or silicon sensors exploit changes in a material's properties e.g. an induced change in material's refractive index to enable highly sensitive measurements. In recent years the dependence of material's refractive index on temperature i.e. the thermo-optic effect has been exploited to for highly sensitive temperature measurements. For example, synthetic sapphire's intrinsically high thermo-optic effect has be exploited for highly sensitive temperature measurement by measuring microwave frequency shifts of monocrystalline sapphire's resonant whispering gallery modes [5, 6]. An optical analog of this, using infrared light to probe strain-free fiber Bragg gratings (FBG), exhibits temperature dependent shifts in resonant wavelength of 10 pm/K [7-10]. Recent studies that demonstrated that silicon ring resonator devices respond rapidly to small temperature variations [11] and can be used to detect temperature differences as small as 80 μK while being insensitive to changes in humidity [4]. Similar ring resonator type devices have been functionalized to enable bio-chemical sensing [12].

Here we have carried out a systematic examination of the impact of structural parameters on device's performance. Our results indicate that device optimization requires achieving a desired balance between extrinsic coupling loses (κ) and the propagation constant (β) values e.g. our results indicate that resonance quality factors of 10^4 are consistently achieved when $\kappa \approx 0.2$, while highest temperature response of the resonance wavelength ($\Delta\lambda/\Delta T$) is achieved when $\kappa \approx 0.07$ to 0.5 and $\beta \approx 0.0172$.

2. Results and Discussion

We have systematically varied the waveguide width (w = 480 nm, 600 nm, 610 nm), air gap (L_{gap} = 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 n_{eff} of the mode, L_{gap} impacts the coupling losses (κ) while ring resonator is expected to primarily impact the free spectral range (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 no 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 1a, the FSR values vary inversely with r while Q-factors show an asymptotic dependence on L_{gap} *(or* κ*)* with highest Q values observed at $\kappa < 0.2$ ($L_{gap} \geq 115$ nm). Temperature response ($\Delta\lambda/\Delta T$) decreases linearly with r, and asymptotically with L_{gap} (Fig 1b). With data available on only two waveguide widths it is difficult to draw any significant conclusions on its impact on sensor response. The observed dependence of ($\Delta\lambda/\Delta T$) on L_{gap} and r can be better understood by examining the behavior of propagation constant (β) on structural parameters. As shown in Fig 1c the magnitude of β steadily declines with increasing r, a result in line with observed behavior of FSR (Fig 1a). The range of β values observed narrows as L_{gap} is increased, effectively narrowing the range of the effective refractive index n_{eff} and its temperature response $\Delta n_{eff}/\Delta T$ as κ increases. The large variability in β values (0.01705 to 0.01725) observed at L_{gap} = 100 nm may derive in part from slight fabrication errors, e.g., the gap distance between the waveguide and the ring may deviate slightly from 100 nm or the walls of the waveguide and the ring may slop downwards, effectively narrowing the air gap.

For thermometry applications, it would advantageous to develop devices that are more tolerant of slight fabrication errors, have a large operating range, can resolve small temperature differences while retaining sufficiently high temperature response. Our results here indicate that highest temperature response ($\Delta\lambda/\Delta T \approx 100$ pm/°C) is achieved when L_{gap} = 100 nm ($\kappa \approx 0.5$, $\beta \approx 0.01705$ to 0.01725) and are r is minimized. Such devices however consistently show low Q-factors ($Q \approx 10^3$) and small FSR which adversely impacts their operating range and ability to resolve small ΔT changes. Devices with large L_{gap} and r values enable fabrication of consistently high Q-factors ($Q \approx 10^4$), large operating range devices; however the temperature response decreases by 20% to 40%. Our results thus indicate that the parameter space of $\kappa \approx 0.1$ to 0.2 and $\beta \approx 0.01710$ to 0.01725 holds the best promise for consistent fabrication of high performance photonic thermometers.

3. Summary

We have systematically characterized the impact of structural parameters on ring resonator's temperature sensing performance. Our results indicate that device optimization requires a striking balance between two competing parameter, κ and β. We determine that the parameter space bounded by $\kappa \approx 0.1$-0.2 and $\beta \approx 0.01710$-0.01725 is likely to be ideal for enabling consistent fabrication of high performance photonic thermometers.

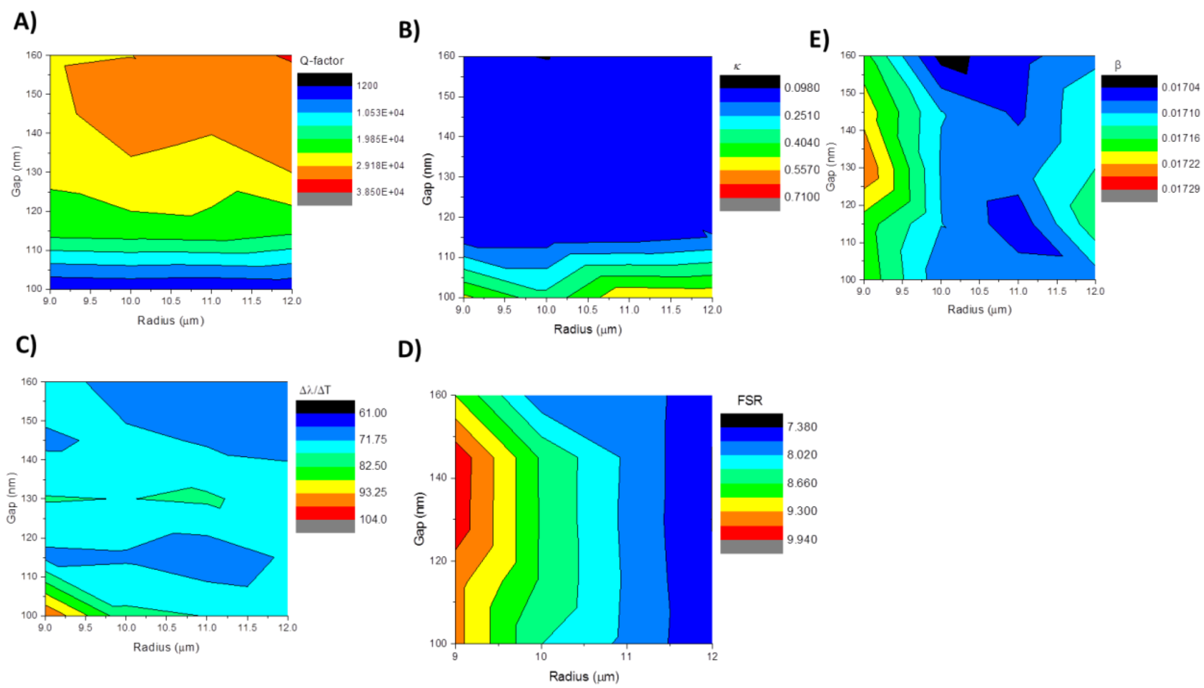

Fig. 1: Impact of structural parameters on a) FSR b) Q-factors c) temperature response d) propagation constant and e) coupling loss.

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