Sant'Anna
Scuola Universitaria Superiore Pisa

Silicon photonic temperature sensor employing a ring resonator manufactured using a standard CMOS process

by

Yaman Parasher

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Prof. Dr. Philippe Velha & Dr. Yisbel Marin
Institute of Communication, Information & Perception Technologies (TeCIP)
Sant'Anna School of Advanced Studies

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Abstract

Integrated photonics technology has great potential for enhancing the performance and reducing the volume and cost of optical sensing systems. Among many integrated photonic structures, silicon microring resonators have received much attention for both sensing and interrogation. Particularly, the high quality-factor of the microring resonators and the large thermo-optic coefficient and high thermal conductivity of silicon make them attractive for temperature sensing and thermally-tunable-filter-based interrogation.

The report was developed around the paper *"Silicon photonic temperature sensor employing a ring resonator manufactured using a standard CMOS process"*, where an ultrasmall integrated photonic temperature sensor has been proposed and demonstrated which incorporates a silicon ring resonator linked to a vertical grating coupler.

To explain overview of different concepts associated with this research paper,the whole report is segregated into 4 chapters where the first chapter starts with an introduction to the Silicon Photonic Temperature Sensors highlighting way to maximize resolution,sensitivity ,sensing range by employing compact interrogator structures. Second chapter begin with a brief on the the concept of sensitivity in ring resonator highlighting its main figure of merits like Sensitivity, FSR, FWHM, Sensing Range together with a brief on the working principle of photonic interrogators.In third chapter an extensive overview of the assigned paper was discussed.Lastly in fourth chapter a critical assessment was done with the follow up work of this paper to get a clear idea about advances in this regime followed with few points towards the probable future work.

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Abbreviations

PIC	**P**hotonic **I**ntegrated**C**ircuit
TO	**T**hermo **O**ptic
CTE	**C**oefficient of **T**hermal **E**xpansion
FOM	**F**igure **O**f **M**erit
FWHM	**F**ull **W**idth **H**alf **M**aximum
FSR	**F**ree **S**pectral **R**ange
WBG	**W**aveguide **B**ragg **G**rating
PD	**P**hoto **D**etector
FBG	**F**iber **B**ragg **G**rating
FP	**F**abry **P**erot
SRRTFs	**S**ilicon **R**ing **R**esonator based **T**hermal **F**ilters
MEMS	**M**icro **E**lectro **M**echanical **S**ystem
CMOS	**C**omplementary **M**etal **O**xide **S**emiconductor
Q-Factor	**Q**uality **F**actor
SOI	**S**ilion **O**n **I**nsultaor
TM	**T**ransverse **M**agnetic
TE	**T**ransverse **E**lectric
CRR	**C**ascaded **R**ing **R**esonator
TP	**T**emprature **P**eriod

Chapter 1

Introduction

1.1 Silicon Photonic Temperature Sensors

In recent times ,optical temperature sensors have received much attention as attractive alternatives to standard electrical resistance thermometers. Although the resistance thermometers have been widely used with advantages of easy implementation and fine resolution (i.e., ∼0.01 °C), the susceptibility to environmental disturbance such as electromagnetic interference, mechanical shock, and humidity causes the resistance to drift over time [1].Hence, they require periodic, time consuming calibration, which potentially increases the sensor ownership cost.Meanwhile, optical temperature sensors are robust to such environmental disturbances. Further, they have advantages of having better performance in harsh environments (i.e. high temperature and corrosive medium) and multiplexing capability [2].

For optical temperature sensing till date, fiber Bragg grating (FBG) sensors and extrinsic Fabry-Perot (FP) cavity sensors have been widely used all over the world. However, temperature sensitivity of the FBG sensors comes out to be low (e.g. $10pm/°C$) due to the low thermo-optic coefficient of silica glass (i.e. $1.0 \times 10^5/°C$). Therefore, bulky and expensive fine-resolution sensor interrogators are usually required in this case for precise temperature monitoring. Note that the sensing resolution is determined by the sensor sensitivity and the resolution of the sensor interrogator altogether. For example, a 10 pm/°C sensitivity of FBG sensor with a 1 pm resolution of sensor interrogator provides only 0.1°C sensing resolution.

Compared to the FBG sensors, the extrinsic FP cavity sensors have demonstrated much higher temperature sensitivity. However, fabrication of the extrinsic FP cavity sensor is complex & thus ain't compatible with batch processing, which are obstacles to low-cost and high-yield fabrication.Furthermore, these fiber optic sensors are not suitable for on-chip temperature monitoring, which is often required for biological and chemical analyses in lab-on-a-chip microsystems.

Silicon photonic temperature sensors can be an attractive solution to address these drawbacks of the optical temperature sensors[3]. In other words, the large thermo- 1.86×10^{-4} optic coefficient of silicon (i.e.,/°C) & the CMOS compatible fabrication of silicon photonic structures help build a compact, on-chip temperature sensor with enhanced temperature sensitivity. Integrated photonics technology thus possess great potential for enhancing the performance and reducing the volume and cost of optical sensing systems, including sensors and interrogators.

For example, integrated photonic structures utilizing nanowire waveguides or photonic crystals have rendered ultracompact sensors with high sensitivity. Furthermore, the integration of multiple photonic sensors into a micro-scale platform has enabled multi-parameter sensing with a compact device footprint[4]. On the other hands, interrogators, which occupy most of the sensing system volume, can be integrated into a miniaturized photonic integrated circuit (PIC) chip in contrast to the bulky and slow interrogators[5].

In particular, silicon Photonic Integrated Circuits (PICs) can be monolithically integrated with complementary metal-oxide-semiconductor (CMOS) circuitry, which helps reduce the volume and cost of optical sensing systems significantly [6]. Among many integrated photonic structures, silicon microring resonators have received much attention for both sensors and interrogators. Particularly, the high quality-factor of the microring resonator and the large thermo-optic coefficient and high thermal conductivity of silicon make them attractive for temperature sensors and interrogators.

Current on-chip optical interrogators are mainly based on two approaches:

- Spectrometers based on diffraction gratings & photodetector arrays
- Tunable filter based devices

The former often makes use of a planar diffraction grating such as arrayed waveguide gratings[7] and echelle gratings[8], to acquire spectrum in parallel, which are then detected by using a large array of high-speed photodetectors (PDs). While this approach can achieve fast interrogation, it often requires a large device footprint.

The latter approach (tunable filter based devices) makes use of a tunable wavelength filter and a single PD to tune the resonance wavelength in serial, and then detect the time-domain signal converted from the spectral information. The resolution of these interrogators is determined by the linewidth of the tunable wavelength filter . By using a narrow-linewidth filter, fine-resolution interrogation can be realized with a small device footprint, and multiple optical sensors can be simultaneously interrogated.

Most of these tunable-filter-based interrogators are usually based on micro-electro-mechanical-system (MEMS) Fabry-Perot (FP) interferometers . Recently, silicon-ring-resonator-based thermally tunable filters (SRRTFs) have received much wider attention due to the following reasons,

- Compared with MEMS FP tunable filters, SRRTFs render a simple fabrication process as well as better long-term reliability due to absence of any moving part
- The large thermo-optic coefficient and high thermal conductivity of silicon enable SRRTFs to achieve efficient, wide-range wavelength tuning
- High quality-factor (Q-factor) ring resonators provide excellent wavelength selectivity, which enables fine-resolution interrogation
- High refractive-index contrast of the silicon-on-insulator (SOI) structure can help achieve an ultra-compact device
- CMOS compatible fabrication process of these filters opens up the opportunity for monolithic integration of all the necessary photonic components, including SRRTFs, light emitting diodes, PDs, couplers, and waveguides for optical interconnection, which could ultimately lead to miniaturization and cost reduction of optical sensor interrogators

However, most of reported SRRTF interrogators suffer from slow interrogation speed (less than a few Hz), which makes them not suitable for monitoring of dynamic parameters. To overcome this recently, a 100 kHz of high-speed interrogation system based on an SRRTF is reported by H.T. et al. [9]. Here, the high-speed interrogation system can be used for real-time monitoring of dynamic parameters which could proved to be a suitable option for compact ultra sensitive photonic temperature sensors.

Chapter 2

Design Overview

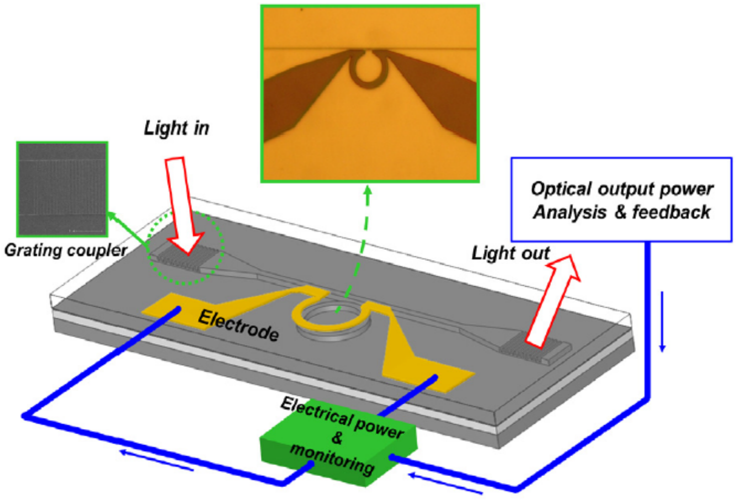

FIGURE 2.1: Configuration of the proposed temperature sensor based on a silicon resonator

This chapter starts with a brief introduction of sensitivity in ring resonator followed by description of its performance metrics in a typical all pass ring resonator structure based temperature sensor as shown in Figure 2.1 .Next, a brief detail about the potential losses in the structure were also discussed in the same section. Lastly, a brief working principle of Silicon photonic interrogators was presented to give an idea on what does it takes to build such ultra sensitive compact portable temperature sensors using ring resonators.

2.1 Sensitivity in Ring Resonator

The resonance of the ring resonator depends on the optical roundtrip length of the ring, and the losses accumulated (all loss mechanisms combined, including coupling to bus waveguides). Therefore, ring resonators will be sensitive to a multitude of effects. that is why they are also attractive for use in sensing applications[10].

Sensitivity is usually defined as the amount of wavelength shift $\Delta\lambda_r$ caused by a certain amount of whatever effect we are studying, be it temperature, physical deformation or compositional changes of the waveguide core or cladding. A shift of this resonance wavelength $\Delta\lambda_r$ is essentially caused by a change of the effective index of the resonant mode n_f.

For an SOI device like this ring resonator,the temperature sensitivity is related to the thermo-optic effect and thermal expansion of the ring waveguide by

$$S = \frac{d\lambda_r}{dT} = \frac{\lambda_r}{n_g}(\frac{\partial n_f}{\partial T} + n_f \alpha_{Si}) \tag{2.1}$$

where n_f is the effective index of the waveguide and α_{Si} is the coefficient of thermal expansion of silicon.

The group index of the waveguide n_g can be expressed as,

$$n_g = n_f - \lambda(\frac{\partial n_f}{\partial \lambda}) \tag{2.2}$$

Note that $\alpha_{Si}(2.5 \times 10^6/°C)$ is $\sim$ 100 times smaller than the thermo-optic coefficients of silicon and silicon dioxide $1.86 \times 10^4/°C$ and $1 \times 10^5/°C$, respectively.

Therefore, the temperature sensitivity is dominated by the thermo-optic effect (i.e. $\partial n_f/\partial T$), which is closely related to the mode confinement of the waveguide. The mode confinement can be controlled by changing the waveguide geometric parameters. For an SOI device with a fixed waveguide thickness, the mode confinement increases with the waveguide width.

The FSR which is generally defined as the wavelength range between two resonances is determined mainly by the ring radius and waveguide width. For a chosen waveguide width, n_g is fixed, and thus the FSR can be controlled by changing the ring radius

$$FSR = \frac{\lambda_r^2}{n_g 2\pi R} \tag{2.3}$$

,where R is the ring radius. For an SOI device like this ring resonator, the temperature sensitivity and Free Spectral Range(FSR)can be controlled by changing the waveguide width and ring radius.

Temperature sensitivity of an individual ring resonator expressed above can also be written as,

$$S_i = \frac{FSR_i}{TP_i} \tag{2.4}$$

Here, the temperature period TP (i.e. the sensing range) of a ring resonator is related to its FSR and temperature sensitivity, and therefore, for a chosen waveguide width it is determined by the ring radius.

Similarly,another crucial factor involved for the performance evaluation of a typical sensor is the full width at half maximum (FWHM) of the resonance spectrum[11],which generally expressed as,

$$FWHM = \frac{(1-ra)\lambda_r^2}{\pi n_g L\sqrt{ra}} \tag{2.5}$$

,where r is the self coupling coefficient, $a^2 = exp(-\alpha L)$, where α is the power attentuation coefficent[1/cm], L is the round trip length, where $L = 2\pi R$

Also,the finesse is defined as the ratio of FSR and resonance width,

$$Finesse = \frac{FSR}{FWHM} = \frac{\pi\sqrt{ra}}{1-ra} \tag{2.6}$$

It is a measure of the sharpness of resonances relative to their spacing.

Another important property of optical waveguide resonator-based sensor is its quality factor, Q, defned as the number of optical oscillations until the resonating energy decays to 1/e of its maximum value. In more simpler terms it is a measure of the sharpness of the resonance relative to its central frequency. High quality factor means improved minimum detectable wavelength shift (leading to improved limit of detection. The quality factor (Q-factor) is thus expressed as,

$$Q - factor = \frac{\lambda_r}{FWHM} = \frac{\pi n_g L\sqrt{ra}}{\lambda_r(1-ra)} \tag{2.7}$$

Physical meaning of the finesse and Q-factor relates to the number of round-trips made by the energy in the resonator before being lost to internal loss and the bus waveguides. Propagation losses in silicon wires originate from multiple sources, and recent advances in process technology (in various groups) have brought the losses down to 2–3dB/cm with air cladding and less than 2dB/cm with oxide cladding.Light scattering at sidewall roughness is considered to be the strongest effect. Due to the nature of the lithography fabrication process, roughness on the vertical sidewalls of the waveguide is unavoidable. Similarly polarization rotation and coupling to higher order modes, also results in increased losses.The sidewalls are expected to exhibit a larger roughness as the typical fabrication process involves a dry etch process. Sidewall treatments can reduce the roughness, and in turn can help in reducing propagation losses. Therefore nowadays researchers are coming with sensor designs operating at the fundamental quasi-TM mode for less susceptibility the waveguide sidewall roughness in comparison to the quasi-TE mode operation for which precise fabrication of the waveguides is required to decrease the sidewall roughness so that the power attenuation can be reduced significantly.

2.2 Working principle of Silicon photonic interrogators

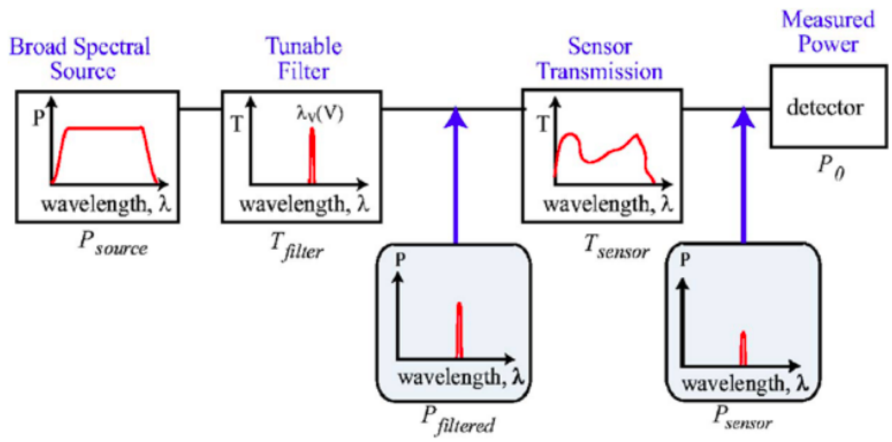

FIGURE 2.2: Schematic of sensor interrogation using a tunable wavelength filter

Silicon photonic interrogators can be categorized into two groups according to their spectrum sampling method:

- Serial sampling
- Parallel sampling.

Silicon photonic interrogators based on the serial sampling method consist of a broadband source, tunable wavelength filter, and photodetector. Figure 2.2 shows the interrogation principle. The broadband source (i.e., P_{Source}) combined with the tunable wavelength filter (i.e., T_{Filter}) produces a narrowband tunable optical source (i.e., $P_{Filtered}$) for scanning across the spectral bandwidth of the optical sensor (i.e. T_{Sensor}). The reflection (or transmission) power intensity from the optical sensor (i.e., P_{Sensor}) is measured by the photodetector. The spectral response of the optical sensor is then reconstructed by calibrating the measured intensity waveform to a fixed wavelength reference.

For the tunable wavelength filter, silicon-ring-resonator-based thermally tunable filters (SRRTFs) have been widely used due to the following advantages.

- Ring resonators provide excellent wavelength selectivity due to their high quality-factor
- Free Spectral Range and Finesse of ring resonators can be easily tailored by changing the in-plane geometric parameters such as a ring radius and ring-to-bus waveguide coupling gap
- High refractive-index contrast of the SOI structure enhances the waveguide mode confinement & reduces the waveguide bending loss.Therefore, it helps build an ultracompact tunable filter
- Large thermo-optic coefficient & high thermal conductivity of silicon helps enable high-speed (∼1 MHz) and wide-range wavelength tuning

Although on-chip spectrometers enable high-speed interrogation of an optical sensor, there exists a tradeoff between the interrogation resolution and device footprint[12]. To achieve fine-resolution interrogation with a wide interrogation range, on-chip spectrometers have to accommodate a large number of waveguides in the arrayed waveguide gratings (or grooves in the diffraction grating) with a corresponding large number of photodetectors, which will significantly increase the device footprint[13].

Chapter 3

Proposed Design

3.1 Structural Overview of the proposed sensor

A 4 m-radius silicon ring resonator was used as a temperature sensor, as shown in Figure 3.1.

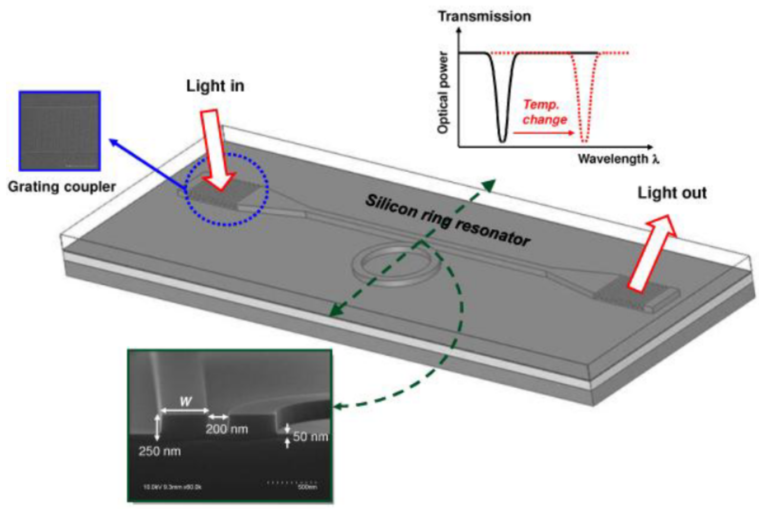

FIGURE 3.1: Configuration of the proposed temperature sensor based on a silicon resonator

The ring is laterally coupled to a bus, which is linked to a grating coupler at either end of the device used for achieving optical coupling. The structural parameters of the waveguide comprising the silicon resonator sensor involved are: a waveguide height of 250 nm, a slab thickness of 50 nm, a ring radius of 4 μm, and a ring-to-bus gap of 200 nm.

3.1.1 Working Principle

When the temperature varies, the refractive index of the silicon is altered by the Thermo-Optic (TO) effect and the circumference of the ring is changed by the thermal expansion effect. It is reported that the overall shift in the resonant wavelength $\Delta\lambda$ due to the temperature is induced by the TO effect $\Delta\lambda_T$ as well as by the thermal expansion effect $\Delta\lambda_L$

$$\Delta\lambda = \Delta\lambda_L + \Delta\lambda_T = \alpha_w \frac{n_f}{n_g}\lambda\Delta T + \frac{\sigma_T}{n_g}\Delta T \tag{3.1}$$

where $\sigma_T \equiv \frac{\partial n_f}{\partial T}$ Here, n_f and n_g are the effective index and the group index of the guided mode of the ring waveguide respectively; ΔT is the temperature change, α_w the coefficient of thermal expansion (CTE), and σ_T the rate of change of the effective index with the temperature.

3.1.2 Device Fabrication Details

The integrated photonic temperature sensor was fabricated by employing the 0.18 μm standard CMOS process. The silicon-on-insulator substrate was 8 inches in diameter and 720μm thick, having a 2-μm thick buried oxide layer coated with a 340-nm thick top-silicon, which was later thinned down to 250 nm prior to the device fabrication. The bus and ring patterns comprising the resonator sensor were created in the top-silicon layer via the photolithography combined with the dry etching. The vertical grating coupler was subsequently formed at both ends of the bus for the light coupling. The sensing resonator was covered with an oxide layer and then underwent a chemical mechanical polishing to achieve a flat surface.

3.1.3 Characterisation Setup

The completed temperature sensor was evaluated by mounting it on a holder placed on a precision stage, whose temperature was adjusted by a built-in thermoelectric cooler and monitored in situ by a k-type thermocouple. A tunable laser, served as the light source and the optical output of the sensor was detected and analyzed by using an optical spectrum analyzer.

3.2 Results & Discussion

In this paper, 83 $pm/^{\circ}C$ of temperature sensitivity was demonstrated with transverse-electric (TE) polarized light, which was the maximum achievable sensitivity under the single mode operation of the ring waveguide at that time. The sensing range was noted to be around 280°C with a 23.4 nm of free spectral range. The sensing resolution was determined by the sensitivity and the resolution of the optical interrogation system. With a 1 pm resolution tunable laser source, 0.01 $pm/°C$ of sensing resolution was achieved.Apart from this, theoretical sensitivity of about of 79 & 72 $pm/°C$ was achieved for the width of 300,400nm respectively. The corresponding quality factor (Q-factor) was ∼20,000, which is high enough to allow for a high sensing resolution.

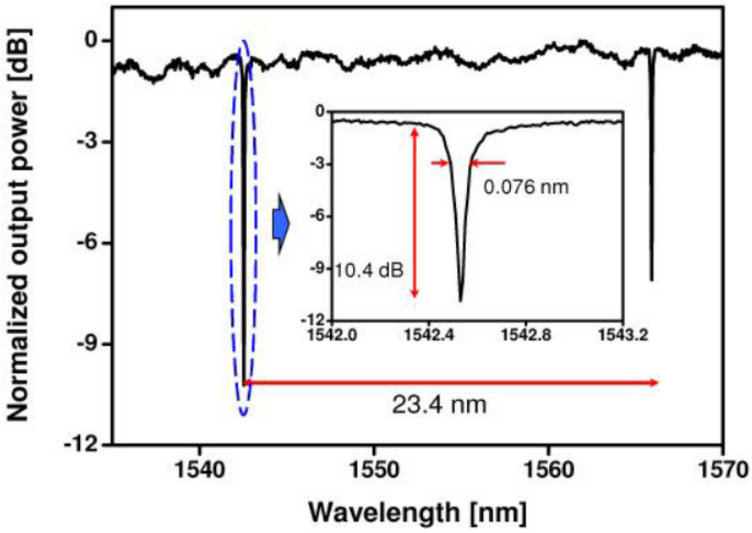

FIGURE 3.2: Optical spectral response of the fabricated silicon resonator

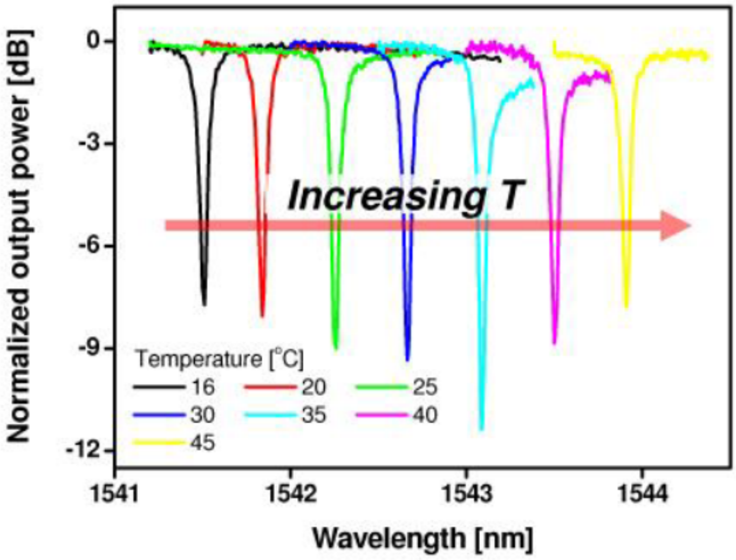

FIGURE 3.3: Optical response of the silicon sensor with the temperature

Temperature was measured by monitoring the resonance wavelength shift of the ring resonator as shown in Figure 3.2 & 3.3. The temperature-dependent resonance wavelength shift resulted from the thermo-optic effect in the ring resonator. In other words, the effective refractive-index of the ring waveguide increased with temperature, which redshifted the resonance wavelength.

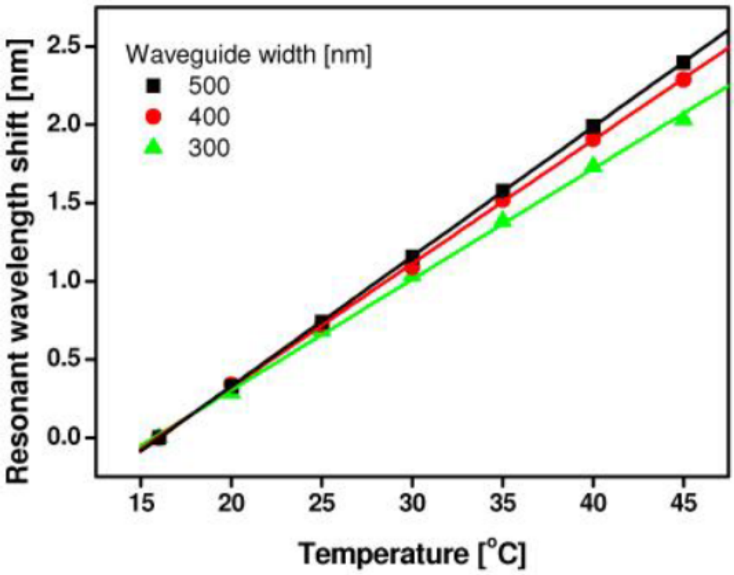

FIGURE 3.4: Resonant wavelength shift with the temperature for different waveguide widths

For the SOI structure, the $\partial n_f/\partial T$(described in the previous chapter) increases with the waveguide mode confinement and thus increases with the waveguide core size. In general, the maximum core size is determined by the single mode condition of the waveguide. For a 220 nm-thick SOI structure like this one, the maximum waveguide width for the single mode condition is ∼450 nm by which the corresponding temperature sensitivity comes to be around ∼85 pm/◦C. Thus if we go beyond this width there is a deviation from the single mode condition leading to saturation of the sensitivity. This could be clearly seen from Figure 3.5 where after 450 nm width the curve in the graph seems to saturate for any larger values of the width.

Figure 3.4 shows the resonant wavelength shift with respect to the temperature for the three different sensors with the width of w=300, 400, and 500 nm. The sensing efficiency,determined by the slope of the linearly fitted transfer curves, was shown to be enhanced when the waveguide width increased. Figure 3.6 shows the optical output of the sensor with the time with an electrical pulse supplied to the heating electrode, indicating a response speed of about $6\mu s$. The response speed of the temperature sensor was then investigated by attaching a heating electrode right onto the sensing resonator as shown in Figure 3.1 of this chapter. A voltage pulse signal was applied to it to generate heat, thereby changing its temperature. When the wavelength of the light source was fixed, the resonant wavelength shift of the sensing resonator was converted into a change in the optical output power.

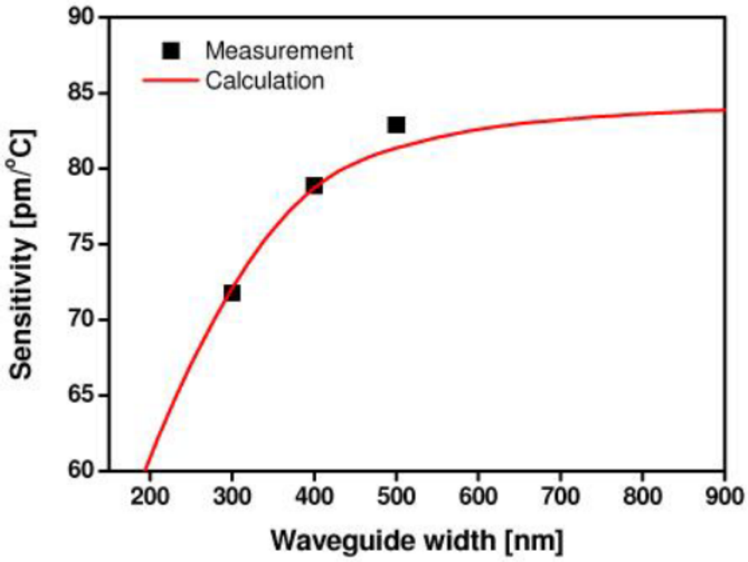

FIGURE 3.5: Sensitivity of the temperature sensor with the width of the silicon waveguide

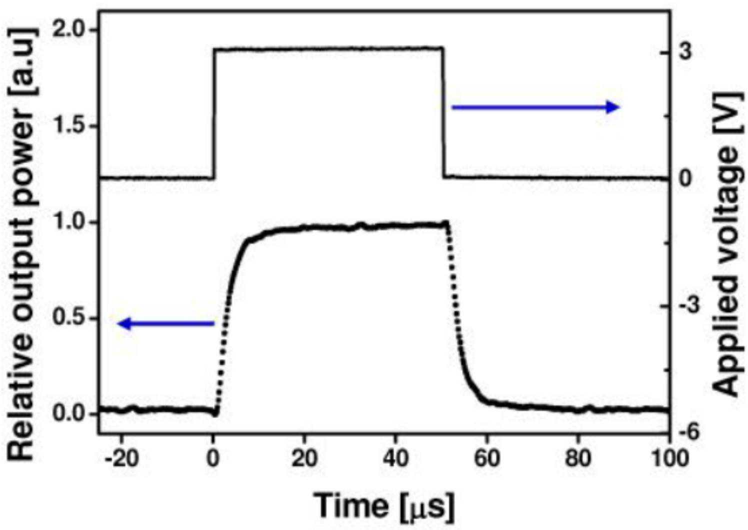

FIGURE 3.6: Temporal response of the fabricated temperature sensor

In summary, a substantially miniaturized photonic temperature sensor incorporating a silicon resonator was presented in this paper. A standard CMOS process was exploited to create the device. The influence of the waveguide width upon the sensitivity was experimentally and theoretically shown in the paper using the results described above. The demonstrated sensor affords to offer salient benefits like a low-cost, homogeneous integration into other electrical/optical devices in silicon. The only main practical issues with the proposed temperature sensor was on how to bring down a compact interrogator on a chip with the sensor to achieve better sensing range & sensitivity[14]. In the next chapter, I briefly discussed a way to overcome this limitation briefly in a separate section.

Chapter 4

Critical Assessment & Future Outlook

Recently, silicon photonics based temperature sensors received much wider attention around the world. The main reason behind it mainly lies in their robustness against electromagnetic interference and drift due to environmental disturbances such as mechanical shock and humidity , which make them superior to conventional electrical temperature sensors in many applications.

Silicon-on-insulator (SOI) based micro ring resonators , waveguide Bragg gratings, and Michelson interferometers have been demonstrated for temperature sensing since a long time[4]. Compared with optical fiber based temperature sensors, these sensors can achieve much higher sensitivity due to the high thermo-optic coefficient of silicon.

Furthermore, the integration of silicon photonic sensors with the complementary metal-oxide-semiconductor (CMOS) process enables cost effective on-chip temperature sensing , which is not readily achievable with optical fiber Bragg gratings or fiber tip based temperature sensors[15].

Among many silicon photonics based structures, SOI micro ring resonators offer some unique features that render them an attractive choice for high performance temperature sensing. One of which is the high quality (Q) factor spectral response of silicon ring resonators that manifests a strong temperature-dependence, ultimately enabling high resolution temperature sensing. Furthermore, the high refractive-index contrast of the SOI waveguide provides excellent optical confinement and reduces the waveguide bending loss, thus facilitates the development of ultra-compact photonic sensors.

4.1 Literature Review

As discussed above Silicon photonic temperature sensors like Silicon-on-insulator (SOI) microring resonators, waveguide Bragg gratings (WBGs), and Michelson interferometers (MIs) have been widely used for temperature monitoring since a long time. Therefore in this section, I will try to provide the pros and cons associated to each one of them by citing two reference article from each.

4.1.1 SOI Microring Resonator

An SOI-ring-resonator-based temperature sensor was first demonstrated by [15], which is also the paper on which this whole report is based. In this paper,a $4\mu m$-radius silicon ring resonator was used as a temperature sensor. Temperature was measured by monitoring the resonance wavelength shift of the ring resonator. The temperature-dependent resonance wavelength shift resulted from the thermo-optic effect in the ring resonator. In other words, the effective refractive-index of the ring waveguide increased with temperature, which red shifted the resonance wavelength. **83** $pm/°C$ of temperature sensitivity was demonstrated with transverse-electric (TE) polarized light, which was the maximum achievable sensitivity under the single mode operation of the ring waveguide. The sensing range comes out to be around **280** $°C$ with a **23.4 nm** of FSR. The sensing resolution was determined by the sensitivity and the resolution of the optical interrogation system. With a 1 pm resolution tunable laser source, **0.01**$pm/°C$ of sensing resolution was achieved. This sensitivity of about of ∼83 $pm/°C$ was achieved for the width of 500nm , while for 300, 400nm it was 79 & 72 $pm/°C$ respectively was achieved theoretically. Finally, the corresponding quality factor (Q-factor) was ∼20,000, which is high enough to allow for a high sensing resolution.

Using a similar SOI ring resonator structure, H. Xu et al demonstrated temperature sensing with much improved resolution [16]. To identify the resonance wavelength shift, they monitored the transmission intensity change. The input laser wavelength was selected to be centered at the side of the resonance (i.e. at the ∼ 3 dB point), so that a small temperature change resulted in a large change in the transmission intensity. The intensity change was then used to estimate the resonance wavelength shift from the known resonance line shape. The sensing resolution was determined by the system noise including both the laser wavelength and the laser power noises. At 296.15 K, an **80** μ**K** of the minimum resolution (noise floor) was achieved at 1 Hz sampling rate, where all variation was minimized. **The measured sensing resolution showed 13 times improvement compared to the wavelength scanning scheme by the one proposed in my paper**. However, the noise floor rose to ±5 K at long time scale (

>1 min). Therefore, **the proposed scheme was not suitable for the temperature measurement requiring long observation times**.

4.1.2 Waveguide Bragg Grating(WBG) based Temperature Sensor

While the free-spectral-range of the **SOI ring resonator temperature sensors imposes a limitation on the maximum achievable sensing range, Waveguide Bragg Grating (WBG)-based temperature sensors have a sole resonance mode (i.e. Bragg resonance) and thus render a much wider sensing range**.

N. Klimov et al reported an SOI WBG temperature sensor [17], where the Bragg gratings were formed in a rectangular waveguide by modulating the waveguide width to a square-wave form and thus modulating the effective refractive-index of the waveguide .The temperature-dependent Bragg wavelength shift was demonstrated from 5°C to 160°C with **82**$pm/°C$ of sensitivity. Although temperature was monitored over a 155° range,it was claimed that the sole resonance mode of the WBG enables to continuously monitor temperature from cryogenic up to silicon melting temperature. The measured sensor resolution was **1.25°C**, which was much coarse than that of the SOI ring resonator temperature sensors (i.e. 0.01°C). The coarse resolution mainly resulted from the error in estimating the center wavelength of the blunt and wide-linewidth Bragg resonance (the resonance linewidth was estimated to be around 5.1 nm).

C. Chang et al developed a silicon WBG temperature sensor that rendered sharp and narrow-linewidth Fano resonance [18]. The sensor consisted of a phase plate and Bragg gratings. The effective refractive-index modulation for the Bragg gratings was achieved by a periodic air hole array aside the silicon waveguide. The interference of reflected beams from the phase plate and Bragg gratings rendered asymmetric resonance with ∼1 nm resonance linewidth. The sensitivity was **77** $pm/°C$ at room temperature, but the sensor resolution was not reported.

4.1.3 Michelson interferometers (MI)based Temperature Sensor

J. Tao et al demonstrated temperature monitoring with an SOI MI structure [19].The MI temperature sensor employed a directional coupler for a light splitter/combiner, two waveguides with different lengths for MI arms, and two loop-waveguides for reflection mirrors. The temperature-dependent phase difference between the two arms shifted the destructive interference wavelength with **113.7** $pm/°C$ sensitivity. The FSR between the adjacent destructive interference wavelengths was **27.9 nm**, which rendered a **246 °C** of sensing range.

S. Tsao et al also reported an SOI MI temperature sensor [20], but it consisted of different photonic components from what was used by J. Tao et al. Instead, here 2×2 multimode interference coupler and waveguide Bragg reflective gratings were used for a beam splitter/combiner and reflection mirrors, respectively. **293** $pm/°C$ of sensitivity was obtained from analytical calculation, but experimental results were not provided. However, the calculated sensitivity is believed to be overestimated, since the thermo-optic coefficient of silicon which was used for the sensitivity calculation was ∼4 times higher than typical values.

4.2 Novel Architectures for Ring Resonator based Sensor

There have been many efforts devoted towards enhancing the performance of ring resonator based sensors by employing various ring resonator architectures. These include cascaded ring resonators (CRR) [9] for realizing the Vernier effect, vertically stacked ring resonators for obtaining resonance splitting , and Bragg grating ring resonators for achieving resonance splitting and Fano resonance[18].

While the resonance splitting and Fano resonance have been used to improve the sensor resolution, the CRR-based Vernier effect has been widely used to enhance the sensitivity of the ring resonator based sensors. It has also been used to tailor the spectral characteristics of ring resonators such as suppressing undesired resonance modes and increasing finesse and consequently the FSR.

Followed by this, H.T.kim [9] proposed the concept of cascaded ring resonator structure utilizing the non-conventional CRR approach for both temperature sensitivity and sensing range enhancement. Instead of using one of the ring resonators as a reference and thermally isolating the reference, he utilized two ring resonators with different temperature sensitivities and different FSRs, both as sensor resonators.Because the proposed approach does not require isolation of one of the ring resonators from a temperature input, the sensor fabrication was able to achieved with a single-mask CMOS-compatible process.

In experiment, the sensor was demonstrated to have an enhancement of 6.3 times in the sensitivity and 5.3 times in the sensing range compared to the single ring resonator sensor that was proposed in base paper of this report. Furthermore, it was theoretically shown that either the sensitivity or the sensing range can be ultimately enhanced by tailoring the ΔS, and both the sensitivity and the sensing range can be enhanced by increasing the Figure of Merit (FOM). FOM represents the product of the sensitivity enhancement and the sensing range enhancement.

As pointed by previous studies [8], owing to the sensitivity enhancement of the proposed temperature sensor, one can potentially use an on-chip, low resolution micro optical spectrometry such as an arrayed waveguide grating for sensor interrogation without significant compromise in resolution. This can help reduce the size and cost of the photonic temperature monitoring system. On the other hand, it is possible to tailor the sensor to obtain an extended temperature sensing range, so that it can be utilized to monitor large temperature changes.

4.3 Future Work

As an extension of this work, future work could be as follows.

- Bringing hybrid Nested Ring Resonator structure that can offer larger measurement range and high Q-factor.
- Miniaturizing the whole optical temperature sensing setup by hybrid photonic integration techniques. Though this will increase the sensitivity and sensing range but the cost of manufacturing will be high in comparison to the CMOS process.

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