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

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Abstract: An ultra-small integrated photonic temperature sensor has been proposed and demonstrated which incorporates a silicon ring resonator linked to a vertical grating coupler. It was manufactured using a 0.18 μm standard CMOS process, rendering a homogeneous integration into other electrical/optical devices. The temperature variation was measured by monitoring the shift in the resonant wavelength of the silicon resonator, which was induced by the thermo-optic effect and the thermal expansion effect. The dependence of its sensing capability upon the waveguide width of the resonator was intensively probed both theoretically and experimentally. The best achieved sensitivity was about 83 pm/°C for a waveguide width of 500 nm, while the sensitivity was boosted by ~10 pm/°C by adjusting the waveguide width from 300 nm to 500 nm. Finally, the response speed of the sensor was as fast as ~6 μs.

OCIS codes: (130.3120) Integrated optics devices; (130.6010) Sensors; (230.5750) Resonators; (120.6810) Thermal effects.

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1. Introduction

Recently silicon photonic devices have attracted enormous attention due to their conspicuous advantages, like an ultra-small footprint and a flexible integration with conventional electronic integrated circuits. Furthermore, they can be manufactured by using a fully matured fabrication technology such as the CMOS (complementary metal-oxide-semiconductor) process, which is believed to be the most prevailing technology used for conventional electronic integrated circuits [1–4]. The operation of both silicon photonic and electronic devices is inevitably dependent upon the ambient temperature, because the silicon itself has temperature dependent optical/electrical properties. In order to mitigate the issue of temperature dependence, various temperature monitoring schemes have been suggested [5].

An optical temperature sensor is preferred to a conventional electrical sensor in view of immunity to electromagnetic interference and robustness. So far, fiber-optic temperature sensors based on Bragg gratings were mainly attempted featuring a high sensitivity and easy fabrication [6]. They are not however suitable to integrate into other electrical/optical devices [7]. Meanwhile, an integrated photonic temperature sensor based on couplers, surface plasmon resonance devices and interferometers is thought to offer salient advantages including a small footprint, a fast response, and a flexible integration with other devices [8–10]. In particular, a ring resonator has been considered to be one of the most prominent candidates owing to its versatility and compact configuration. A temperature sensor incorporating a polymer waveguide resonator, which has a low $\Delta n = \sim 0.1$, was previously reported, having the size a few hundred μm [10]. However, the size of a silicon resonator could be reduced down to a few μm with the help of a high $\Delta n = \sim 2$, while an equivalent level of sensitivity is acquired due to the comparable thermo-optic (TO) coefficient of silicon ($\sim 1.8 \times 10^{-4}$). The ultra-small dimension of the silicon resonator is expected to help extend the sensing temperature range due to its broad free spectral range (FSR) [8].

In this paper, an ultra-small integrated photonic temperature monitoring device, relying on a silicon ring resonator connected to a grating coupler, has been proposed and designed; it was especially constructed by utilizing a standard CMOS process. The feasibility of controlling the sensor sensitivity by virtue of the silicon waveguide width was intensively examined both theoretically and experimentally. The response speed of the proposed sensor was also discussed.

2. Proposed silicon temperature sensor and its design

The proposed temperature sensor, taking advantage of a silicon ring resonator, is illustrated in Fig. 1. 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 ring resonator is well known to give rise to a periodic notch-filter like spectral response, where the position of the resonant wavelength offering a minimum transmission is determined by the radius of the ring, and the distance between the two adjacent resonant wavelengths is defined as the FSR. When the temperature varies, the refractive index of the silicon is altered by the TO effect and the circumference of the ring is changed by the thermal expansion effect. It is reported that the

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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 $\Delta\lambda_L$ [11,12]:

$$\Delta\lambda = \Delta\lambda_L + \Delta\lambda_T = \alpha_W \frac{n_{eff}}{n_g}\lambda\Delta T + \frac{\sigma_T}{n_g}\lambda\Delta T, \text{ where } \sigma_T \equiv \partial n_{eff} / \partial T \tag{1}$$

where n_{eff} 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. The effective index of the silicon waveguide is surely determined by its width. The fact that the relationship between the effective index and the width is mostly dependent on the temperature through the TO effect indicates that σ_T may vary with the width, which has been theoretically confirmed. As a result, the sensitivity of the proposed temperature sensor could be controlled by adjusting the waveguide width, according to the above Eq. (1).

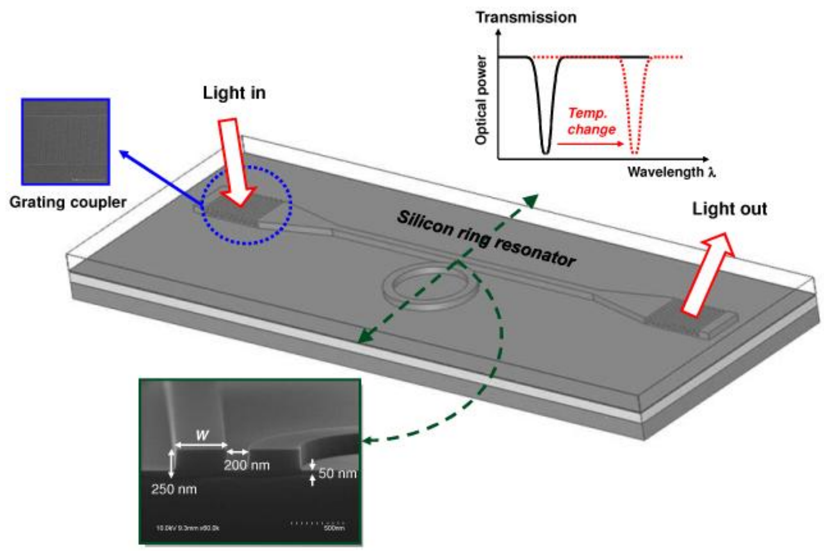

Fig. 1. Configuration of the proposed temperature sensor based on a silicon resonator.

Unlike polymer waveguides based on a low index contrast Δn, silicon waveguides based on a high Δn will be suitable to realize a resonator with an ultra-small radius. Therefore, the FSR of the resonator, which is given by $\lambda^2/n_g 2\pi R$, is enlarged to offer a greater sensing range. Here R is the ring radius. 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. The waveguide width of concern ranges from 200 to 900 nm, but it has been practically limited to ~500 nm to satisfy a single-mode guiding condition.

A theoretical investigation into the dependence of the sensitivity upon the waveguide width has been conducted focusing on the waveguide width of 300, 400, and 500 nm, but the sensitivity for a broader range of waveguide width will be discussed later in Fig. 5. The sensitivity of the proposed temperature sensor was calculated via the Eq. (1) with the assistance of the film mode matching method [13]. Some of the crucial parameters used for the analysis are: the TO coefficients of the silicon and SiO_2 were 1.86×10^{-4}/°C and 1.0×10^{-5}/°C respectively, and the CTE of the silicon was α_W = ~2.5×10^{-6}/°C [14] while that of the oxide layer was ignored assuming the thickness of the silicon substrate was much larger than the oxide layer. For the waveguide width of 500 nm, the observed effective index and group index were n_{eff} = ~2.56 and n_g = ~3.89. The resulting rate of change of the effective

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index with the temperature, which is induced by the TO effect, was σ_T = ~1.97×10^{-4}/°C. Consequently, the theoretical sensitivity of the proposed temperature sensor for the width of 500 nm was ~82 pm/°C. It is also noted that the sensitivity was about 79 and 72 pm/°C for the width of 400 and 300 nm respectively. Finally, in view of the calculated FSR of ~24.6 nm of the resonator, the proposed temperature sensor was anticipated to cover up to ~300°C.

3. Device fabrication and experimental results

The integrated photonic temperature sensor was fabricated by employing the 0.18 μm standard CMOS process at the National NanoFab Center, Korea. The silicon-on-insulator substrate from SOITEC was 8 inches in diameter and 720 μm 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. Figure 1 shows the scanning electron micrographs of the fabricated silicon ring and the grating coupler. We attempted to build a temperature sensor with three different widths of 300, 400, and 500 nm as discussed earlier.

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, Agilent 81640A, served as the light source and the optical output of the sensor was detected and analyzed by using an optical spectrum analyzer. According to the measured bandstop filtering characteristics of the silicon resonator displayed in Fig. 2, the FSR was ~23.4 nm, the extinction ratio ~10 dB, and the bandwidth ~0.076 nm. The corresponding quality factor (Q-factor) was ~20,000, which is high enough to allow for a high sensing resolution.

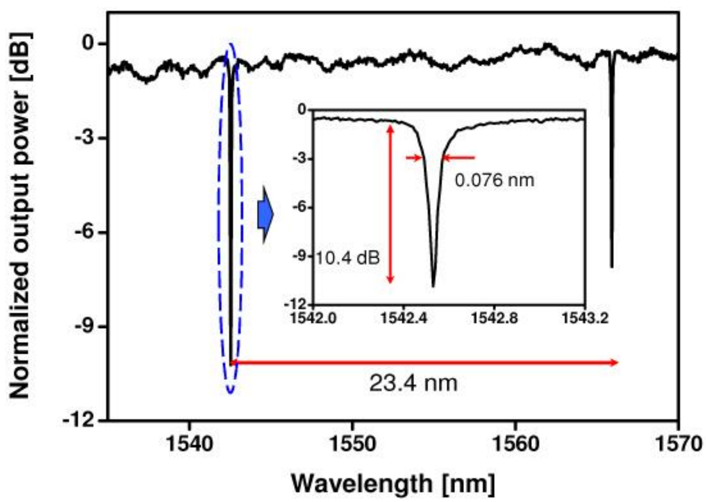

Fig. 2. Optical spectral response of the fabricated silicon resonator.

As shown in Fig. 3, the evolution of the optical spectral response of the silicon sensor was observed for the waveguide width of 500 nm, when the temperature varied from 16 to 45°C around the room temperature. The resonant wavelength shifted toward longer wavelengths with increasing temperature, starting from 1541.5 nm. And the Q-factor of the device changed slightly within the range of 20,000 to 22,000, which does not seriously degrade the sensing capability. Figure 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,

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determined by the slope of the linearly fitted transfer curves, was shown to be enhanced when the waveguide width increased. The sensitivity for the fabricated sensor is plotted in Fig. 5, and the theoretical sensitivity for the waveguide width ranging from 200 to 900 nm is also provided there. A decent agreement was obtained between the calculated results and the experimental results. The sensitivity was elevated by ~10 pm/°C by changing the waveguide width from 300 to 500 nm; it was peaked at ~83 pm/°C for the case of w=500 nm. The demonstrated sensitivity of our sensor is approximately comparable to that of other types of sensors based on a fiber Bragg grating [6], a silicon nitride resonator [9] and a polymer resonator [10]. It may be improved by incorporating a cladding with higher TO coefficient than SiO_2. And the demonstrated operation range was about 30°C, but it will be potentially extended up to ~280°C in light of the achieved FSR and sensitivity of the resonator sensor. Next, the resolution of the temperature sensor is estimated to be about 0.01°C considering the wavelength resolution of 1 pm, which is available from the present test setup.

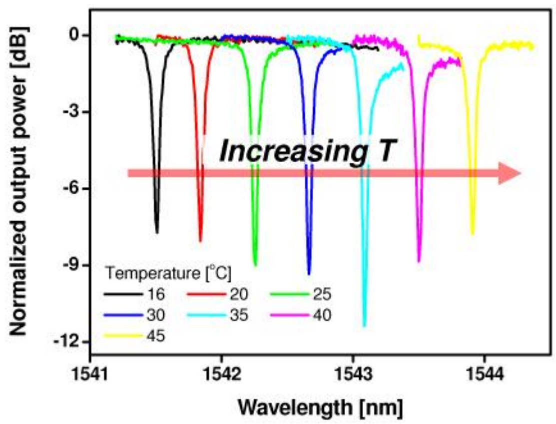

Fig. 3. Optical response of the silicon sensor with the temperature.

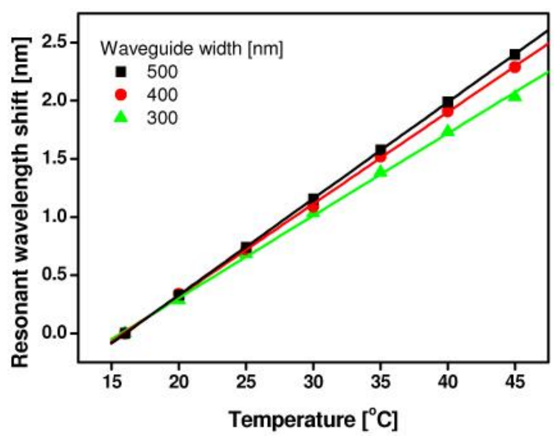

Fig. 4. Resonant wavelength shift with the temperature for different waveguide widths.

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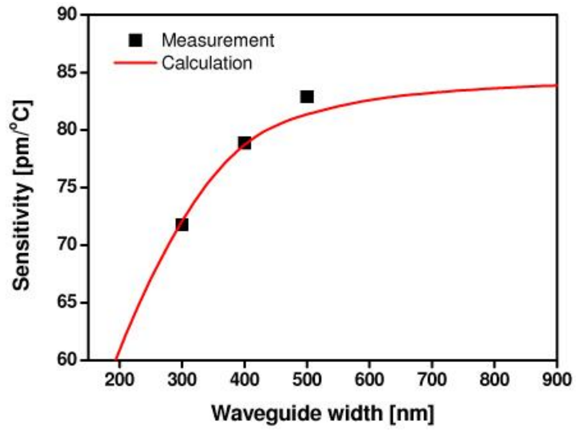

Fig. 5. Sensitivity of the temperature sensor with the width of the silicon waveguide.

The response speed of our temperature sensor was then investigated by attaching a heating electrode right onto the sensing resonator. A voltage pulse signal was applied to it to generating 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 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 μs.

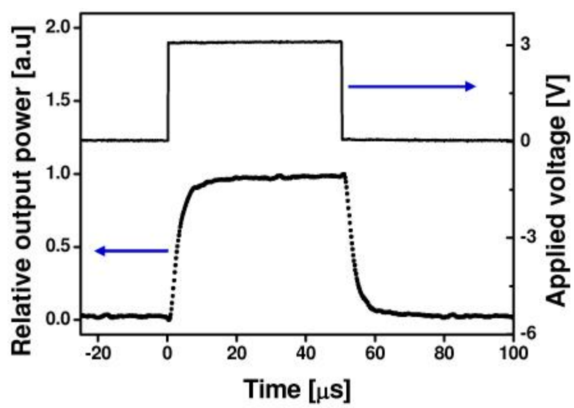

Fig. 6. Temporal response of the fabricated temperature sensor.

Finally, two practical issues with the proposed temperature sensor are discussed: First, the silicon temperature sensor is desired to provide an appropriate selectivity so that the variation due to the temperature could be differentiated from that resulting from other physical quantities like the strain. For instance, the effect caused by the strain may be efficiently compensated for by integrating a strain sensor exhibiting negligibly small temperature dependence with the main temperature sensor [15,16]. Second, an interrogator is necessary to convert an optical wavelength shift into an electrical signal, and it is readily constructed by taking advantage of a matched filter or an arrayed waveguide grating in conjunction with a broadband light source [17,18].

4. Conclusion

In summary, a substantially miniaturized photonic temperature sensor incorporating a silicon resonator was presented. A standard CMOS process was exploited to create the device. The influence of the waveguide width upon the sensitivity was experimentally and theoretically

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examined. The demonstrated sensor affords to offer salient benefits like a low-cost, homogeneous integration into other electrical/optical devices in silicon.

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