Temperature Stability of Integrated Gyroscope Performance based on SiN and InP Ring Resonators

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A feasibility study of Silicon Nitride (SiNx) and Indium Phosphide (InP) integrated optical gyroscopes in a wide temperature range of -40 ℃ to 90 ℃ is presented in this paper. Our investigation primarily centers on resolution that governs gyroscope performance. The properties of ring resonator over this temperature range are simulated, which directly affect stability for gyroscopic performance. A variation of less than 1.2 °/h in the gyroscope resolution is derived with SiNx waveguide, which shows temperature robustness. As comparison, we also explore the potential to use an InP platform for constructing integrated optical gyroscope with reasonable resolution variation.

Introduction

Gyroscopes are commonly used to measure angular rotation and are becoming increasingly popular in modern applications, such as stabilization systems for robotics and vehicles. Miniaturized optical gyroscopes based on resonant ring resonators have been gaining traction in recent years [1]. The resonant optic gyroscope (ROG) is a promising approach to create low-energy, small-scale, and reliable gyroscopes. Several designs have been proposed to enhance the resolution of ROGs, but there is less focus on robust performance, particularly when temperature fluctuates.

The basic theory of measuring rotation rate is based on the Sagnac effect. The shot noise limited sensor resolution can be expressed as [2]

$$\delta\Omega = \frac{Lc}{AQ}\sqrt{\frac{Bhf_s}{8\eta_{pd}P_{pd}}} \times 3600\ (^\circ/h)$$

where L is the circumference of the ring, A is the effective area of the ring, c is the speed of light in vacuum, Q is the resonator quality factor (Q-factor), B is the gyroscope bandwidth, h is Plank's constant, f_s is the gyroscope operation frequency, η_{pd} is the quantum efficiency of the photodetector, and P_{pd} is the input optical power of the photodetector. It describes the smallest angular rotation rate that a ROG can detect. The ring resonator is the key component that can significantly affect the gyroscope's performance.

The SiNx platform is a viable option for creating a temperature-resistant gyroscope system, as dielectric materials are less sensitive to temperature fluctuations. Waveguides on SiNx have low contrast, leading to low propagation losses ranging from 0.003 dB/cm to 1.0 dB/cm in the 400 to 2350 nm range[3]. The low propagation loss allows SiN ring resonators to reach high Q-factor with small footprint, which means gyroscopes with SiN rings can achieve a high resolution with a relatively small size.

In this paper, we present the simulation results of four SiNx ring resonators in a temperature range from -40°C to 90°C. By applying a 800μm radius ring, the resolution variation of gyroscope can be lower than 0.11°/h, while 1.2 °/h resolution variation can be derived with 100 μm -radius rings. The results demonstrate a good temperature

stability. Simulations on InP platform were also conducted for comparison. The resolution can be improved to 24°/h by using 1600 µm radius. While the resolution variations in the temperature range can be 0.28 °/h, which is comparable to SiNx (~0.11°/h).

Ring Resonator Simulations

Simulations are conducted to investigate the effects of temperature on the SiNx rings. We assumed that the rings are uniformly heated and the temperature change range is from -40 °C to 90 °C, as it encompasses the operating temperature range of the majority of gyroscopes. The refractive index models of the materials are constructed based on the experimental results from the previous studies, as demonstrated in Figure 1(b) [5][6][7]. The simulated SiNx ring resonator is based on the standard TriPleX Asymmetric Double-Stripe (ADS) waveguide, as Figure 1(a) shows [4]. The typical value of the loss is <0.1 dB/cm, which allows high-Q ring resonators. A coupling length of 16 μm with a gap of 1.4 μm was chosen, resulting in a coupling coefficient of 0.1. The dimensional change of the silicon nitride waveguide due to the thermal expansion is of the order of pm, so the effect on the coupling length and gap is not taken into account.

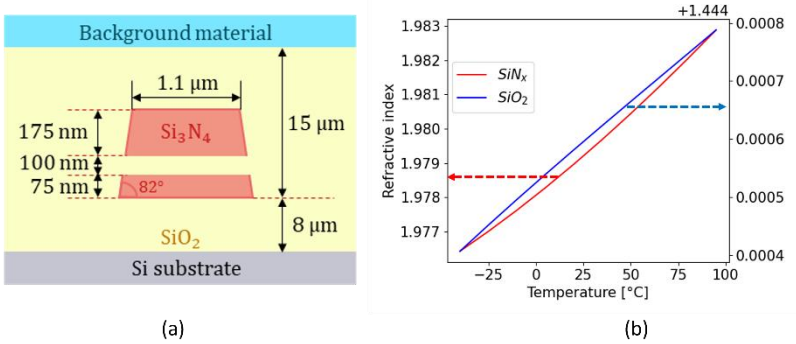

Figure 1. (a) Cross-configuration of standard TriPleX ADS waveguide[4]. (b) Refractive index of SiN and SiO with temperature change.

Four rings with different radii were simulated and the results at 20°C are presented in Table 1. By taking the values at 20°C as a reference, the variations of the Q-factor and resolution with temperature change were shown in Figure 2(a) and (b). Over the temperature range, the ring with an 800 µm radius has the largest change in the Q-factor, but the smallest change in resolution (about 0.11°/h). The rings with higher Q-factors indicate better stability to temperature changes. Although resolutions of rings with the smaller radii are more sensitive to temperature changes, the largest variation is smaller than 1.2°/h over this temperature range, indicating a good temperature robustness.

Simulations of four rings on InP platform with similar performance are conducted as a comparison with a coupling coefficient of 0.5. The waveguide structure is deep-etched and proposed by D'Agostino, which has a loss of less than 0.5 dB/cm [8]. The cross section is depicted in Figure 3(a). According to the thermal-dependent refractive index model proposed by Melati [9], the refractive index of InP and InGaAsP (Q=1.25) in the range of -40 °C to 90 °C is shown in Figure 3(b). Around 0.6% variation of refractive index can be observed which is doubled than the SiNx platform.

Table 1. Q-factor and Resolution for SiNx rings at 20 ℃

Radius	100 μm	200 μm	400 μm	800 μm
Q-factor	10127.17	20211.78	40179.48	79287.40
Resolution [°/h]	346.42	177.20	89.67	45.12

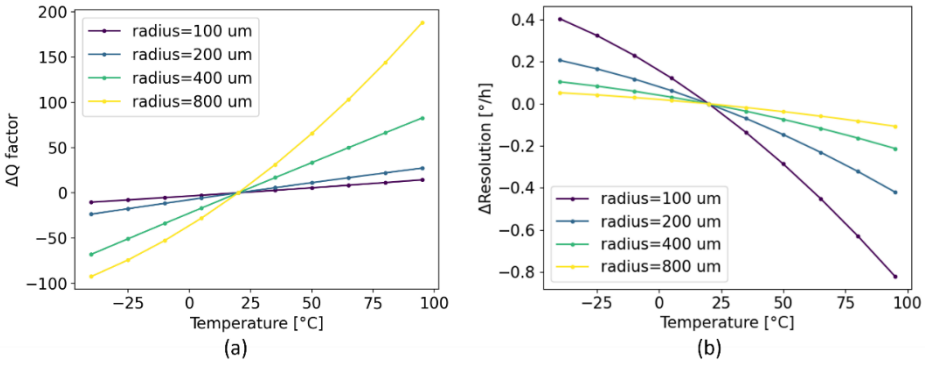

Figure 2. SiN ring resonators: (a)Variation of Q-factor. (b)Variation of Resolution.

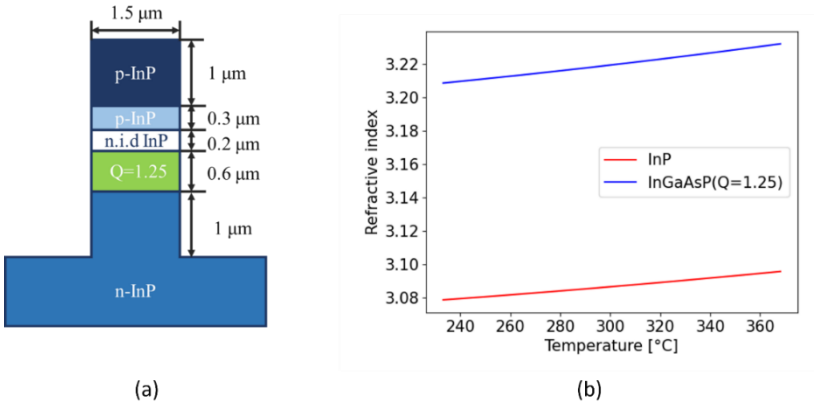

Figure 3. (a)Cross-configuration of the low-loss InP deep-etched waveguide. (b)Refractive index of InP and Q=1.25 with temperature change.

The values of Q-factor from InP ring resonator and resolution derived for gyroscope with different radii at 20°C are indicated in Table 2., which used as a reference. The variations of Q-factor and resolution over -40 °C to 90 °C are shown in Figure 4(a) and (b).The values of Q-factor from InP ring resonator and resolution derived for gyroscope with different radii at 20°C are indicated in Table 2., which used as a reference. The variations of Q-factor and resolution over -40 °C to 90 °C are shown in Figure 4(a) and (b). Compare the SiNx and InP ring resonators at the same Q-factor level ~ 10000, the radii for them are100 µm and 200 µm, respectively. The resolution for gyroscope structure derived are 350 and 1400 and the resolution variations are 1.2 °/h and 15 °/h, respectively. The SiNx shows irreplaceable advantages. However, if relatively good Q-factors (~80000) for the SiNx and InP ring resonators are considered, the radii are 800um and 1600um, respectively. The resolution for gyroscope derived from InP ring resonators is 24°/h, which is better than 45°/h based on SiNx. Further, the resolution variations in the temperature range are 0.28 °/h and 0.11 °/h for InP and SiNx, respectively. The InP rings hold a good potential to compete with SiNx.

Table 2. Q-factor and Resolution for InP rings at 20 ℃

Radius	200 μm	400 μm	800 μm	1600 μm
Q-factor	10098.05	19990.39	39193.72	75361.61
Resolution[°/h]	1391.36	355.67	91.27	23.81

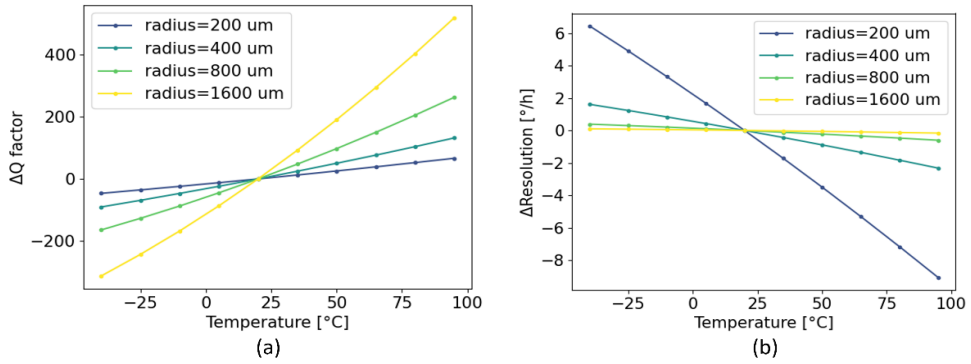

Figure 4. InP ring resonators: (a)Variation of Q-factor. (b)Variation of Resolution

Conclusion

In this paper, we present a feasibility study of both SiNx and InP integrated optical gyroscopes in a wide temperature range of -40 ℃ to 90 ℃. The Q-factors of ring resonators as well as the resolutions for gyroscopes are discussed to represent temperature stability performance. A variation of less than 1.2 °/h in resolution is derived for SiNx which shows better temperature robustness than InP(< 15 °/h). By improving the Q-factor of InP ring, a variation of less than 0.28 °/h can be derived which is comparable with SiNx (~0.11°/h), despite the size of InP ring is two times than SiNx ring. Gyroscopes using InP rings have potentials to be improved as they are attractive for one-chip solutions that require integrated lasers and photodetectors.

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