

Integrated Silicon Nitride Optical Gyroscope: Design and Path to Quantum Enhancement

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Photonic integration promises optical gyroscopes with strongly reduced size, weight, power and cost, but chip-scale devices remain far below fiber-optic and ring-laser performance. We present ultra-low-loss waveguide crossings for silicon nitride Sagnac coils, reaching 0.01 dB per crossing in simulation, and assess whether quantum-optical resources can provide a practical advantage for increased precision.

1 Introduction

Optical gyroscopes measure rotation via the Sagnac effect [1], which occurs when two optical beams propagate in opposite directions along a closed path on a rotating platform. Rotation induces a non-reciprocal phase difference between the two beams, which can be measured interferometrically. For a loop enclosing an area A and rotating at angular velocity Ω , the Sagnac phase shift is given by

$$\phi_S = \frac{8\pi \vec{A} \cdot \vec{\Omega}}{\lambda c}, \quad (1)$$

where λ is the optical wavelength and c is the speed of light. Fiber-optic (FOG) and ring-laser gyroscopes reach strategic-grade performance, with angle random walk (ARW) below $0.0003 \text{ deg}/\sqrt{\text{h}}$ and bias drift below $0.001 \text{ deg}/\text{h}$ [2], but remain bulky and expensive. Micro-electro-mechanical systems (MEMS) gyroscopes are compact yet mechanically unstable, since vibration and acceleration can be misinterpreted as rotation. Photonic integrated circuits (PICs) promise to bridge this gap by replacing the fiber coil of a FOG with a waveguide coil, reducing SWaP-C (Size, Weight, Power and Cost) while enabling scalable fabrication and improved robustness.

Integrated interferometric optical gyroscopes have been demonstrated on several platforms, most notably silicon nitride (SiN) [3], where propagation losses below 1 dB/m are attainable, and silica [4]. Their performance remains far below that of mature fiber-based systems, because miniaturization reduces the enclosed area while optical loss and technical noise persist. A coil confined to a planar surface additionally requires closely spaced waveguide crossings, each contributing loss. Beyond these classical limitations, the phase resolution of any interferometer is ultimately bounded by photon shot noise, which motivates the use of quantum-optical

resources. The two aspects are connected: quantum enhancement becomes meaningful only in a device that is already low-loss and shot-noise limited. We therefore first present ultra-low-loss crossing arrays in SiN, and then assess whether quantum-optical enhancement can offer a practical rather than merely theoretical advantage.

2 Ultra-low-loss silicon nitride crossings

We adapt the low-loss Bloch-wave crossing array demonstrated in silicon by Liu *et al.* [5] to the SiN platform. The crossings are embedded periodically in a multimode waveguide, with the period matched to the beat length of the fundamental TE_0 mode and the second-order TE_2 mode. The Bloch wave formed by these two modes produces an optical field with periodic foci that jump across the crossing gaps, strongly suppressing diffraction loss. A short symmetric taper launches the required superposition, while the antisymmetric TE_1 mode is excluded by symmetry.

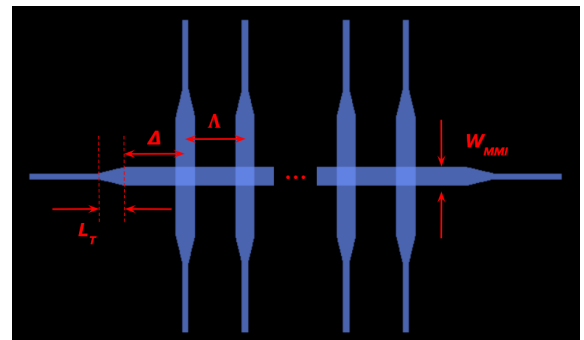


Fig. 1 Geometry of the Bloch-wave crossing array.

The geometry was optimized by 3D FDTD simulations (Lumerical Inc. [6]) for the fundamental TE mode at $\lambda = 810 \text{ nm}$. The input waveguides are

250 nm high and 450 nm wide, while the multimode section is widened to $W_{\text{MMI}} = 1.4 \mu\text{m}$ to support the first three TE-like modes (Fig. 1). An optimization sweep of the taper length, the taper-to-crossing offset and the period yields $L_T = 1.9 \mu\text{m}$, $\Delta = 3.77 \mu\text{m}$ and $\Lambda = 4.72 \mu\text{m}$ for an array of ten crossings. Fig. 2 shows the transmission as a function of the period alone, with the remaining parameters held at these optimized values.

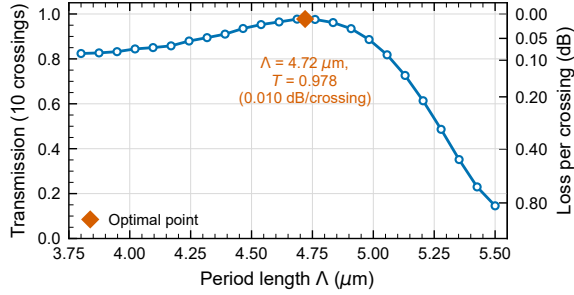


Fig. 2 Simulated transmission of the ten-crossing array as a function of the period Λ .

At the optimum the design reaches 0.01 dB per crossing, following from a transmission of $T = 0.978$ through the full array, thus a total insertion loss of 0.1 dB. This is an upper bound, since it includes the loss of the two tapers. A simple strip crossing between the single-mode waveguides, simulated under identical conditions, gives 0.7 dB per crossing.

3 Path to quantum enhancement

Once technical noise is suppressed, the phase resolution of a classical interferometer is bounded by shot noise, $\Delta\phi_{\text{SNL}} = 1/\sqrt{M}$, with M the number of detected photons. Two non-classical resources are commonly proposed to surpass this bound.

Path-entangled N00N states, in which N photons are in an equal superposition of the two interferometer modes, can reach a phase uncertainty of $\Delta\phi_{\text{N00N}} = 1/\sqrt{MN}$ for $\nu = M/N$ consecutively detected states, improving on the SNL by a factor $\sqrt{N}$. This has been successfully demonstrated in a FOG [7], but a practical on-chip advantage remains out of reach. Photon-pair sources are typically limited to rates of about 10 MHz, so that inserting $\Delta\phi_{\text{N00N}}$ into Eq. (1) with $N = 2$ and the coil area of Ref. [3] gives an ARW of around 500 deg/ $\sqrt{\text{h}}$ even for a lossless measurement, two orders of magnitude worse than state-of-the-art chip-scale gyroscopes. Loss is equally restrictive, since surpassing the SNL requires $\sqrt{(\eta^{-N} + 1)/2N} < 1$ [8], that is $\eta > 57.7\%$ for $N = 2$, whereas the best reported integrated coil shows an insertion loss of 8.37 dB ($\eta \approx 14.55\%$) [4].

Squeezed vacuum is the more realistic route, since the photon flux is still carried by a bright classical field. A noise reduction of 4.5 dB below the SNL

has been demonstrated in a fiber Sagnac interferometer [9]. Loss remains critical here as well, with the squeezed quadrature variance scaling as $\eta e^{-2R} + (1-\eta)$, where R is the squeeze factor, so that an insertion loss of 8.37 dB would degrade 10 dB of squeezing to about 0.6 dB. Theoretical models of SiN coils moreover predict thermo-refractive noise, relative intensity noise and detector electronic noise one to two orders of magnitude above the shot-noise floor [10].

4 Conclusion

Quantum-optical metrology can improve chip-scale gyroscopes only once technical noise and optical loss are sufficiently suppressed for the device to approach shot-noise-limited operation. Squeezed-light-assisted architectures are the most plausible candidates, but their advantage is conditional on progress in the classical waveguide coil. The ultra-low-loss crossings presented here are one building block toward that goal.

Acknowledgments

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