A compact silicon photonic quantum coherent receiver with deterministic phase control

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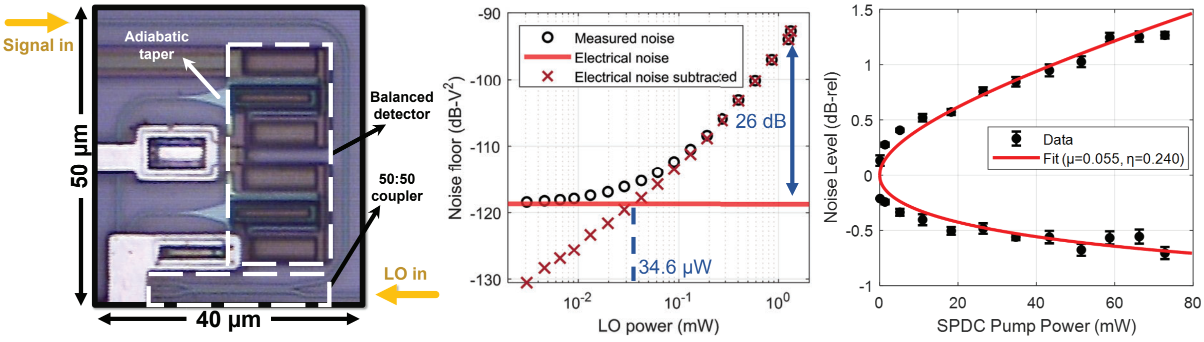
Abstract: We demonstrate a quantum-limited silicon photonic coherent receiver with 26.0 dB shot noise clearance, 34.6 μW knee power, and 0.00200 mm^2 chip area. We measure squeezed vacuum with the integrated receiver and demonstrate phase-locking to the squeezed quadrature.

1. Introduction

Manipulating and detecting quantum fluctuations in light offer additional degrees of control over the shape and structure of the signal constellations in optical communications and sensing systems while enabling quantum advantage beyond the classical limit. Silicon photonics offers a promising platform for large-scale, yet compact, integration of complex quantum optical circuits at higher levels of parallelism and lower costs [1]. This is enhanced by their potential for integration with electronics toward large-scale quantum optoelectronic circuits. Quantum-limited balanced detection enables coherent processing and readout of classical and quantum light in these circuits at room temperature. Recently, integrated coherent receivers have been demonstrated to detect squeezed light for quantum state tomography [2]. In this work, we demonstrate a quantum-limited silicon photonic coherent receiver with a shot noise clearance (SNC) of 26.0 dB, a knee power (P_{knee}) of 34.6 μW, and a chip area of 0.00200 mm^2.

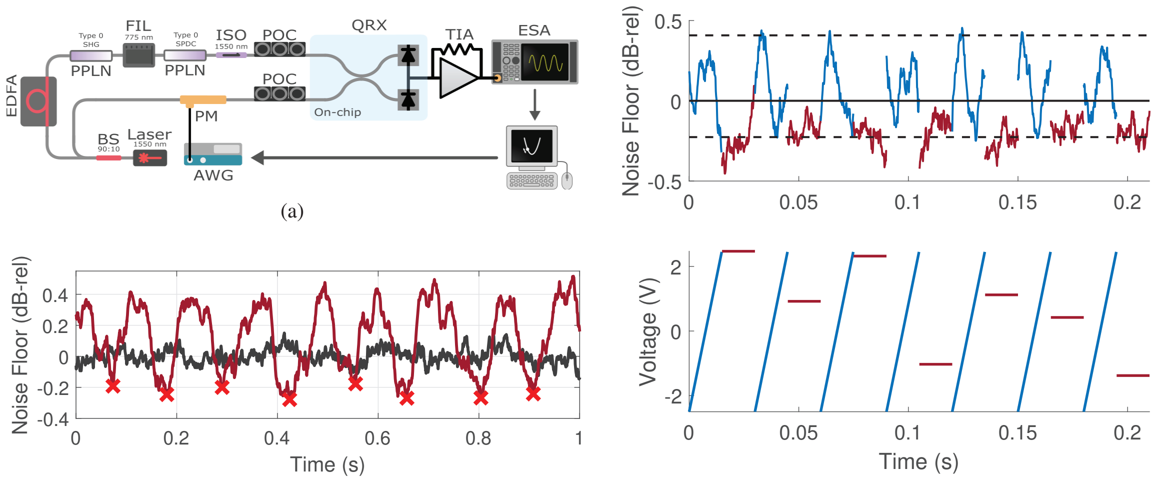
2. Quantum Coherent Receiver



(a) (b) (c)

Fig. 1: a) Micrograph of the integrated receiver with an area of 0.00200 mm^2. b) Noise floor integrated over 3 MHz of bandwidth with varying LO powers showing 26.0 dB SNC and 34.6 μW P_{knee}. c) Pump power sweep of the SPDC source showing μ=0.055 mW$^{1/2}$.

The quantum coherent receiver (QRX) consists of a silicon-photonic chip and the associated electronics. Two grating couplers are used to couple signal and local oscillator (LO) light into on-chip waveguides routed to a 50:50 directional coupler. The coupler mixes the signal and LO and sends the resulting light to two matched on-chip Ge photodiodes. Electrical outputs from the photodiodes are subtracted on-chip, and the resulting output is amplified using a trans-impedance amplifier (TIA). A micrograph of the compact photonic chip with its dimensions is shown in Fig. 1a. The integrated receiver has a core chip area of 0.00200 mm^2 (50 μm× 40 μm), making it the smallest detector with demonstrated quantum light detection capability. SNC and P_{knee} are two key design specifications that characterize the quantum noise performance of the QRX [3,4]. As seen in Fig. 1b, the QRX has 26.0 dB SNC and 34.6 μW P_{knee} with a noise floor integrated over 3 MHz of bandwidth.



(a)

(b)

(c)

Fig. 2: a) Setup with the silicon photonic receiver for squeezed light measurements. b) Oscillations between quadratures of the squeezed vacuum. Red crosses signify the squeezed quadrature. c) Demonstration of phase locking to the squeezed quadrature showing the noise floor (top) and modulator voltage (bottom).

3. Squeezed Light Measurements

The QRX was used to detect squeezed vacuum and demonstrate an easy-to-deploy phase-locking approach to lock onto the squeezed quadrature with the setup shown in Fig. 2a. The squeezed vacuum was generated with a periodically-poled lithium niobate (PPLN) waveguide. The PPLN was characterized with a tabletop coherent receiver. As seen in Fig. 1c, the μ from the fit is 0.055 $\mathrm{mW}^{1/2}$, which characterizes the squeezing parameter of the waveguide, given by $r = \mu\sqrt{P}$, where P is the SPDC pump power. The measured noise level at phase θ is then characterized by $\Delta X_m^2(\theta) = \eta\left[e^{2r}\cos^2\theta + e^{-2r}\sin^2\theta\right] + 1 - \eta$, where η is the detection efficiency. After source characterization, squeezed vacuum was coupled to chip, and noise floor oscillations in the output with 4 Hz LO phase modulation were measured with an electrical spectrum analyzer (ESA). A 100-second trace was recorded for both squeezed vacuum (red) and vacuum (black). A 1-second section of this data is shown in Fig. 2b. Over 100 seconds, noise floors 0.226 ± 0.096 dB below and 0.408 ± 0.146 dB above shot noise level (SNL) were observed.

Phase locking in quantum coherent receivers is useful for reaching sub-shot-noise-limited sensitivities with squeezed light and enabling phase-determinate quantum state tomography. A software-based phase-locking process can be useful for easily deploying coherent quantum links without the need for additional hardware in a quantum coherent transceiver system. Therefore, a phase-locking algorithm was employed to phase-lock the squeezed vacuum detected on-chip to its squeezed quadrature. The algorithm utilizes the phase modulator to do a π phase sweep and finds the phase voltage setting for the squeezed quadrature. The voltage setting is then applied to set the phase to the squeezed quadrature. This procedure is repeated at 67 Hz, as shown in Fig. 2c. This closed-loop phase locking enables sustained operation at sensitivities below the shot noise floor.

4. Conclusion

To our knowledge, the QRX has the highest SNC, lowest P_{knee}, and smallest footprint among the coherent receivers with demonstrated quantum light detection capability. With the first demonstration of phase locking to squeezed quadrature and sustained operation at noise floors below the SNL with on-chip balanced detection, this work enables large-scale integration of quantum coherent receivers toward practical quantum-enhanced optical sensors and transceivers. This compact building block and phase-locking demonstration will have applications in optical communications, sensing, and photonic quantum computing with large-scale quantum optoelectronic circuits.

References

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