Design of Silicon Quantum Squeezer

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Abstract: We present a silicon squeezer optimized for high-degree of squeezing and integration with balanced detection. The design entails linear properties (dispersion engineering and cavity finesse) and proper choice of pumping parameters for the nonlinear properties.

Quantum squeezing has broadened its application spectrum, from sensing gravitational waves to quantum simulation and communication, necessitating high squeezing levels alongside device compactness and integration. Silicon photonics, particularly through microring cavities [1], has advanced as a reliable source for squeezed vacuum in the photon pair generation regime [2, 3]. However, silicon's displays two-photon absorption (TPA) and a resulting free carrier absorption (FCA) that pose challenges for multi-photon per mode states [4], leading to a preference for SiN and LiNb nanophotonics despite silicon platforms maturity and compatibility with germanium detectors [5]. For applications like gaussian boson sampling that require monomode squeezing, dual pump non-degenerate four-wave mixing (FWM) in silicon emerges as a potent solution, enhancing the squeezing parameter well beyond unity. Addressing silicon photonics' TPA and FCA, our approach (see Fig. 1a.) harnesses the Kerr nonlinearity by pumping beyond silicon's half-bandgap, circumventing TPA [6,7] while the second (auxiliary) beam is at shorter wavelength and weaker intensity complying with boundaries set in [4]. To avoid that the strong main pump induces alone parasitic optical parametric oscillation or frequency comb generation [7], we can resort to extra loss in the spectral vicinity of the main pump to quench further this parametric gain that is already limited by a large phase mismatch [8]. The main pump wavelength, λ_{pump}, is thus strategically chosen at $\lambda_{\text{pump}} \approx 2350 \pm 30$ nm to exploit silica bottom cladding's loss window (2200-2300 nm) and substrate leakage (> 2600 nm), thereby mitigating parametric gain solely from the pump. With a targeted squeezing wavelength of $\lambda_{\text{sq}} = 1550 \pm 30$ nm, the auxiliary pump must be $\lambda_{\text{aux}} = 1156 \pm 40$ nm through energy conservation. In figure 1c, we scrutinize phase matching in relation to waveguide width assuming a silicon thickness of 220 nm, a partial etched depth of 150 nm, and exact wavelengths of 2350, 1567, and 1175 nm. The results show that phase matching is possible both for TE and for TM configurations. The TE configuration is selected because of the large bending loss of the TM waveguide at λ_{pump}.Optimizing cavity coupling is pivotal and challenging, seeking critical coupling at auxiliary and pump wavelengths to maximize intracavity power, while demanding overcoupling for the squeezed wave to give a high escape probability. As depicted in Fig. 1b, we employ separate couplers for the squeezed/auxiliary waves and the pump. For the pump-side coupler (Fig. 1d), a large gap ensures suitable pump coupling (1-10%) and negligible coupling for the other waves (below 1/1000) with a 600 nm waveguide

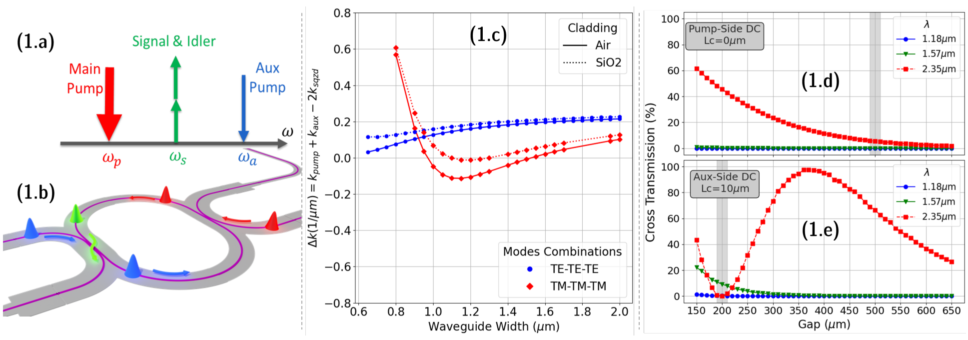

Fig. 1. Visualization of the quantum squeezer configuration, featuring: (1.a) the two-pump four-wave mixing scheme, (1.b) the micro-resonator outline, (1.c) the phase mismatch (Δk) against waveguide width under air and SiO_2 claddings, and (1.d-e) coupling factors for the two bus-to-waveguide directional couplers as function of the gap width (grey zones mark chosen parameters; see text)

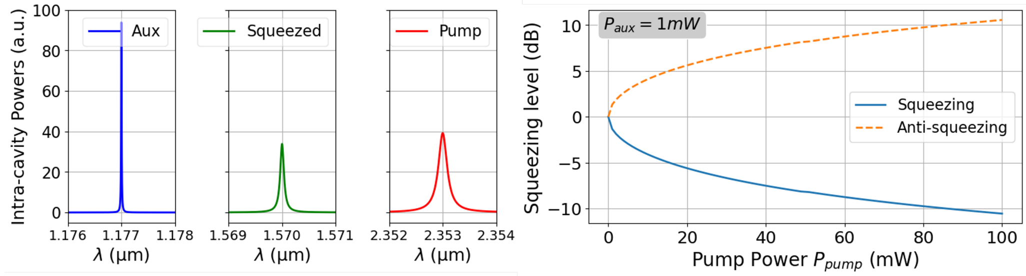

Fig. 2. (Left) Intra-cavity power enhancement factors for the three waves. (Right) Predicted levels of squeezing and anti-squeezing (dB) [see text for the assumed parameters].

and TE polarization. Selected parameters (500 nm gap and 0 μm straight coupling section) result in an coupling $\kappa_{\text{pump}} = 7.5\%$. The auxiliary coupler (Fig. 1d) requires weak coupling at λ_{pump} yet strong coupling at λ_{sq} and λ_{aux} which can be attained by leveraging the directional coupler's periodicity with its length. Scanning waveguide widths, gap sizes, and coupling lengths, an optimal parameter set emerged, featured in Fig. 1e's grey-shaded area (200 nm gap with a 10 μm coupling section), resulting in $\kappa_{\text{aux}} = 2\%$ and $\kappa_{\text{sq}} = 10\%$. Our simulations, conducted via FDTD, consider coupling across the directional coupler's bend, ensuring an accurate representation of wave transmissions. A racetrack cavity, with a 200 μm length, 20 μm bend radius and air top cladding, is modeled considering propagation losses of $\alpha_{\text{aux}} = 2$ dB/cm , $\alpha_{\text{sq}} = 1.4$ dB/cm, $\alpha_{\text{pump}} = 2.5$ dB/cm and the coupling coefficients here-above. The anticipated cavity resonances in the linear regime are shown in Fig.2(left). Estimating the squeezing factor and variance from our parameters and input powers, we calculate photon generation via FWM, quantified by the spectral brightness [9]. The squeezing factor $r = \ln(R)$, derived from $\langle n \rangle = \sinh^2(r)$ [10], determines the squeezing and anti-squeezing variances $\langle \Delta X^2 \rangle = \frac{1}{2R^2}$ and $\langle \Delta P^2 \rangle = \frac{R^2}{2}$, respectively. Squeezing levels, $10\log_{10}(2V)$ (dB), correlate with pump power are graphed in Fig. 2 (right), with $P_{\text{aux}} = 1$ mW. In our analysis the cross phase modulation (XPM) and the cross two photon absorption have been neglected. While, the XPM may help in fine tuning the phase matching to our advantage, the cross two-photon absorption,and hence FCA, may demand the addition of a junction to sweep photo generated carriers [2]. Finally, we note that the strong pump regime comes with nonlinear phase shifts that result in bifurcation of the intracavity power requiring a dedicated spectral tuning between pump and cavity lines [11]. This design can be readily fabricated using existing technological process. It thus offers a pathway for an experimental realization and underscore the potential of the silicon platform for quantum squeezing. **Acknowledgments.** Stéphane Clemmen is a research associate of the Fonds de la Recherche Scientifique (FNRS). This work was supported by the FWO-Weave grant G092922N.

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