Scalable squeezed light source for continuous variable quantum sampling

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Abstract: We propose a squeezed light source meeting the stringent requirements of continuous variable quantum sampling. With typical parameters, squeezed states with mean photon number of 10 or higher can be generated at repetition rates of over 100MHz.

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No degenerate squeezed light source has yet been proposed which satisfies all the requirements for practically useful quantum sampling. These stringent requirements are:

(i) Scalability: the ease with which many tens or hundreds of identical mutually coherent and stabilized squeezed light sources can be integrated on one monolithic platform.
(ii) Single-mode operation: the capability of producing squeezed light in a *single* spatiotemporal mode, consistent across multiple sources and a wide range of squeezing levels, obviating the need for bulky and lossy mode-selective elements.
(iii) Squeezing levels sufficient to enable a genuine quantum advantage in computation [1], simulation [2], and sampling [3].
(iv) Compatibility with single photon and photon number-resolving detectors [4], which are highly sensitive to noise from residual pump or spuriously generated light, and require squeezed light without bright classical mean fields.

The requirements (ii) and (iii) can be succinctly stated in mathematical terms: an ideal source provides an output quantum state of the form $e^{(r/2)A^2-\text{H.c.}}|\text{vac}\rangle$, with squeezing factor r reliably tunable, and in which $A=\int d\omega f(\omega)a(\omega)$ is the annihilation operator for a single well-defined spatiotemporal mode, the characteristics of which do not vary over the tuning range of r.

We propose a novel squeezed light source meeting the stringent requirements of continuous variable quantum sampling. With *typical* realistic parameters, squeezed states with mean photon number of 10 or higher can be generated in a single consistent temporal mode at repetition rates of over 100MHz. Over 15dB of squeezing is expected in existing ultra-low loss platforms. To attain a source with this performance, that is compatible with established nanophotonic platforms, we use the time-dependent effective second-order nonlinear interaction induced by a strong driving beam in the presence of the χ_3 response in a microresonator [5]. This allows us to write an effective squeezing Hamiltonian for 3 resonator modes, driving (D), pump (P) and squeezer (S) as

$$H_{\text{sq}} \sim \chi_3 b_D b_P b_S^\dagger b_S^\dagger + \text{H.c.} \to (\chi_3\beta_D)\beta_P b_S^\dagger b_S^\dagger + \text{H.c.} = \chi_2^{\text{eff}}\beta_P b_S^\dagger b_S^\dagger + \text{H.c.}, \tag{1}$$

where the classical amplitudes satisfy $\beta_D \gg \beta_P$ and β_D is quasi continuous-wave. This operation regime allows us to suppress spurious effects such as dynamical detunings induced by self- and cross-phase modulation of the pumps since, for our proposal, the largest contribution of these effects is a static detuning proportional to $|\beta_D|^2$. We verify the operation of the device by solving for the dynamics of the second order moments of the output operators describing light scattered off the ring after the nonlinear interaction has occurred inside it. The output operators $\psi_{S,\text{out}}(t)$ are linked to the input operators $\psi_{S,\text{in}}(t)$ via the standard input-output relation $\psi_{S,\text{out}}(t) = \psi_{S,\text{in}}(t) - i(\gamma_S/v_g)b_S(t)$, where γ_S determines the decay rate of the resonator mode S into the waveguide via $\Gamma_S = |\gamma_S|^2/(2v_g)$ and v_g is the group velocity of the waveguide mode coupled to the ring. In turn, the input operators drive vacuum fluctuations into the resonator dynamics via

$$\frac{d}{dt}\begin{pmatrix} b_S(t) \\ b_S^\dagger(t)\end{pmatrix} = \begin{pmatrix} -\bar{\Gamma}_S + i\left(\frac{\Delta_{\text{net}}}{2} + 2\Lambda|\beta_P(t)|^2\right) & g(t) \\ g^*(t) & -\bar{\Gamma}_S + i\left(\frac{\Delta_{\text{net}}}{2} + 2\Lambda|\beta_P(t)|^2\right)\end{pmatrix}\begin{pmatrix} b_S(t) \\ b_S^\dagger(t)\end{pmatrix} + \mathbf{d}_{\text{in}}(t), \tag{2}$$

where the input fluctuation operators are

$$\mathbf{d}_{\text{in}}(t) = \begin{pmatrix} -i\gamma_S^* \psi_{S,\text{in}}(t) - i\mu_S^* \phi_{S,\text{in}}(t) \\ i\gamma_S \psi_{S,\text{in}}^\dagger(t) + i\mu_S \phi_{S,\text{in}}^\dagger(t) \end{pmatrix}. \tag{3}$$

Here the function $g(t) \equiv 2i\Lambda\overline{\beta}_D\overline{\beta}_P(t)$ describes the time-dependent nonlinearity in the resonator, and $\overline{\Gamma}_S = \Gamma_S + M_S$ the total damping rate of the resonator S mode, to which both scattering loss (with associated rate $M_S = |\mu_S|^2/(2v_g)$) and the resonator-channel coupling (with associated rate $\Gamma_S = |\gamma_S|^2/(2v_g)$) contribute. These are related to the full loaded quality factor $Q_S = \omega_S/(2\overline{\Gamma}_S)$ and the escape efficiency $\eta_S^{\text{esc}} = \Gamma_S/\overline{\Gamma}_S$. Finally, $\Delta_{\text{net}} = \Delta_{\text{res}} + \Delta_{\text{SPM}} - \Delta_{\text{XPM}}$ is the net detuning due to the resonances being unevenly spaced and due to self- and cross-phase modulation, $\phi_{S,\text{in}}$ are operators used to account for scattering in non-guided modes (scattering loss) and $\Lambda \approx \hbar\omega_S v_g^2 \gamma_{NL}/(2L)$, with L the resonator length, and γ_{NL} the waveguide nonlinear parameter.

We consider a device optimized for a CW drive input power of 200 mW and include the effects of time-dependent self-phase modulation and cross-phase modulation from the pump pulse. In Fig. 1 (a) we show the squeezing performance for a structure with 400 μm round-trip length, $\omega_S = 2\pi \times 193$ THz, nonlinear parameter $\gamma_{\text{NL}} = 1\ (\text{Wm})^{-1}$, group velocity $v_g = c/1.7$, and intrinsic quality factor of 2×10^6 for all three resonances with escape efficiencies of 0.5 (critically coupled) for the drive mode D, 0.9 for the S mode, and 0.98 for the pump mode P; the corresponding loaded quality factors are then respectively 1×10^6, 2×10^5, and 4×10^4. In Fig. 1 (b) We show the mean photon-number occupation of the first ten Schmidt modes; note that the dominant mode lies about 100x above the next largest mode. These results show that our design satisfies desiderata (ii) and (iii) of our list and together with appropriate fabrication and pump suppression techniques can also be made to satisfy desiderata (i) and (iv).

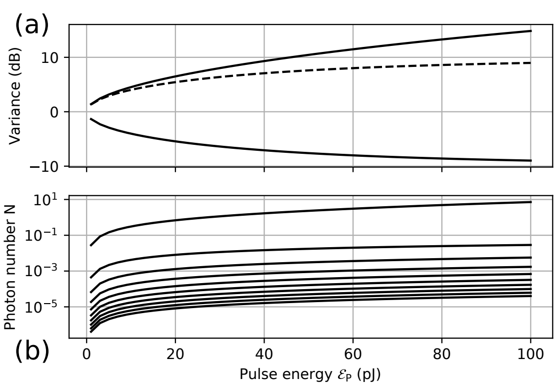

Fig. 1: System performance for a device with realistic parameters (details in text): (a) Variance relative to vacuum of the squeezed quadrature (bottom solid curve) and anti-squeezed quadrature (top solid curve) for the dominant mode. Dashed curve shows variance of anti-squeezed quadrature for an ideal pure state; Some excess anti-squeezing is evident from the finite escape efficiency. (b) Mean photon number of the first ten Schmidt modes as a function of pulse energy; the dominant mode (top curve) consistently lies about 100x above the next largest mode.

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