Intracavity squeezing as a tool for improving the QND measurement scheme

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Plan of presentation

01 QND concept

XPM, SPM nonlinear effects; microresonators

02 Kerr QND scheme

Proposal & results

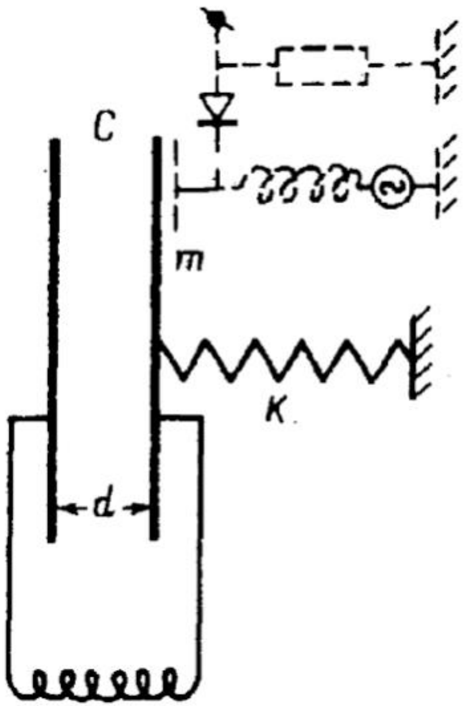
03 Application of squeezed light

Input, output, accounting for losses

04 Intracavity squeezing

Estimations on sensitivity, comparison of different schemes

Quantum nondemolition measurement concept



$$\Delta A \Delta B \geq \frac{1}{2}|\langle \hat{A}\hat{B} - \hat{B}\hat{A}\rangle|$$

$$[\hat{A}(t_j), \hat{A}(t_k)] = 0$$

$$[\hat{A}(t), \hat{H}(t)] = 0$$

$$\hat{H}(t) = \hat{H}_M(t) + \hat{H}_A(t) + \hat{H}_I(t).$$

$$[\hat{A}(t), \hat{H}_I(t)] = 0$$

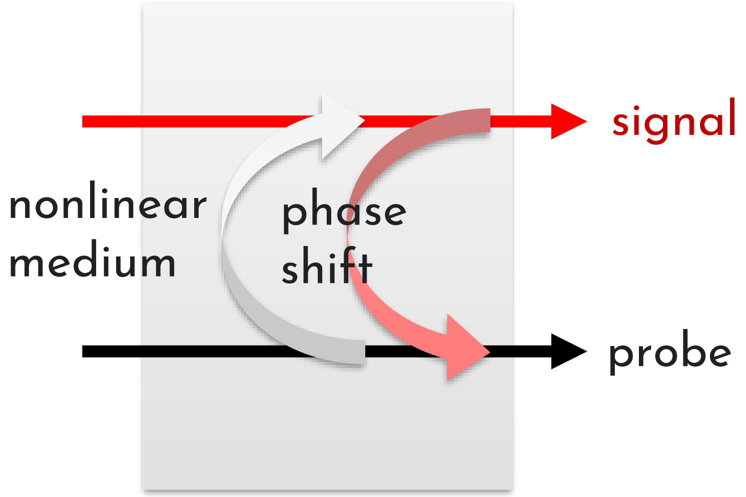
A(t) — observable
H_I(t) — Hamiltonian of interaction between system & the meter
H_M(t) — Hamiltonian of meter
H_A(t) — Hamiltonian of object

V. B. Braginsky, Yu. I. Vorontsov, and F. Ya. Khalili, Quantum singularities of a ponderomotive meter of electromagnetic energy, Zh. Eksp. Teor. Fiz. 73, 1340 (1977) [Sov. Phys. JETP 46, 705 (1977)].

XPM

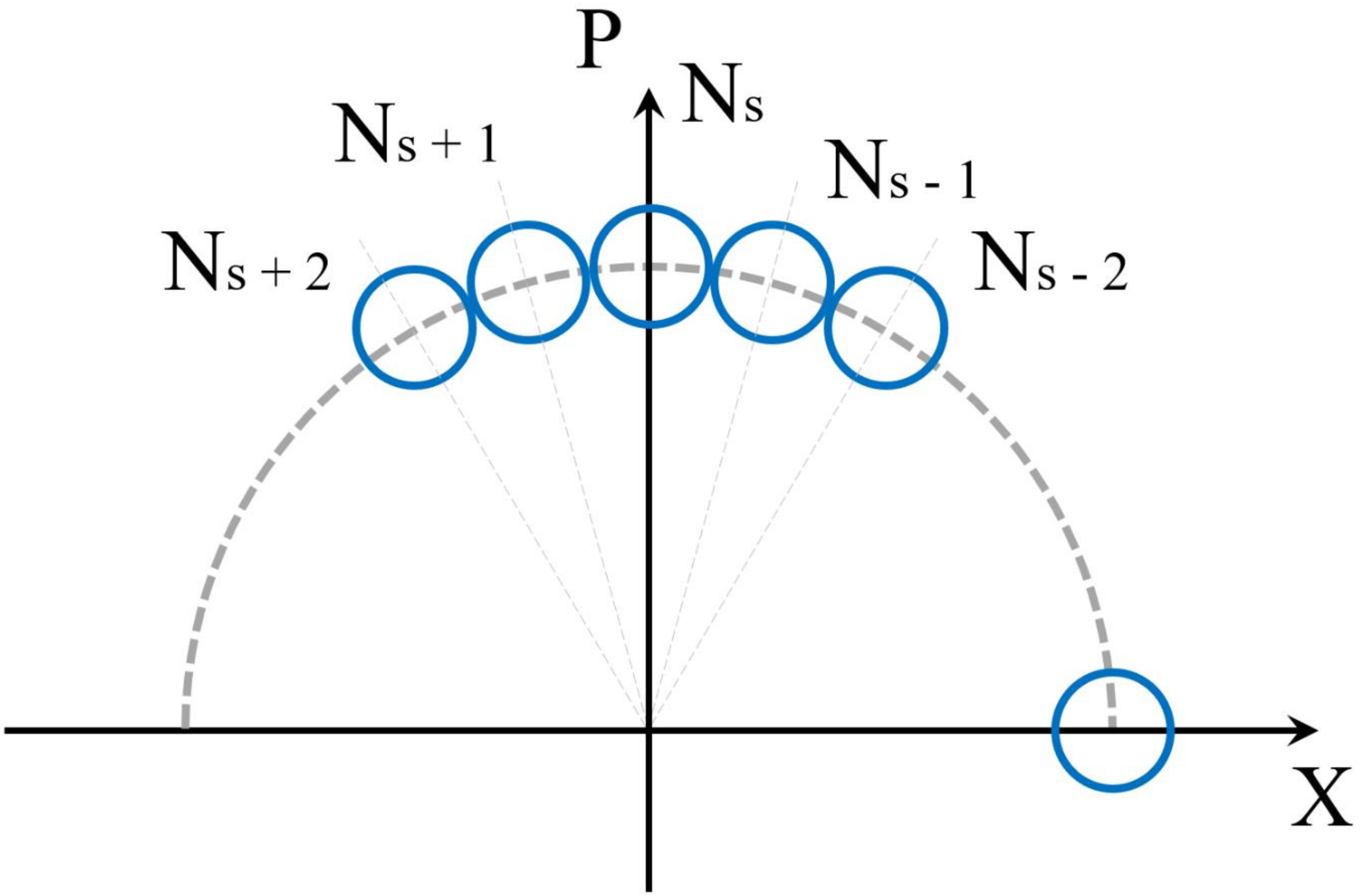
cross-phase modulation effect — one wavelength of light can affect the phase of another wavelength of light through the optical Kerr effect

$$n = n_0 + \frac{3\chi^{(3)}}{8n_0}|E_0|^2 = n_0 + n_2 I$$



$$\delta\phi_p = \Gamma_X N_s$$

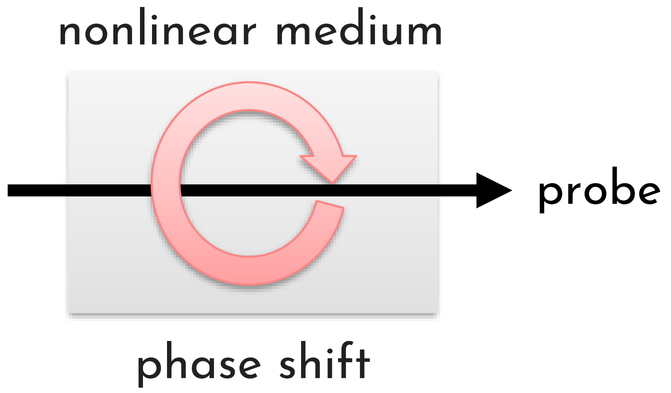
$$\delta\phi_s = \Gamma_X N_p$$


P
N_s
N_{s+1}
N_{s-1}
N_{s+2}
N_{s-2}
X

undesirable effect

SPM

self-phase modulation effect — light, when travelling in a medium, will induce a change of refractive index of the medium due to the optical Kerr effect. This variation in refractive index will produce a phase shift in the pulse



$$\delta\phi_p = \Gamma_S N_p$$

CaF_2

$Q_{intr} = 3 \times 10^{11}$

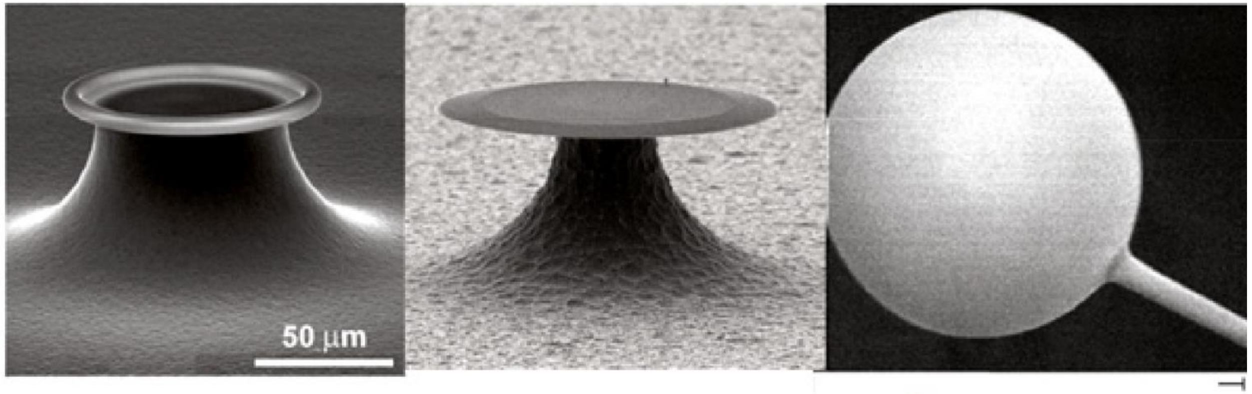
$n_2 = 3.2 \times 10^{-20}\ m^2/W$

$\Gamma_X \approx \Gamma_S \approx 0.85 \times 10^{-6} \times Q_{load} / 10^9$

Microresonators

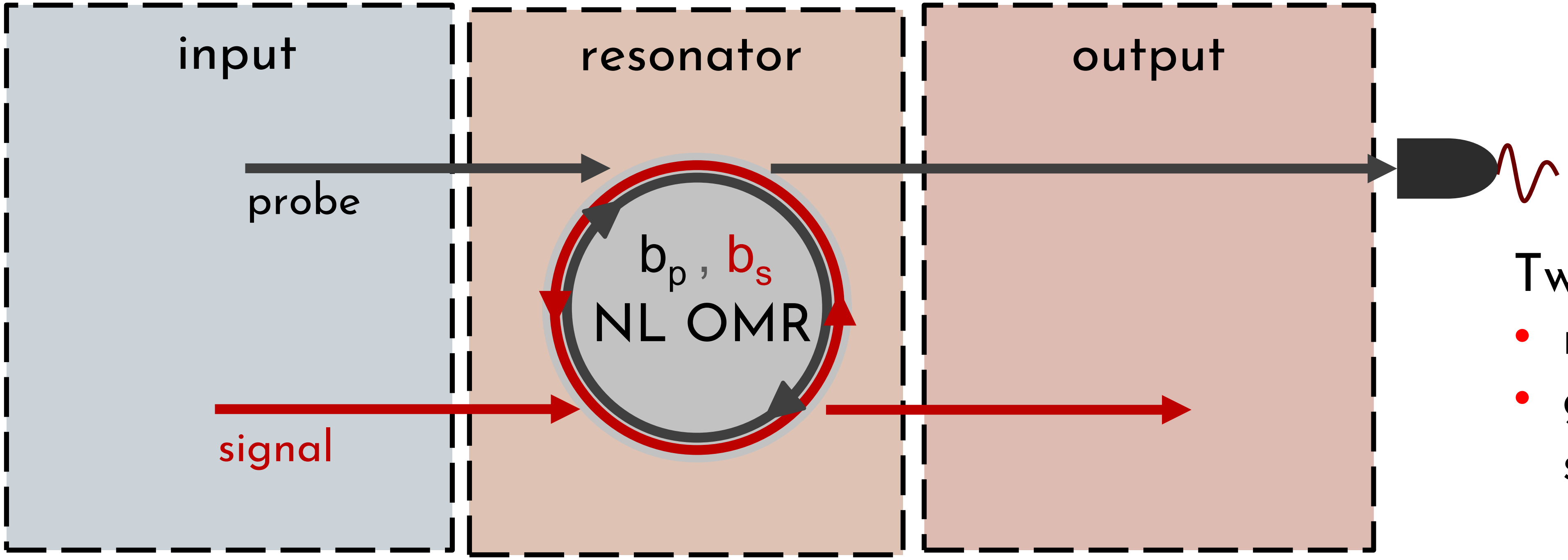
- High Q-factor
- Big nonlinearity
- Can be implemented on a chip

Toroidal Microresonators Microdisk Resonator Microsphere Resonator



Schliesser, Albert, and Tobias J. Kippenberg. "Cavity optomechanics with whispering-gallery mode optical micro-resonators." *Advances In Atomic, Molecular, and Optical Physics.* Vol. 58. Academic Press, 2010. 207-323.

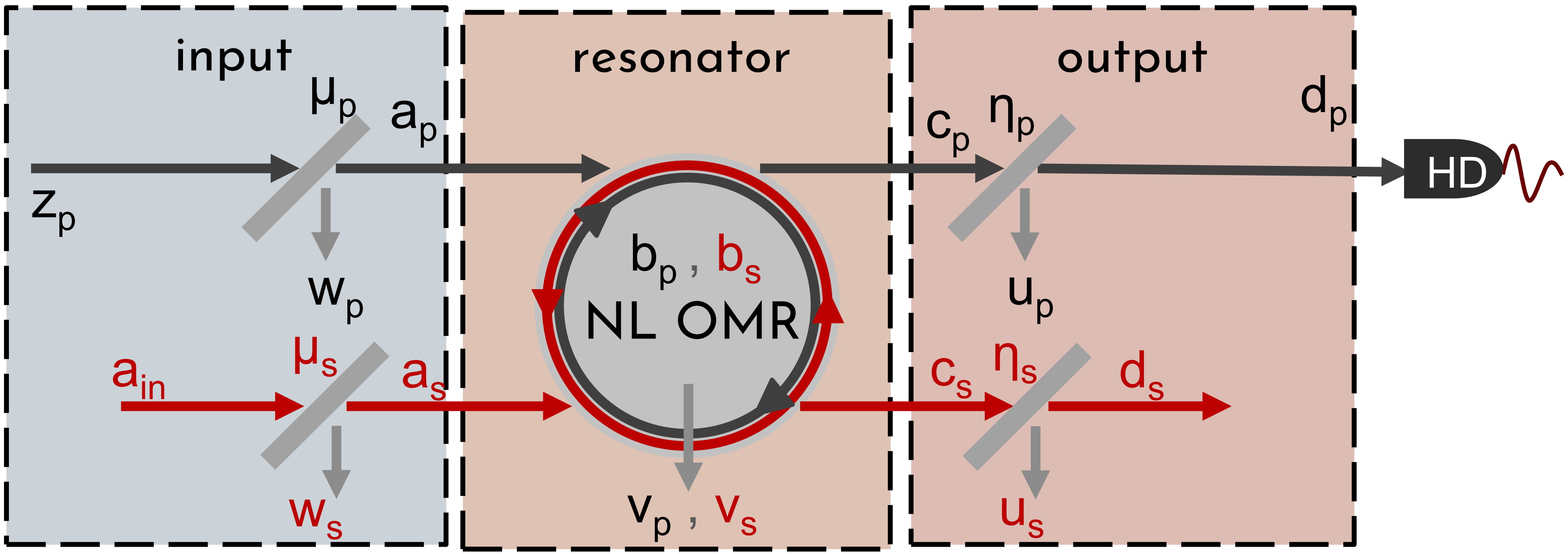
QND scheme



Two tasks:
- measurement
- generation of states

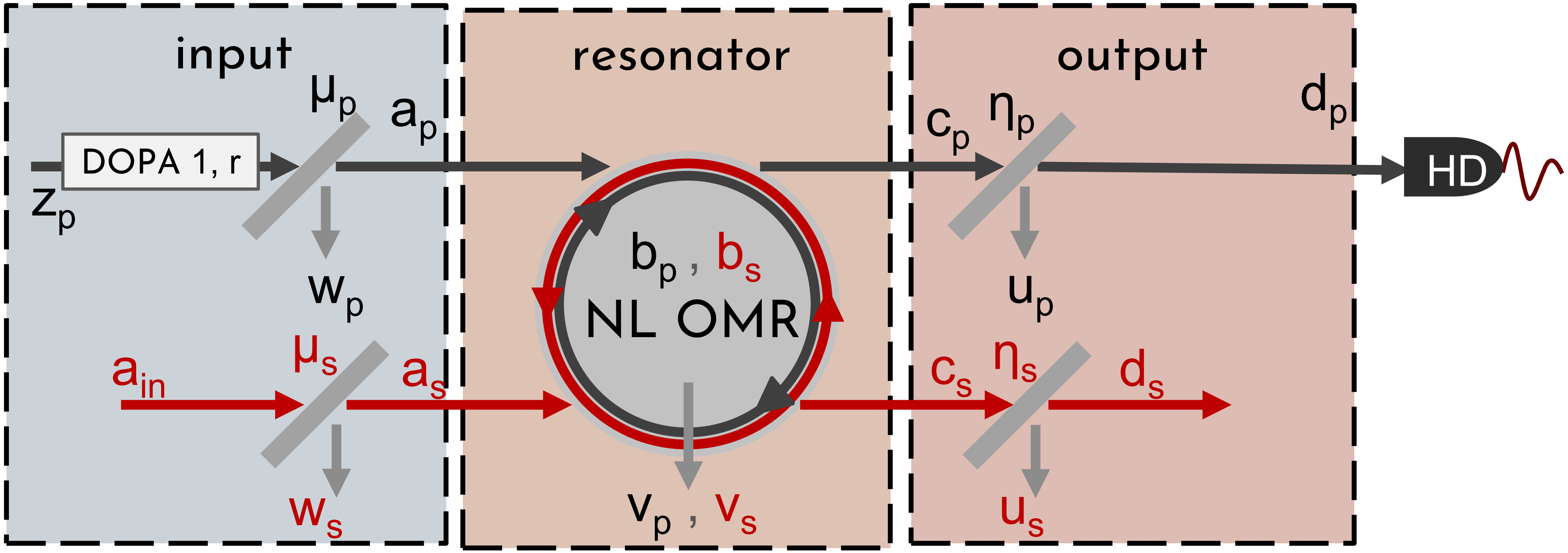
Balybin, S. N., et al. "Quantum nondemolition measurements of photon number in monolithic microcavities." *Physical Review A* 106.1 (2022): 013720.

Losses: Imaginary beamsplitter model

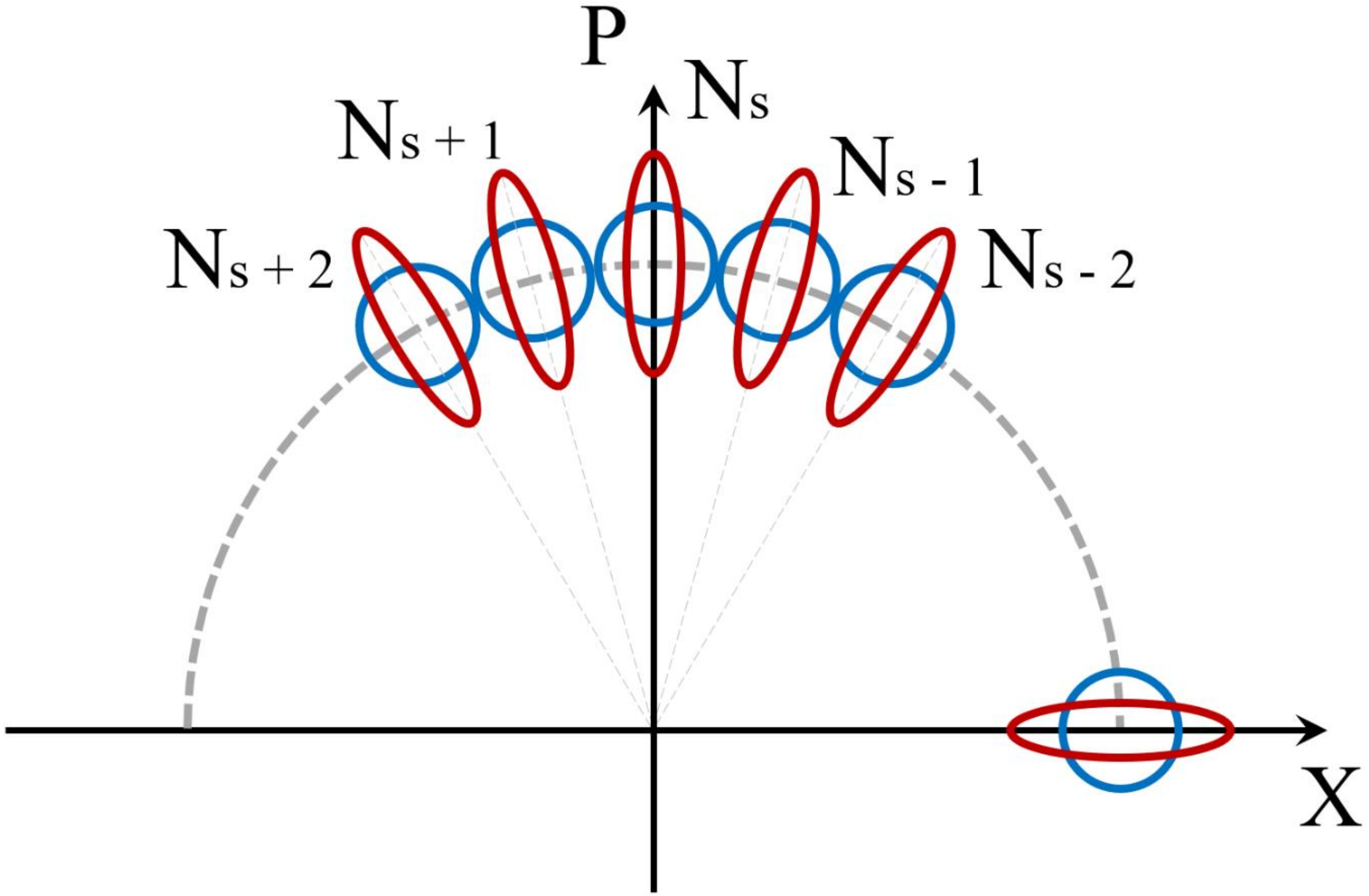


Balybin, Stepan, Dariya Salykina, and Farid Ya Khalili. "Improving the sensitivity of Kerr quantum nondemolition measurement via squeezed light." *Physical Review A* 108.5 (2023): 053708.

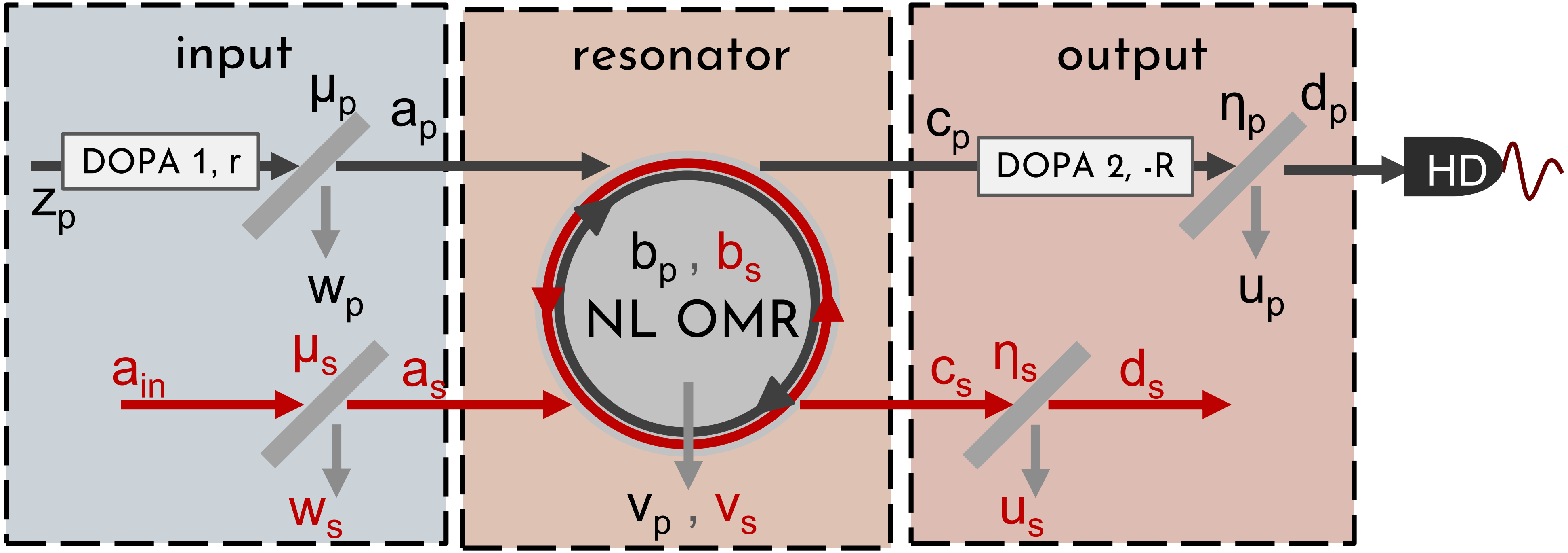
QND scheme + squeezed input



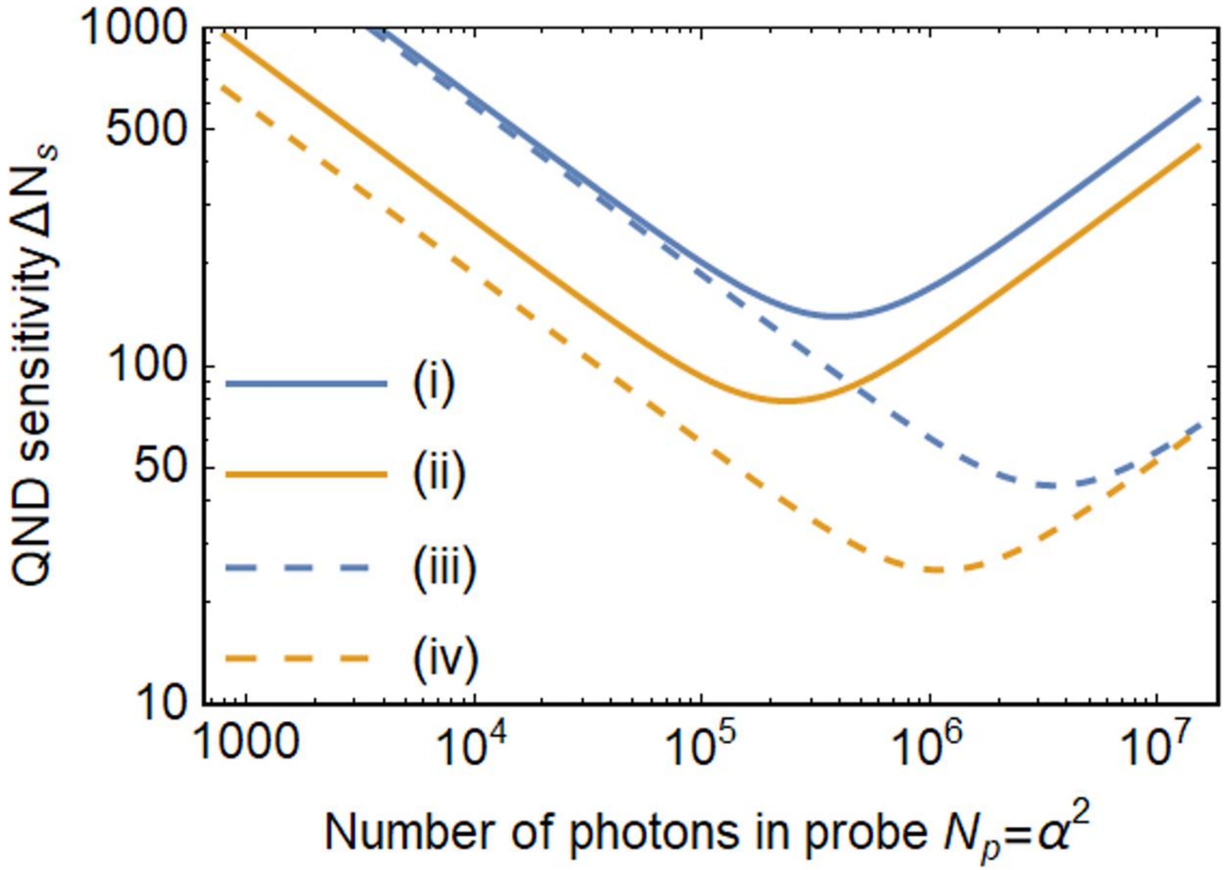
Balybin, Stepan, Dariya Salykina, and Farid Ya Khalili. "Improving the sensitivity of Kerr quantum nondemolition measurement via squeezed light." *Physical Review A* 108.5 (2023): 053708.


P
Ns
Ns + 1
Ns - 1
Ns + 2
Ns - 2
X

QND scheme + squeezed input + DOPA before detection



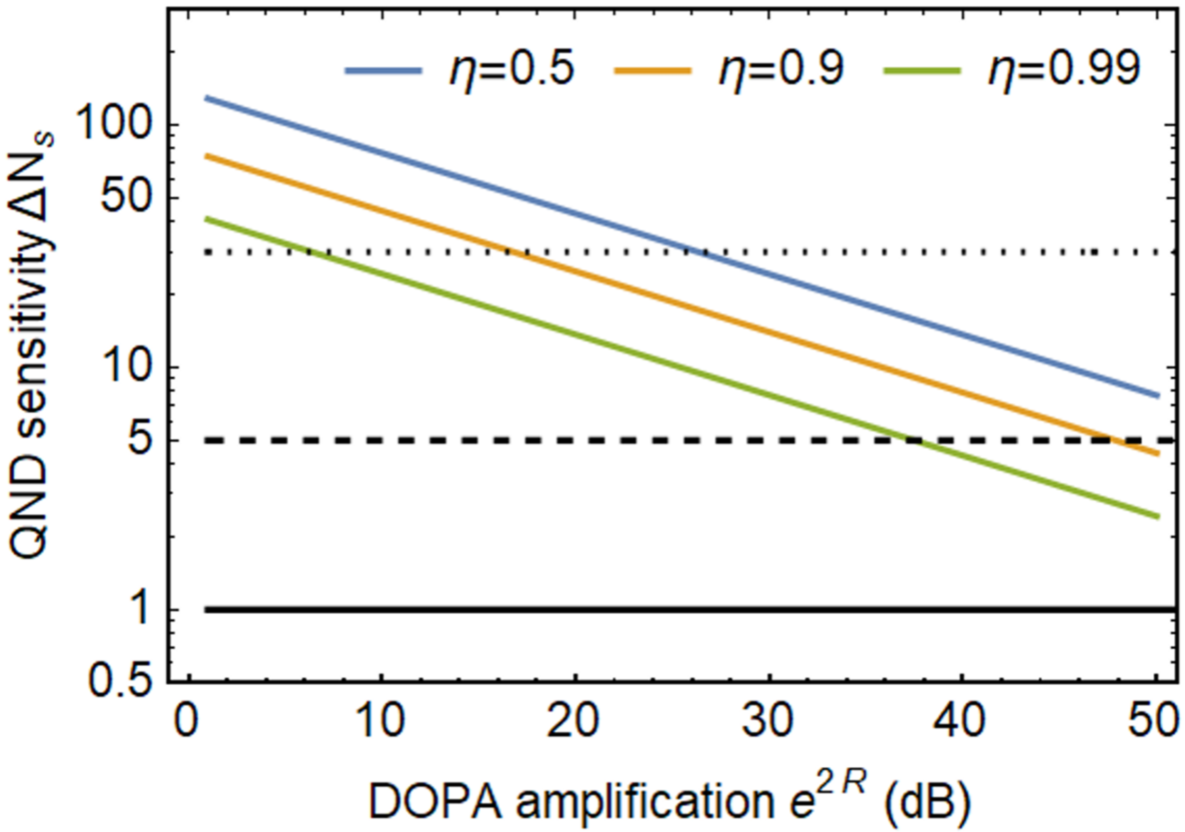
Results



(i) No squeezing: $e^{-2r} = e^{-2R} = 1$
(ii) Input DOPA: $e^{-2r} = 0.1$ and $e^{-2R} = 1$
(iii) Output DOPA: $e^{-2r} = 1$
and $e^{-2R} = 0.01$
(iv) Input + output DOPAs: $e^{-2r} = 0.1$
and $e^{-2R} = 0.01$

Balybin, Stepan, Dariya Salykina, and Farid Ya Khalili. "Improving the sensitivity of Kerr quantum nondemolition measurement via squeezed light." *Physical Review A* 108.5 (2023): 053708.

Results



Criterion for non-Gaussianity of state

$$\Delta N \lesssim N^{1/3}$$

the black dotted line ΔNs = 30 approximately corresponds to the non-Gaussianity limit for $Ns \sim 10^3 - 10^4$

M. Kitagawa and Y. Yamamoto, Number-phase minimum-uncertainty state with reduced number uncertainty in a kerr nonlinear interferometer, Phys. Rev. A 34, 3974 (1986).

Balybin, Stepan, Dariya Salykina, and Farid Ya Khalili. "Improving the sensitivity of Kerr quantum nondemolition measurement via squeezed light." *Physical Review A* 108.5 (2023): 053708.

QND scheme + intracavity squeezing

$$\frac{\hat{H}}{\hbar} = \sum_{x=s,p}\left(\omega_x \hat{b}_x^\dagger \hat{b}_x - \underbrace{\frac{\gamma_S}{2}\hat{b}_x^{\dagger 2}\hat{b}_x^2}_{\text{SPM}}\right) - \underbrace{\gamma_X \cdot \hat{b}_p^\dagger \hat{b}_s^\dagger \hat{b}_p \hat{b}_s}_{\text{XPM}} + \underbrace{\frac{ik}{2}\left(\hat{b}_p^{\dagger 2} e^{-2i\omega_p' - i\phi} - \hat{b}_p^2 e^{2i\omega_p' + i\phi}\right)}_{\text{parametric interaction}}$$

Salykina, Dariya, Stepan Balybin, and Farid Ya Khalili. "Intracavity squeezing for a Kerr quantum nondemolition measurement scheme." *Physical Review A* 111.1 (2025): 013715.

QND scheme + intracavity squeezing

$$k_c = k \cos\phi\,, \quad k_s = k \sin\phi$$

Equation of motion:

SPM XPM

$$[\ell_p(\Omega) + k_c]\hat{b}^s_p + (k_s - B_{pp})\hat{b}^c_p(\Omega) = B_{sp}\hat{b}^c_s(\Omega) + \sqrt{2\kappa'_p}\hat{a}^s_p(\Omega)$$

= 0 => elimination of SPM

$$k_s = B_{pp}$$

$$k_c = \frac{(\kappa'_p - \kappa''_p)e^{-2r} - \epsilon^2\kappa_p e^{-2R}}{e^{-2r} + \epsilon^2 e^{-2R}}$$

— sign depends on the loss ratio

Salykina, Dariya, Stepan Balybin, and Farid Ya Khalili. "Intracavity squeezing for a Kerr quantum nondemolition measurement scheme." *Physical Review A* 111.1 (2025): 013715.

Comparison of the results

QND scheme

$$(\Delta N_s)^2 = \frac{\Gamma_S}{\Gamma_X^2}\sqrt{\frac{1-\eta}{\eta}}$$

QND scheme + DOPAs

$$(\Delta N_s)^2 = \frac{\Gamma_S}{\Gamma_X^2}\sqrt{\frac{1-\eta}{\eta}e^{-r-R}}$$

QND scheme + DOPAs + intracavity squeezing

$$(\Delta N)^2_{\text{intr}} = \frac{\epsilon e^{-r-R} + \kappa_p''\tau}{2\Gamma_X^2 \boxed{N_p}}$$

Salykina, Dariya, Stepan Balybin, and Farid Ya Khalili. "Intracavity squeezing for a Kerr quantum nondemolition measurement scheme." *Physical Review A* 111.1 (2025): 013715.

Estimations

To achieve single-photon sensitivity, the average number of photons in the signal mode is limited by the condition:

$$N_s < \frac{1}{\epsilon^2_{\text{in, out}}} \qquad \epsilon^2_{\text{in, out}} \sim 0.1 \qquad N_s \lesssim 10$$

To achieve the limit of obtaining non-Gaussian states of light, the following limit must be met:

$$N_s \lesssim \frac{1}{\epsilon^6_{\text{in, out}}} \qquad N_s \lesssim 10^3$$

Conclusions

- It is shown that the use of internal squeezing in the scheme makes it possible to suppress the effect of self-phase modulation. The sensitivity of the considered scheme is limited only by the available power of the pump beam and losses in the signal beam.
- Estimates show that single-photon sensitivity can be achieved for the number of photons inside the microresonator, and bright non-Gaussian states of light with up to 10^3 photons can be generated and verified.

Thank you for your attention!