The squeezing spectrum

- The power spectrum density of the quadrature’s quantum noise (squeezing spectrum):
\[ P(\omega, \theta) = 1 + \int_{-\infty}^{\infty} \text{d} \omega' \frac{\text{d}^2 \Phi_\theta(\omega', \theta)}{\text{d} \omega'^2}, \]
where \( \Phi_\theta(\omega', \theta) \) is the quadrature of the \( \theta \)th output field.

- The squeezing figure of merit measured in decibels is:
\[ Q(\omega, \theta) = 10 \log_{10} P(\omega, \theta). \]

- The maximum and minimum of \( P(\omega, \theta) \) as a function of \( \theta, N(\omega, \theta) = \max_\theta P(\omega, \theta) \) and \( \text{S}(\omega, \theta) = \min_\theta P(\omega, \theta) \), are spectra of the quantum noise in anti-squeezed and squeezed quadratures, respectively. The corresponding logarithmic spectral measures of anti-squeezing and squeezing:
\[ Q(\omega) = 10 \log_{10} P(\omega), \]
(15)

- Using Eq. (12), we find:
\[ P(\omega, \theta) + N(\omega, \theta) + \text{S}(\omega, \theta) = 2 |M(\omega)|^2. \]
(16)

The physical description of the CQFN of two coupled OPOs

- Pump fields for both OPOs are assumed to be classical and not shown in the scheme.
- From the control theory perspective, OPO1 is considered to be the plant and OPO2 the (quantum) controller.
- Each OPO cavity has a fictitious third mirror to model intracavity losses.
- Beam splitters B1 and B2 represent the light diverted to lock the cavities as well as losses in optical transmission lines between the OPOs.
- Phase shifters P1 and P2 are inserted into transmission lines between the OPOs to manipulate the interference underlying the CQF control.
- Taking into account the feedback loop between the plant and controller, the CQFM has seven input ports, seven output ports, and two cavity modes (\( n = 1, m = 2 \)).
- With \( \xi_c = |\xi_c|^2 \) and \( \xi_e = |\xi_e|^2 \), there is a total of 17 real parameters.
- The relationship between leakage rate and power transmittance of a mirror:
\[ \kappa_i = cT_i/(2l_{eff}), \quad i = 1, 2, 3, \]
(17)

The model of a network of two coupled OPOs

- A schematic depiction of the CQFN of two coupled OPOs:
- The model of a network of two coupled OPOs:
- The double-length column vectors notation:
\[ \begin{pmatrix} a_1 \ a_2 \ \cdots \ a_n \end{pmatrix} = \text{vec}(a), \]
where \( a = [a_1, a_2, \ldots, a_n]^T \).

- The model of a network of two coupled OPOs:
- The squeezing spectrum of the quadrature’s quantum noise (squeezing spectrum):
\[ P(\omega, \theta) = 1 + \int_{-\infty}^{\infty} \text{d} \omega' \frac{\text{d}^2 \Phi_\theta(\omega', \theta)}{\text{d} \omega'^2}, \]
where \( \Phi_\theta(\omega', \theta) \) is the quadrature of the \( \theta \)th output field.

- The squeezing figure of merit measured in decibels is:
\[ Q(\omega, \theta) = 10 \log_{10} P(\omega, \theta). \]

- The maximum and minimum of \( P(\omega, \theta) \) as a function of \( \theta, N(\omega, \theta) = \max_\theta P(\omega, \theta) \) and \( \text{S}(\omega, \theta) = \min_\theta P(\omega, \theta) \), are spectra of the quantum noise in anti-squeezed and squeezed quadratures, respectively. The corresponding logarithmic spectral measures of anti-squeezing and squeezing:
\[ Q(\omega) = 10 \log_{10} P(\omega), \]
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- Using Eq. (12), we find:
\[ P(\omega, \theta) + N(\omega, \theta) + \text{S}(\omega, \theta) = 2 |M(\omega)|^2. \]
(16)

Numerical optimization results for the squeezing spectrum

- Optimized squeezing spectra for different values of intracavity loss:
- Optimized squeezing spectra for different values of OPO pump power:

Conclusions and future directions

- The (S, L, H) model makes it possible to evaluate the squeezing spectrum of the output field from the CQFN of two OPOs for various values of experimental parameters.
- We use Sequential Least Squares Programming (SLSQP) to maximize squeezing at a chosen frequency by searching over the space of model parameters.
- Since SLSQP is a local (deterministic) algorithm, it can be trapped at a local maximum.
- We are working on using global (stochastic) algorithms such as Differential Evolution, to identify globally optimal parameter sets.