Perfect pulsed inline twin-beam squeezers

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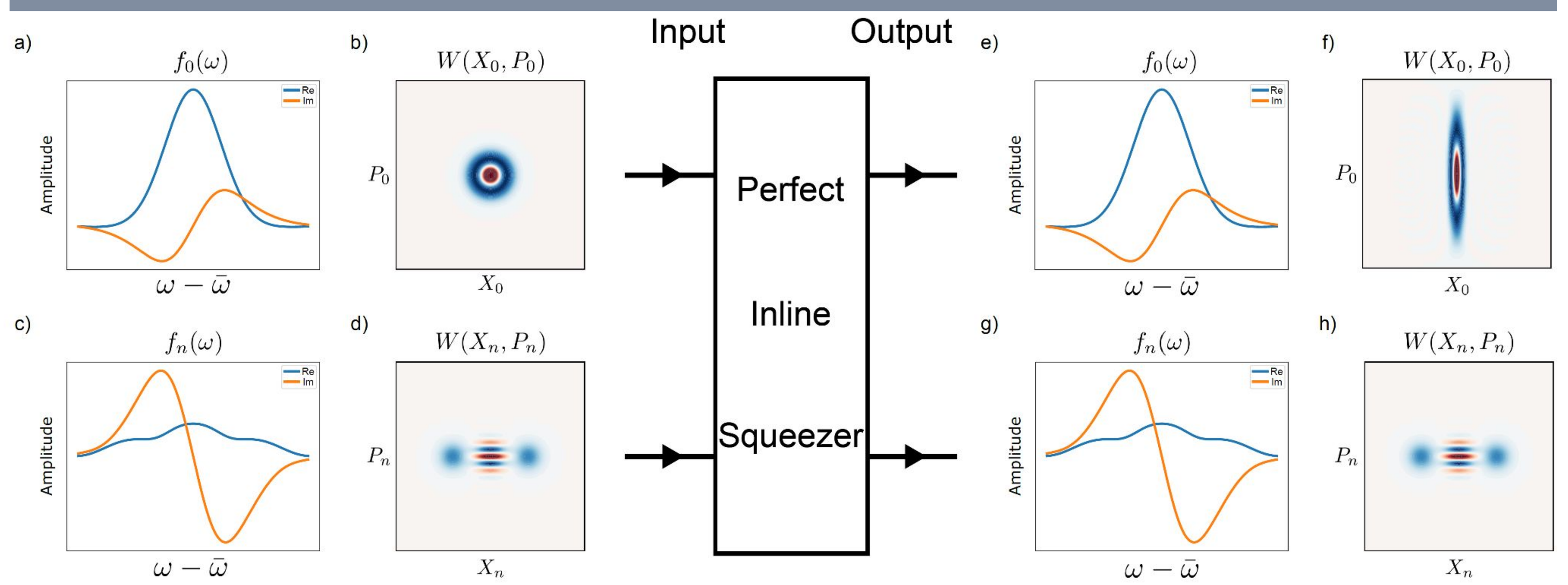
MOTIVATION

Inline squeezers have been shown to be important in non-Gaussian state generation using heralding, quantum metrology using su(1,1) interferometers, simulation of quantum field theories, and as continuous-variable quantum computing gates.

An inline squeezer is any type of squeezer that is seeded by an arbitrary quantum state which differs from vacuum. They are characterized by two sets of Schmidt modes: the Input Schmidt modes and the Output Schmidt modes.

We provide analytical relations between the Input and Output modes for different waveguide configurations to identify which ones lead to perfect inline squeezers.

PERFECT INLINE SQUEEZER



- Single mode operation.
- Matched Input/Output modes.

BLOCH-MESSIAH DECOMPOSITION

In the quadrature basis:

$$a_{S/I,n} = \frac{1}{\sqrt{2\hbar}}\left(X_{S/I,n} + iP_{S/I,n}\right) \qquad \boldsymbol{r}^T = (X_{S,1},\dots,X_{S,N},X_{I,1},\dots,X_{I,N}, P_{S,1},\dots,P_{S,N},P_{I,1},\dots,P_{I,N}).$$

Covariance Matrix takes the form:

$$\boldsymbol{V} = \langle\{\boldsymbol{r},\boldsymbol{r}^T\}\rangle/2 \qquad \boldsymbol{V} = \tfrac{\hbar}{2}\boldsymbol{S}\boldsymbol{S}^T$$

$$\boldsymbol{r}^{\text{out}} = \boldsymbol{S}\boldsymbol{r}^{\text{in}} = \mathcal{U}^\dagger \boldsymbol{r}^{\text{in}}\mathcal{U}$$

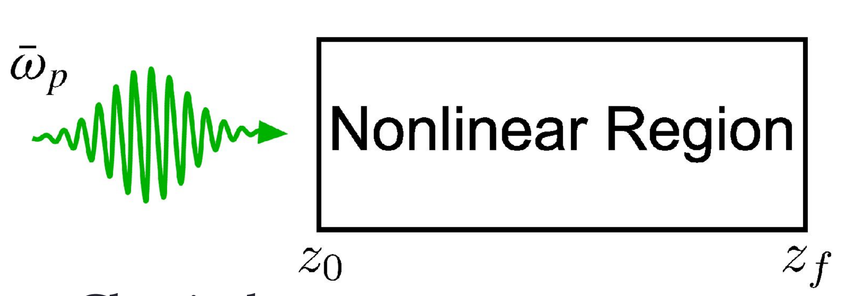
S(Heisenberg Propagator) is Real and Symplectic: Bloch-Messiah

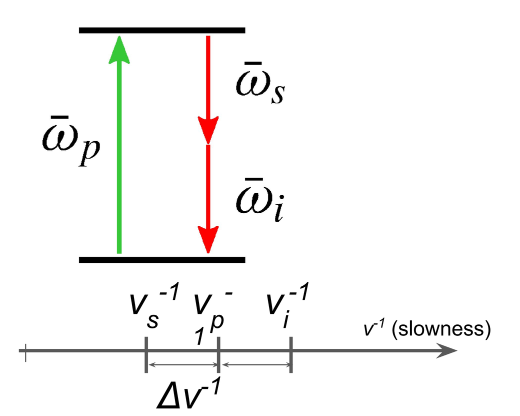
$$\boldsymbol{S} = \boldsymbol{O}\boldsymbol{\Lambda}\tilde{\boldsymbol{O}}^T \qquad \boldsymbol{\Lambda} = \mathrm{diag}(\lambda_1,\dots,\lambda_{2N},\lambda_1^{-1},\dots,\lambda_{2N}^{-1})$$

O, ***Õ*** are orthogonal and symplectic.
O→Output modes.
Õ→Input modes.

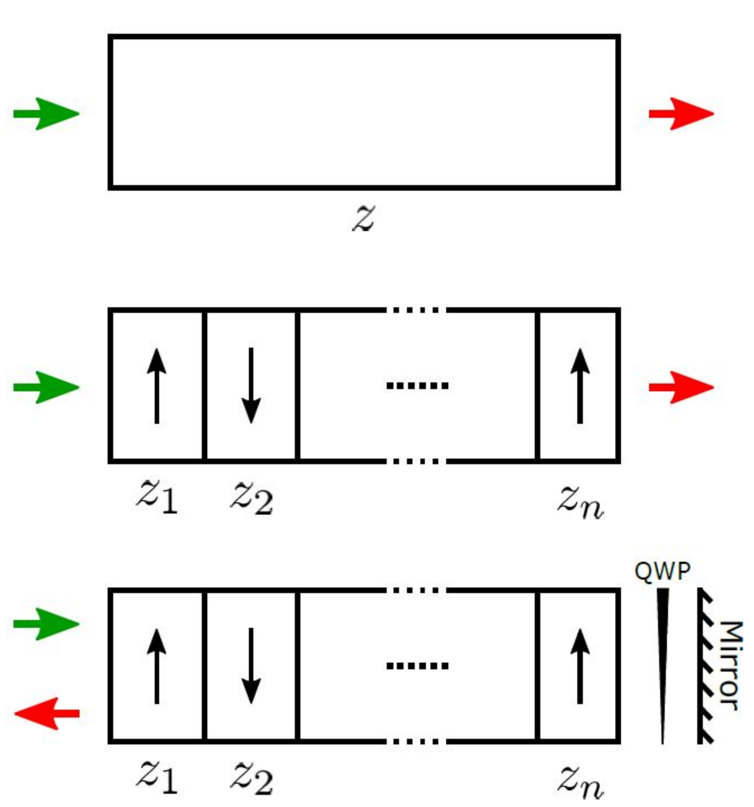
$$\boldsymbol{O} = \begin{pmatrix} \mathrm{Re}(\boldsymbol{U}) & -\mathrm{Im}(\boldsymbol{U}) \\ \mathrm{Im}(\boldsymbol{U}) & \mathrm{Re}(\boldsymbol{U}) \end{pmatrix}$$

MODEL: TWIN-BEAM GENERATION AND WAVEGUIDE CONFIGURATION





- Classical pump.
- Ignore self and cross-phase modulation.
- Poling to induce Gaussian phase-matching function.
- Symmetric group velocity matched regime.

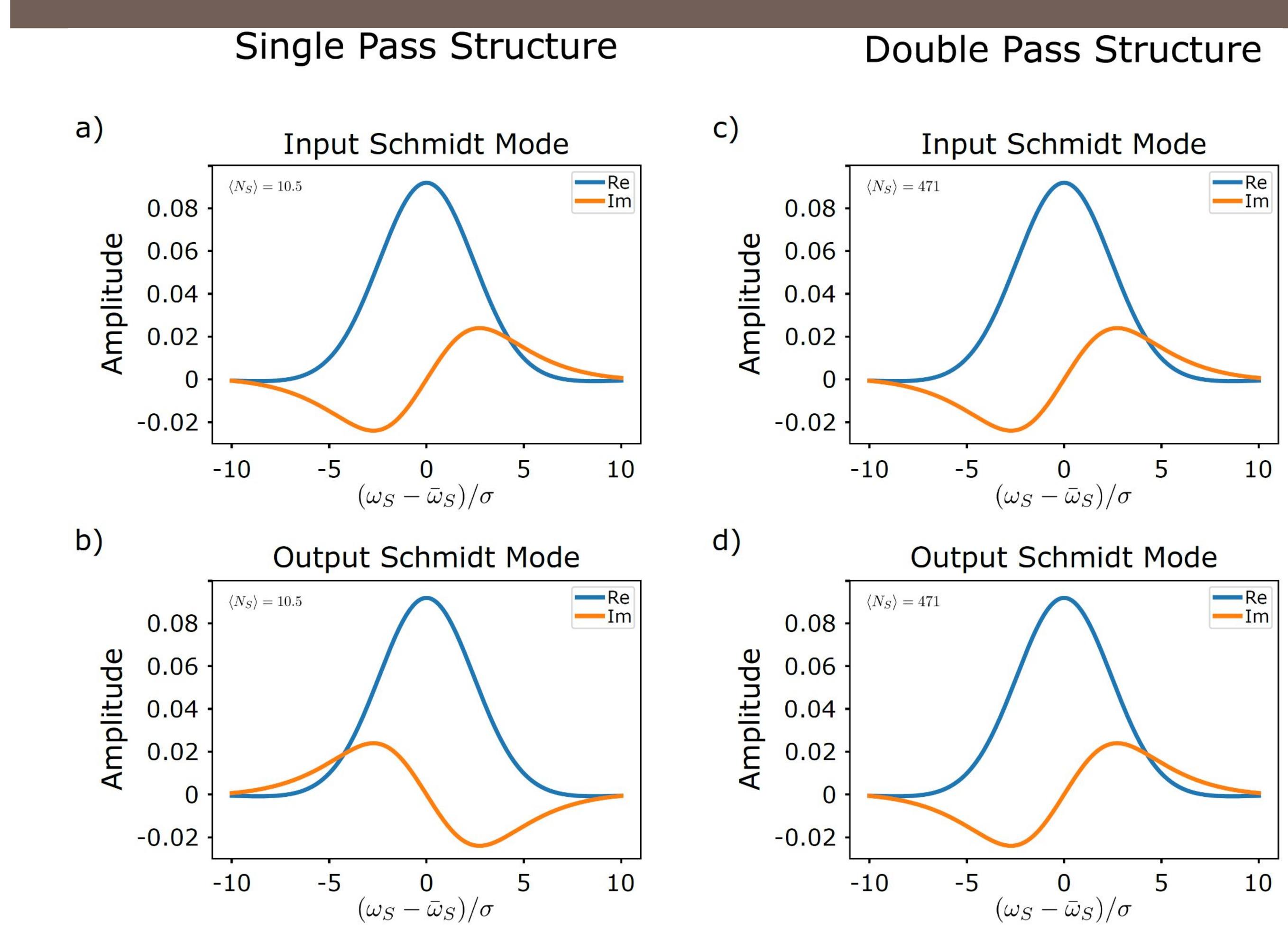


$$\frac{\partial}{\partial z}a_s(z,\omega) = i\left(\frac{1}{v_s}-\frac{1}{v_p}\right)(\omega-\bar{\omega}_s)a_s(z,\omega) + i\frac{\gamma_{SPDC}\,g(z)}{\sqrt{2\pi}}\int d\omega'\beta(\omega+\omega')a_i^\dagger(z,\omega')$$

$$\frac{\partial}{\partial z}a_i^\dagger(z,\omega) = -i\left(\frac{1}{v_i}-\frac{1}{v_p}\right)(\omega-\bar{\omega}_i)a_i^\dagger(z,\omega) - i\frac{\gamma^*_{SPDC}\,g(z)}{\sqrt{2\pi}}\int d\omega'\beta^*(\omega+\omega')a_s(z,\omega')$$

g(z): Poling function β(ω):Pump envelope

NUMERICAL TEMPORAL MODE STRUCTURE



- Input and Output modes differ for Single Pass configuration. The imaginary parts are "flipped".
- Input and Output modes are identical for Double pass configuration.

ANALYTICAL RELATIONS BETWEEN INPUT AND OUTPUT MODES

- Discretize EOMs (N frequencies).
- Work in Quadrature Basis.
- Heisenberg Propagator is a Matrix Exponential (4Nx4N).
- Use underlying symmetries to transform into Bloch-Messiah form.

Single Pass Structure

$$\boldsymbol{O} = \begin{pmatrix} 0_{N\times1} & \boldsymbol{a}_1 & & 0_{N\times1} & -\boldsymbol{a}_1^f & \\ \boldsymbol{a}_1 & 0_{N\times1} & \cdots & \boldsymbol{a}_1^f & 0_{N\times1} & \cdots \\ 0_{N\times1} & \boldsymbol{a}_1^f & & 0_{N\times1} & \boldsymbol{a}_1 & \\ -\boldsymbol{a}_1^f & 0_{N\times1} & & \boldsymbol{a}_1 & 0_{N\times1} & \end{pmatrix}$$

$$\tilde{\boldsymbol{O}} = \begin{pmatrix} 0_{N\times1} & \boldsymbol{a}_1^f & & 0_{N\times1} & -\boldsymbol{a}_1 & \\ \boldsymbol{a}_1^f & 0_{N\times1} & \cdots & \boldsymbol{a}_1 & 0_{N\times1} & \cdots \\ 0_{N\times1} & \boldsymbol{a}_1 & & 0_{N\times1} & \boldsymbol{a}_1^f & \\ -\boldsymbol{a}_1 & 0_{N\times1} & & \boldsymbol{a}_1^f & 0_{N\times1} & \end{pmatrix}$$

- Both Real and Imaginary are flips of each other.
- In proper gauge, obtain same structure as numerical results.

Double Pass Structure

- Input/Output modes of 2nd pass are the Output/Input modes of 1st pass.
- Overall effect: Input/Output modes are identical and are the Input modes of the 1st pass.

CONCLUSION AND OUTLOOK

- Double Pass Structure in the symmetric group velocity matching regime is a perfect inline squeezer.
- Extend model to different types of SPDC (i.e. Type-I).
- Extend model to try and include self- and cross-phase modulations as well as loss.

https://arxiv.org/abs/2401.10197