Squeezing in higher-order Hermite-Gaussian modes

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Take-Home Messages/Conclusion:
• Fundamental light fields in pure higher-order spatial modes generate individual superposition of modes in the harmonic field in second harmonic generation (SHG).
• The highest-order of these harmonic modes is most efficient to pump the respective squeezing.
• In the same cavity, higher-order modes require more pump power than TEM\(_{0,0}\) to achieve the same conversion efficiency in SHG and the same squeezing level.
• In a first test, we have measured a squeezing level of 11dB in TEM\(_{0,0}\), 7dB in HG\(_{1,1}\) and 6dB in HG\(_{2,2}\).
motivation

... is based on the proposal to mitigate coating Brownian thermal noise in gravitational wave detectors by using higher-order spatial laser modes

additional requirement: maintain quantum noise reduction by injecting squeezed vacuum states in the used laser mode into the detector

The typical scheme to generate squeezed vacuum states for gravitational wave detectors is based on two subsequent processes conducted in nonlinear crystals:

1. cavity-enhanced **second harmonic generation**
2. cavity-enhanced **parametric down-conversion**
pump mode

- Squeezing is generated if the power gain in the squeezed field is non-zero:

\[ \Delta P \propto \left| \int (A_{sqz}^*)^2 A_p \, dA dz \right| > 0 \]

- Most efficient pump mode is always the pump mode with the highest mode order: \( \text{HG}_{2m,2n} \).

- These modes have the highest overlap with \((A_{sqz})^2\) and provide the best phase matching with the squeezed field (shown for \(\text{HG}_{1,1}\)):

\[ \Delta P \propto \text{phase relation (rad in } \Delta P \text{)} \]

Any mode which has a non-zero spatial overlap with \((A_{sqz})^2\) can serve as a pump mode:

for \(\text{HG}_{m,n}\): \(\text{HG}_{k,j}\)

with \(k = 0, 2, ..., 2m\) and \(j = 0, 2, ..., 2n\)

pump mode generation

• Higher-order modes have less intensity. Their SHG efficiency is smaller for a given pump power:

• More efficient:

  - This method makes use of the high SHG conversion efficiency of TEM$_{0,0}$.
  - A spatial light modulator converts the harmonic TEM$_{0,0}$ into the required pump mode.

Legend explanation:

- ext.: *external*, ratio of total harmonic output power to pump power
- eff.: *effective*, takes output mode purity into account

conceptual setup at 1064nm

Spatial light modulators can be bypassed for a pure TEM\(_{0,0}\) operation.

squeezing cavity (OPA) parameters

- Crystal material: PPKTP
  - \(L = 9.3\text{mm}\)
  - \(\omega_0 \approx 30\mu\text{m}\)
  - \(R_{1064\text{nm}} = 0.92\)
  - \(R_{532\text{nm}} = 0\)
  - \(n = 0.9997\)
  - \(n = 0.999\)
first measurement and future steps

So far, squeezing cavity is set to resonance by hand.
Phase of local oscillator is scanned.

Future steps:

1. Finish OPA length lock with additional control field at 1064 nm.
2. Implement phase lock between this control field and the pump field.
3. Optimise mode matchings, detector contrast and detector balancing.