Squeezing in higher-order Hermite-Gaussian modes

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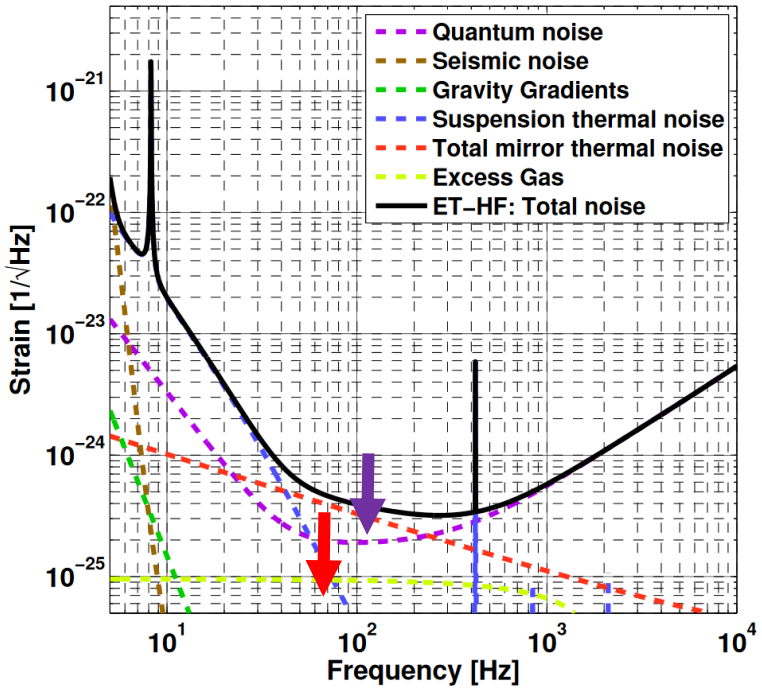
Take-Home Messages/Conclusion:

- 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 $\mathrm{TEM}_{0,0}$ to achieve the same conversion efficiency in SHG and the same squeezing level.
- In a first test, we have measured a squeezing level of $11\mathrm{dB}$ in $\mathrm{TEM}_{0,0}$, $7\mathrm{dB}$ in $\mathrm{HG}_{1,1}$ and $6\mathrm{dB}$ in $\mathrm{HG}_{2,2}$.

motivation

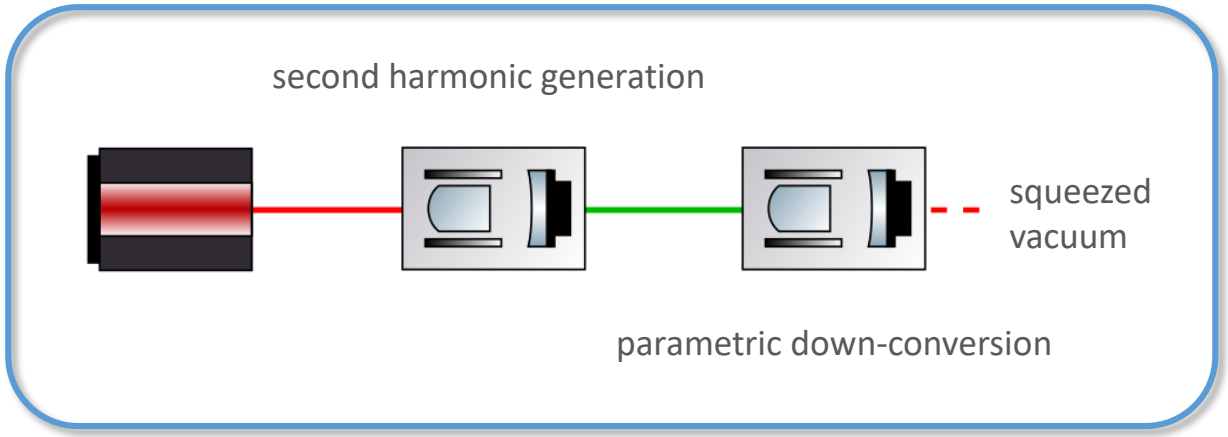
… is based on the proposal to mitigate coating Brownian thermal noise in gravitational wave detectors by using higher-order spatial laser modes

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**



arXiv:1012.0908v1(2010)

pump mode

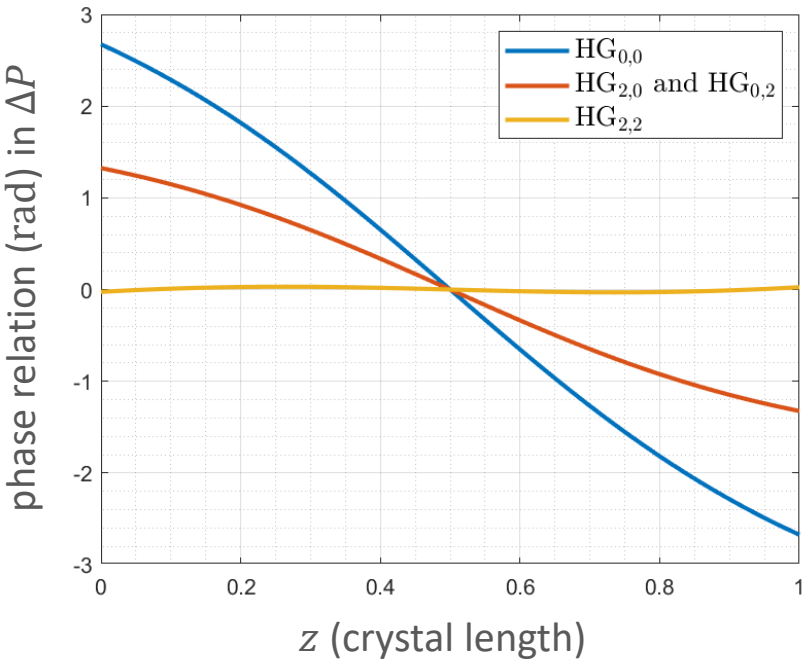
- Squeezing is generated if the power gain in the squeezed field is non-zero:

$$\Delta P \propto \left| \int \left(A^*_{sqz}\right)^2 A_p \, dA dz \right| > 0$$

A_{sqz}: squeezed field
A_p: pump field
dA: cross-section of crystal
dz: along propagation axis

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

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



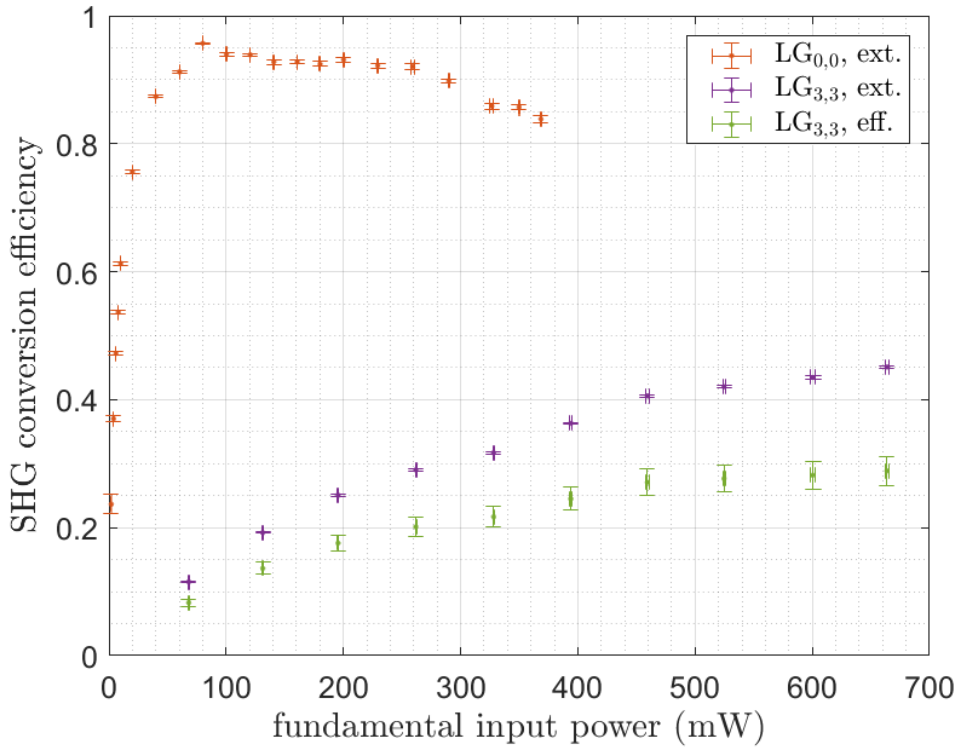
➢ Any mode which has a non-zero spatial overlap with $\left(A_{sqz}\right)^2$ can serve as a pump mode:

for $\mathrm{HG}_{m,n}$: $\mathrm{HG}_{k,j}$
with $k = 0, 2, \ldots, 2m$ and $\mathrm{j} = 0, 2, \ldots, 2n$

ΔP equation: G. D. Boyd and D. A. Kleinmann, J. Appl. Phys. 39, 3597 (1968)

pump mode generation

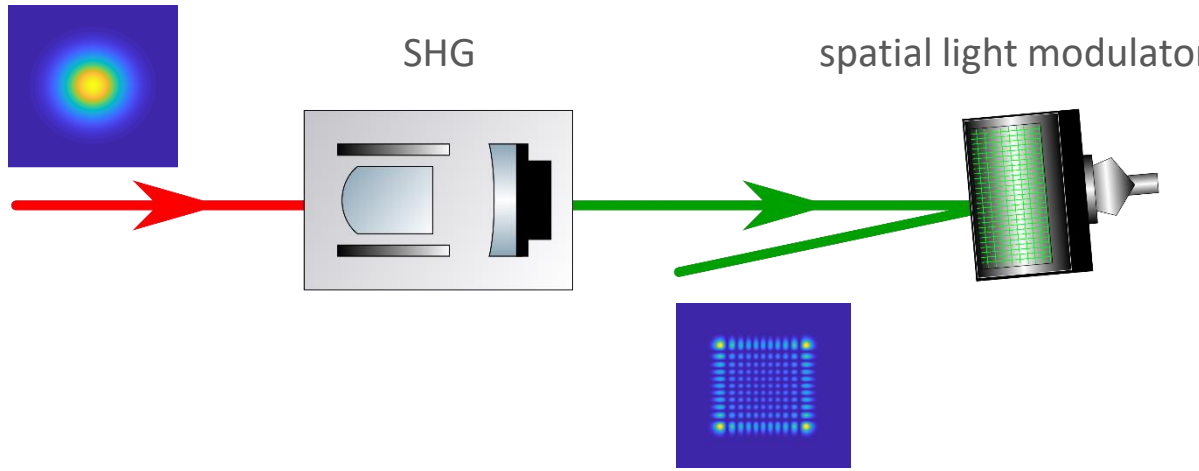
- Higher-order modes have less intensity.
  Their SHG efficiency is smaller for a given pump power:



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

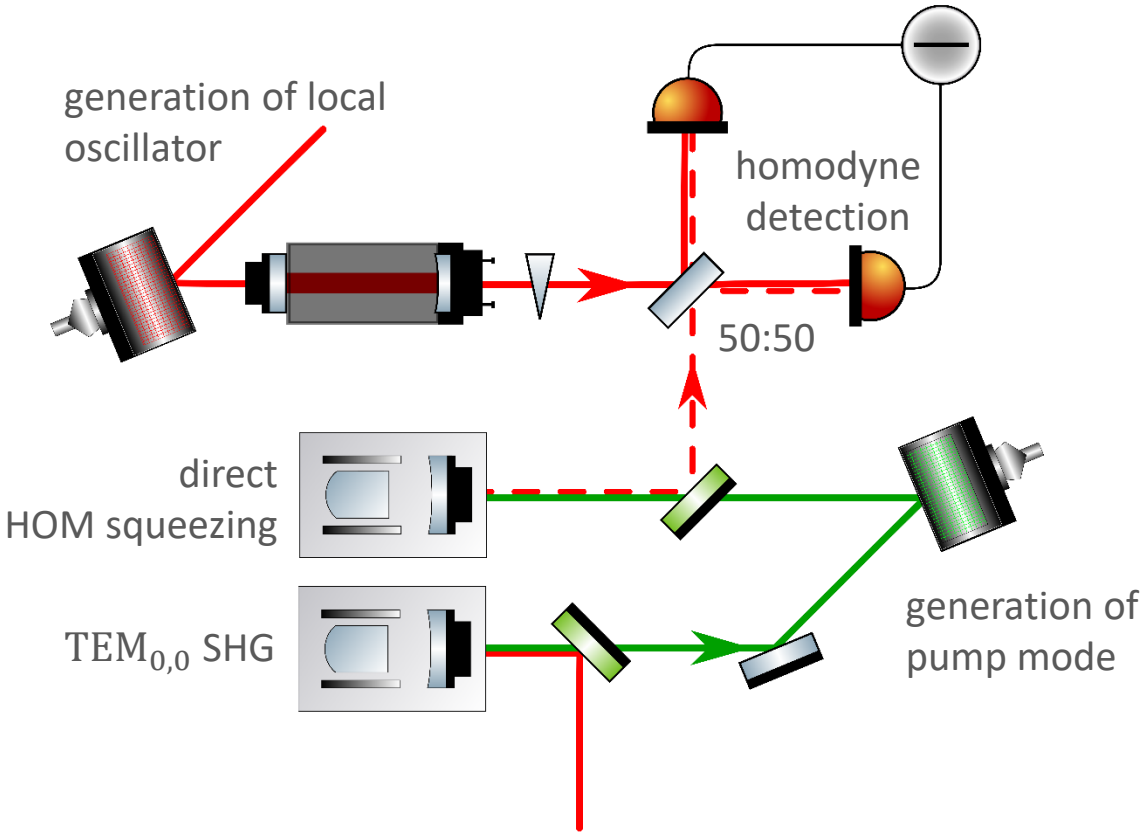
J. Heinze, H. Vahlbruch, and B. Willke, Opt. Lett. **45**, 5262-5265 (2020)
J. Heinze, H. Vahlbruch, and B. Willke, Opt. Express **28**, 35816-35832 (2020)

- More efficient:



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

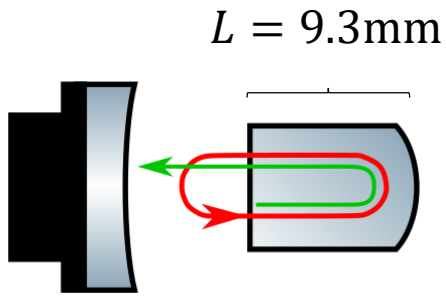
conceptual setup at 1064nm



Spatial light modulators can be bypassed for a pure $TEM_{0,0}$ operation.

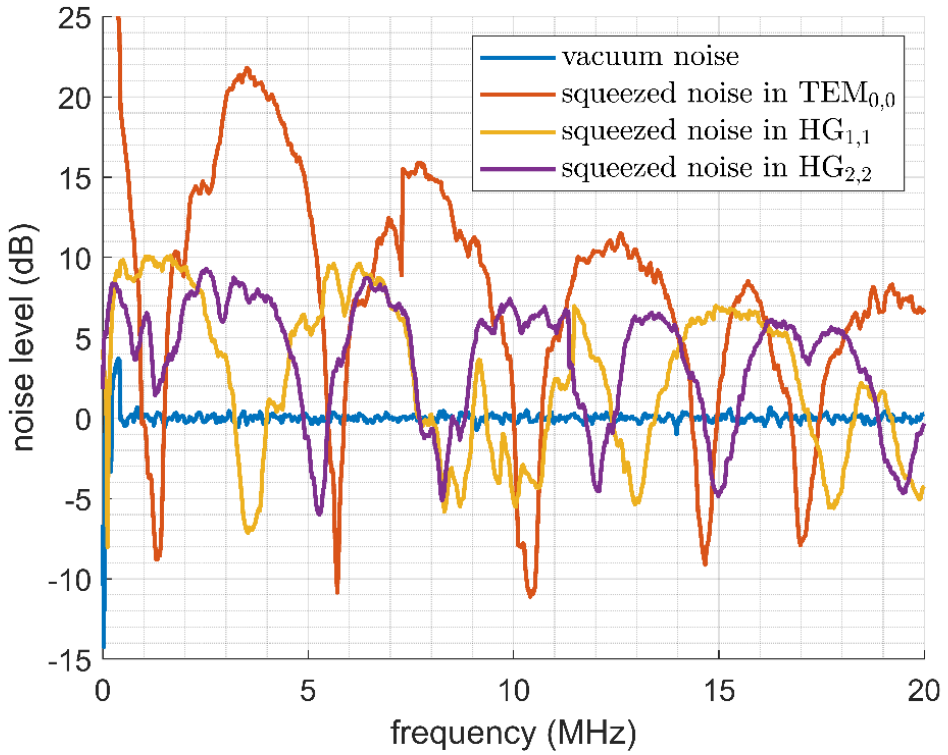
squeezing cavity (OPA) parameters

crystal material: PPKTP



$R_{1064nm} =$	0.92	0.9997
$R_{532nm} =$	0	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 $1064\mathrm{nm}$.
2. Implement phase lock between this control field and the pump field.
3. Optimise mode matchings, detector contrast and detector balancing.