Quantum Correlated Twin Beams in Cascaded Quadratic Processes

Iolanda Ricciardi
Istituto Nazionale di Ottica - CNR

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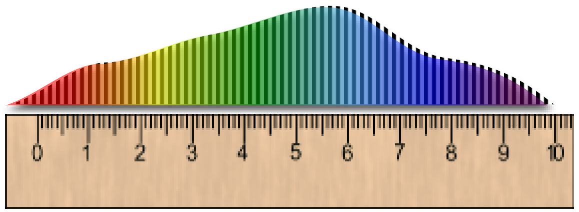
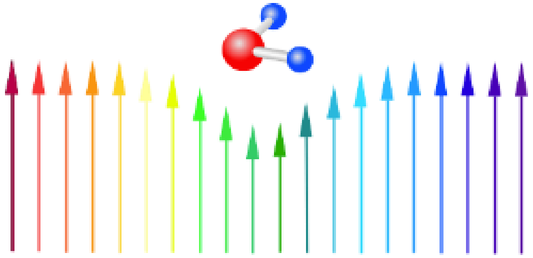
Optical frequency combs

$$\nu_n = f_o + n f_r$$



A precise frequency ruler for metrology



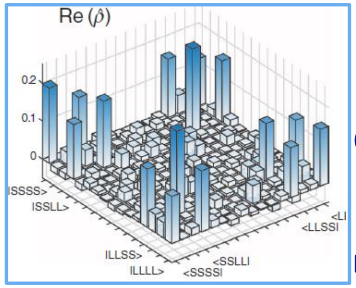
Lots of lasers for high resolution spectroscopy

- *synchronization of telecommunication systems*
- *astronomical spectral calibration*
- *biomedical and environmental spectrometry*

Laser generation: Mode locked ultrafast lasers
Quantum cascade lasers

Nobel Prize to Teodor Hänsch

Parametric generation: $\chi^{(3)}$ interaction (Kerr-microresonators)



Complex quantum states

Reimer et al. Science 2016

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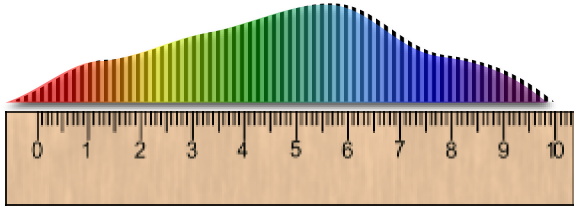

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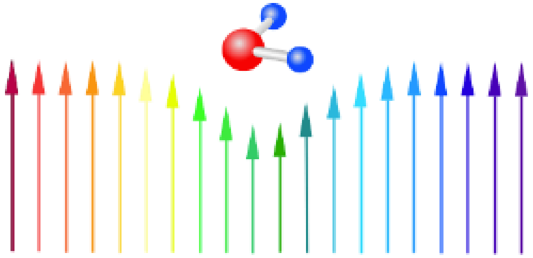

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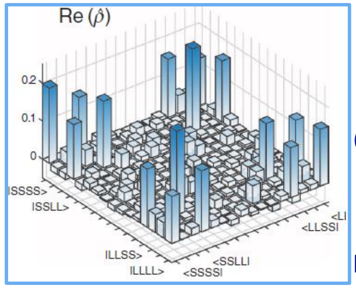


Complex quantum states

Reimer et al. Science 2016

Parametric generation: $\chi^{(3)}$ interaction (Kerr-microresonators)
$\chi^{(2)}$ interaction (our work)

$\chi^{(2)}$-combs: pure quadratic combs

Cascaded $\chi^{(2)}$ mimic $\chi^{(3)}$ nonlinearities

- High efficiency in $\chi^{(2)}$ processes: viable alternative to Kerr combs
- Spectral tailoring of nonlinear efficiency
- Simultaneous generation of OFC in spectral regions far away from the pump

Cascaded nonlinearities can produce entangled beams

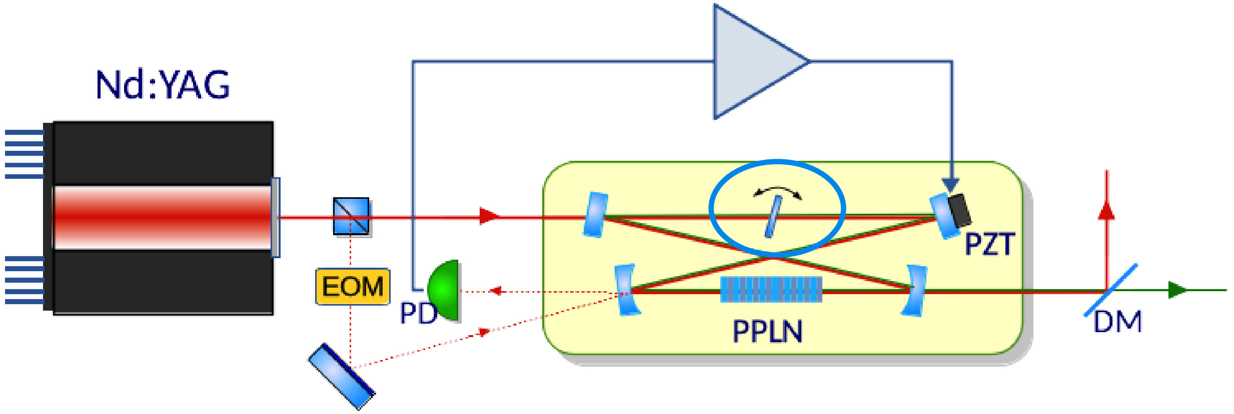
- quantum sensing (spectroscopy and imaging)
- quantum metrology (GW detection)

Outline

- Introduction to the physics of $\chi^{(2)}$ combs
  - Experimental realization in Second Harmonic Generation cavities

- Observation of nonclassical correlation
  - Squeezing in intensity difference of the twin beams

$\chi^{(2)}$-comb generation in doubly resonant SHG



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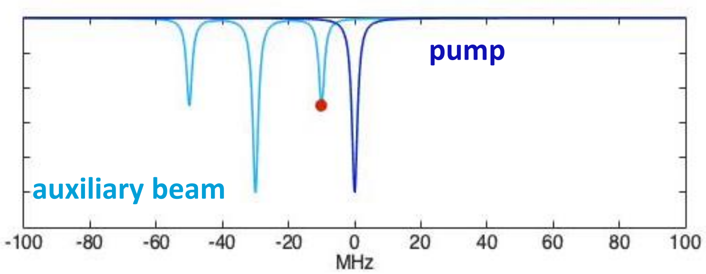
- very rich dynamics
- mW-level threshold for comb generation

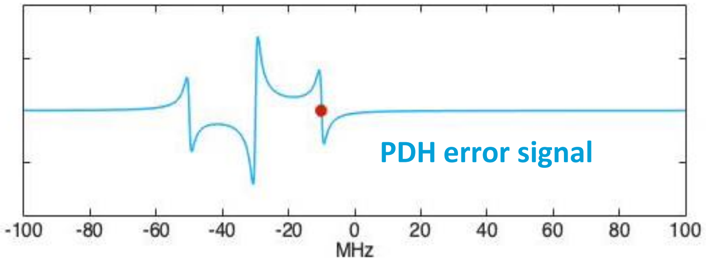


- Cavity mirrors: HR> 99.9% @1064/532 nm
  Output coupler: PR: 96.0 % @ 532 nm,
  91.5% @1064 nm
- Measured finesse @ 1064 nm: 60
  FSR: 506 MHz
  Cavity linewidth: 8.4 MHz (HWHM)
- Nonlinear crystal: PPLN
- Fused silica window: resonance condition for FF and SH

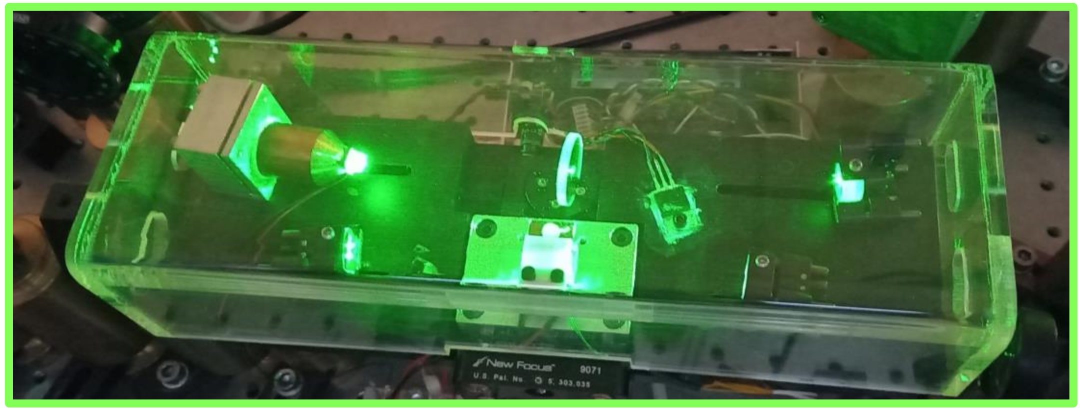
Locking system

Pound-Dever-Hall offset locking technique on an orthogonally polarized auxiliary beam

detuning control up to several cavity linewidths



$\chi^{(2)}$-comb generation in intracavity SHG



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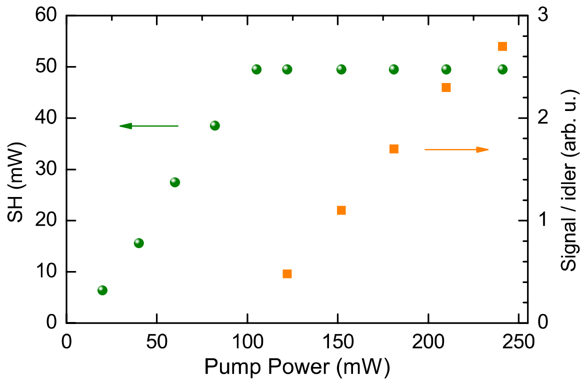
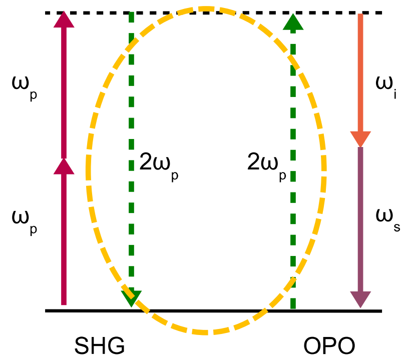
SH clamping: onset of Internally pumped Optical Parametric Oscillator



SHG+OPO: analogous to FWM mediated by "virtual" SH photons

$$\omega_p = \omega_i + \omega_s$$



I. Ricciardi *et al.*, Phys. Rev. A **91**, 063839 (2015)

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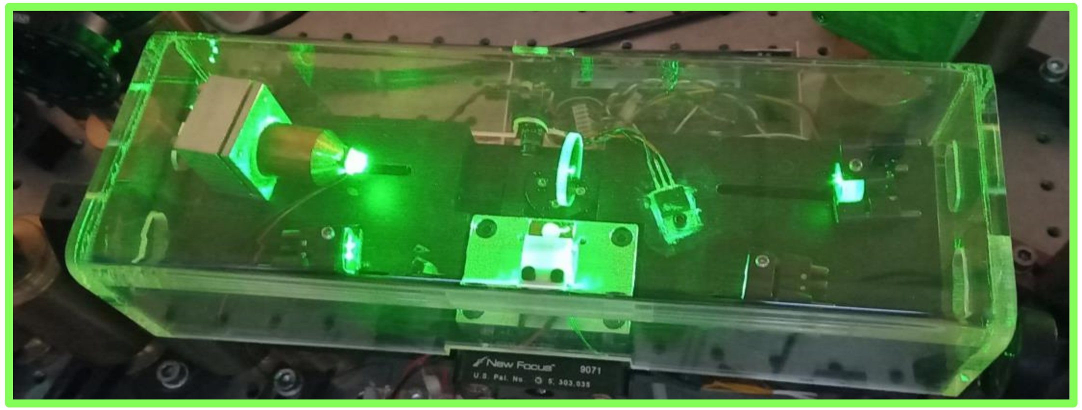

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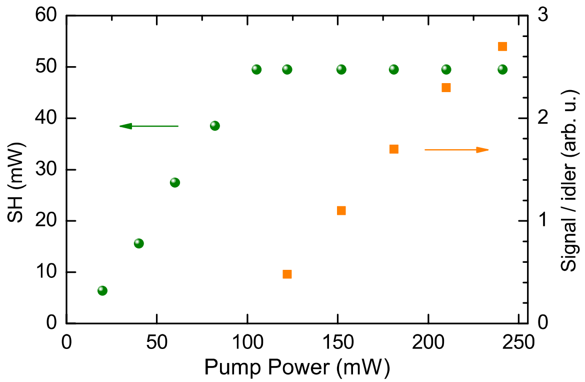

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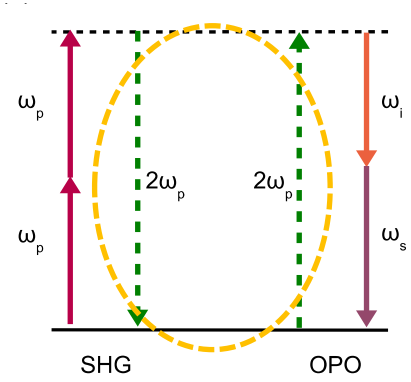

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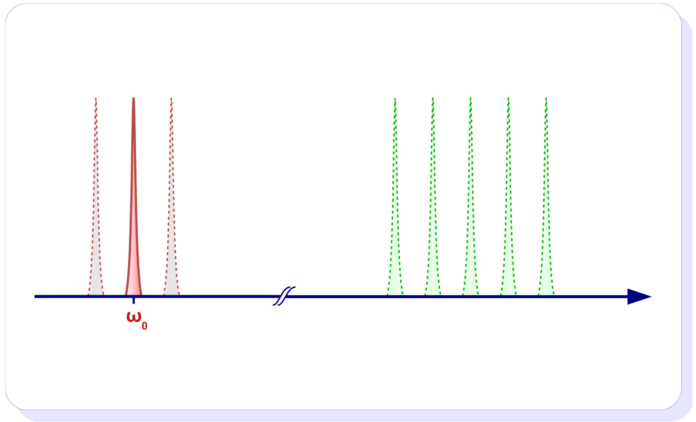

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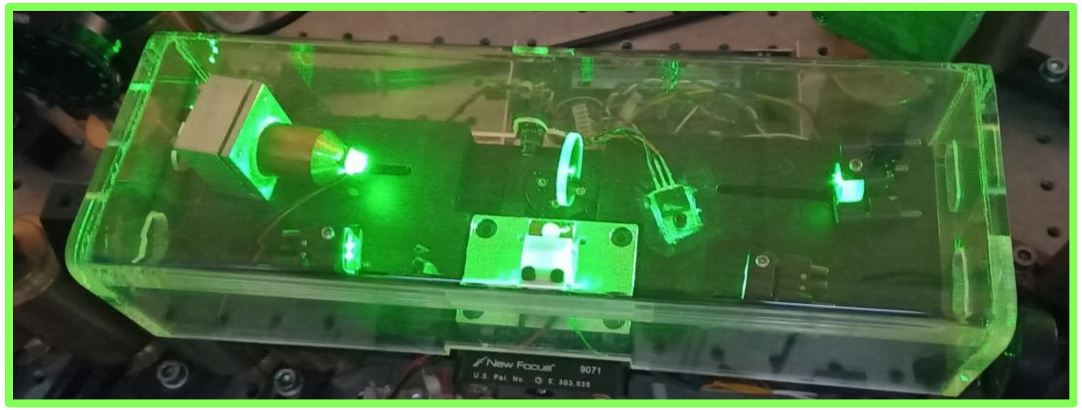

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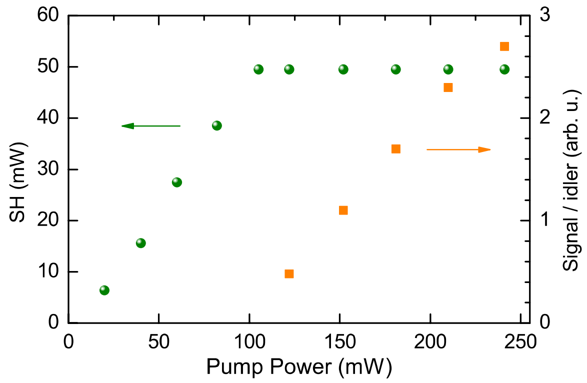

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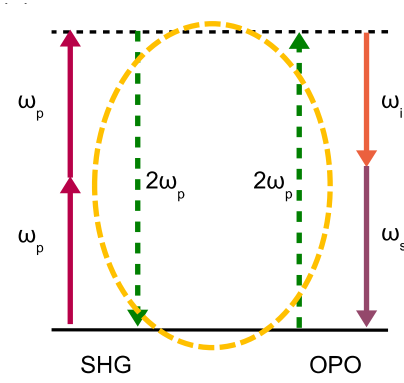

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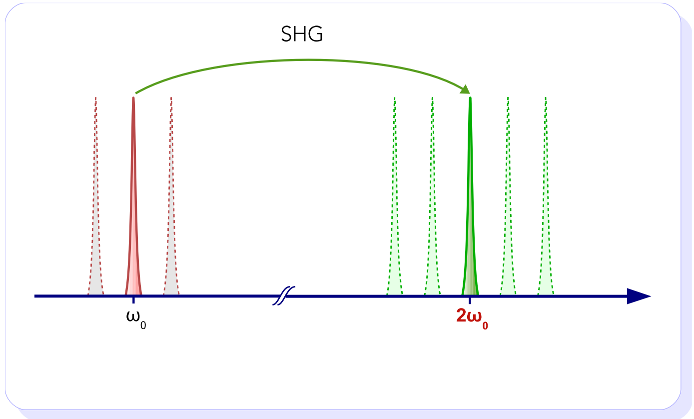

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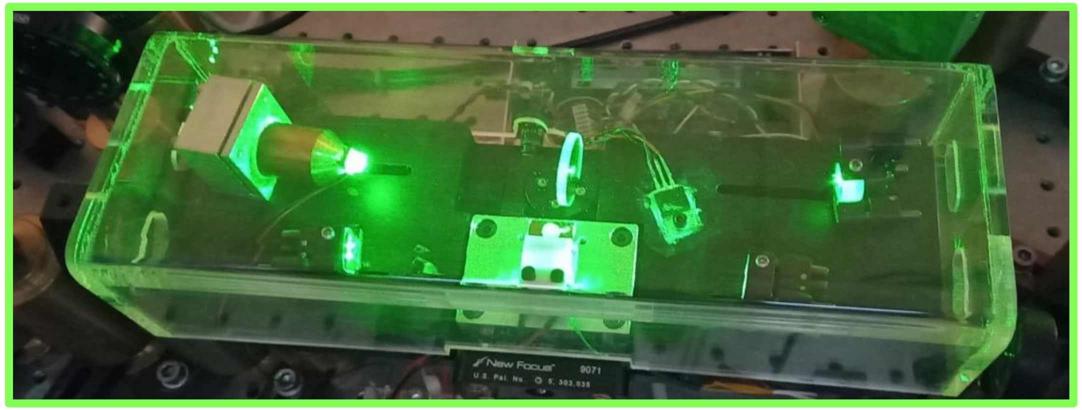

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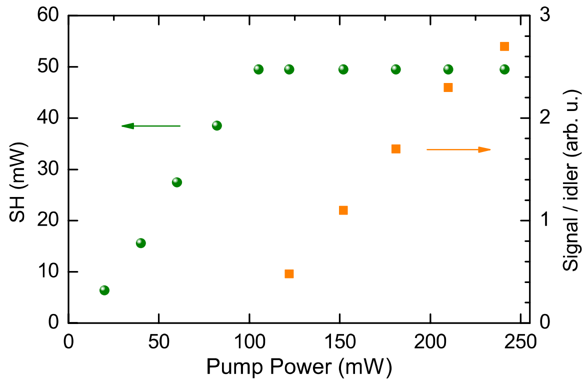

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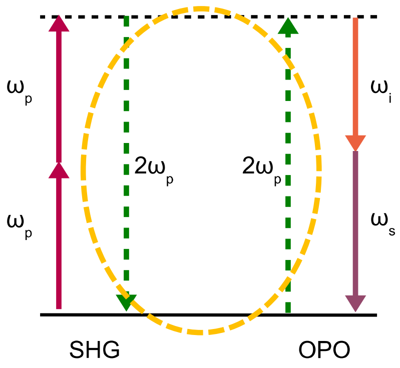

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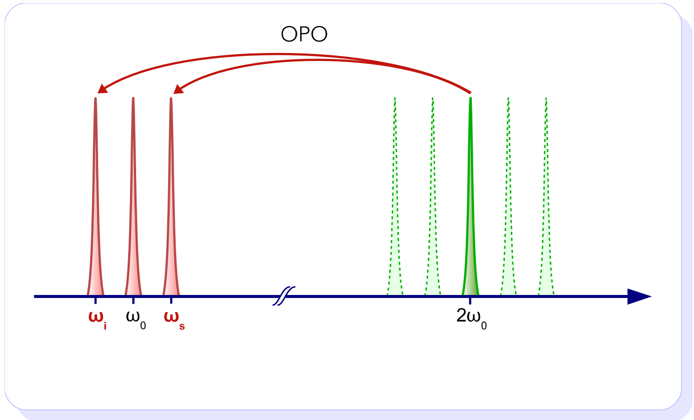

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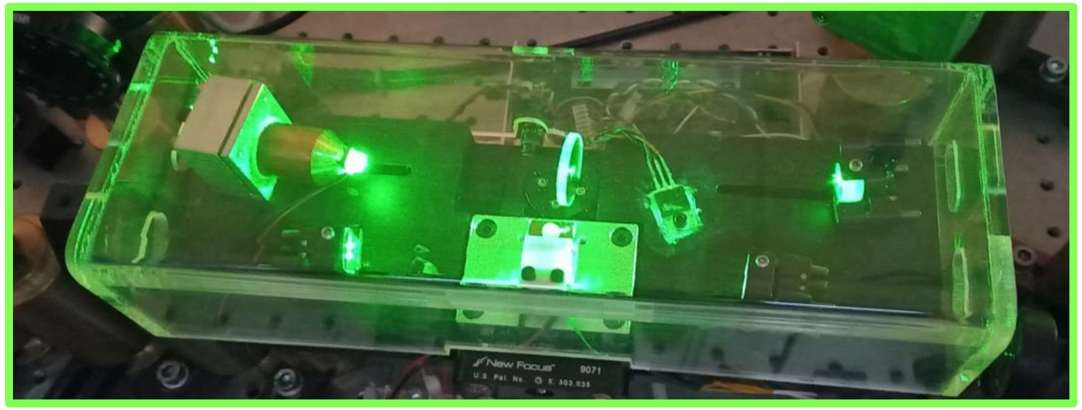

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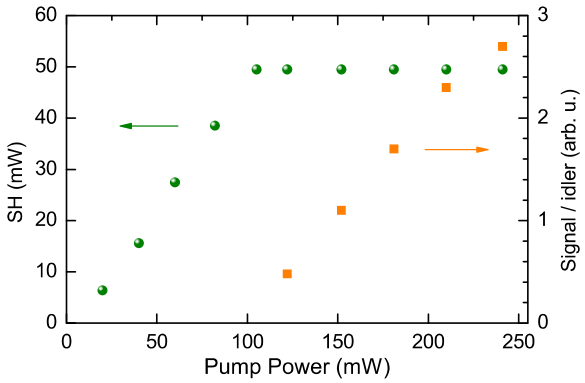

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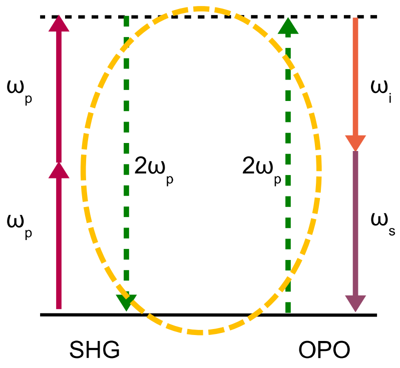

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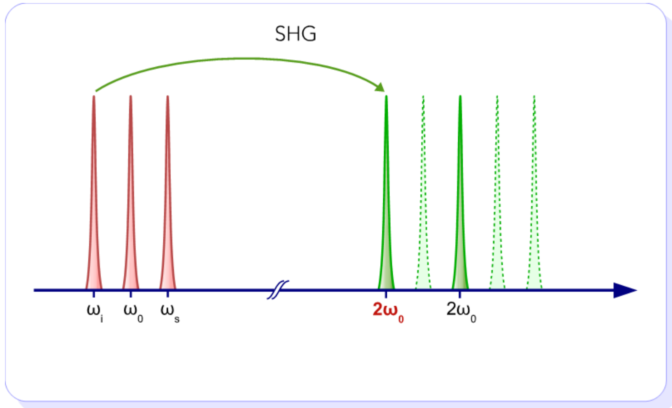

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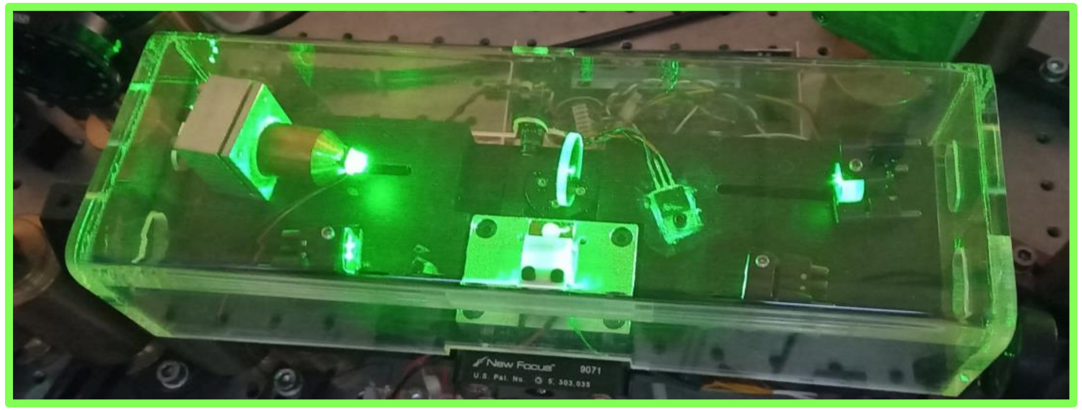

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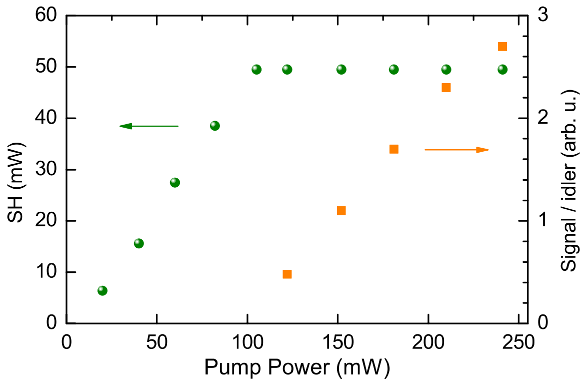

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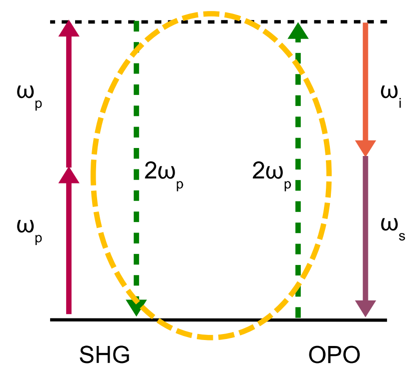

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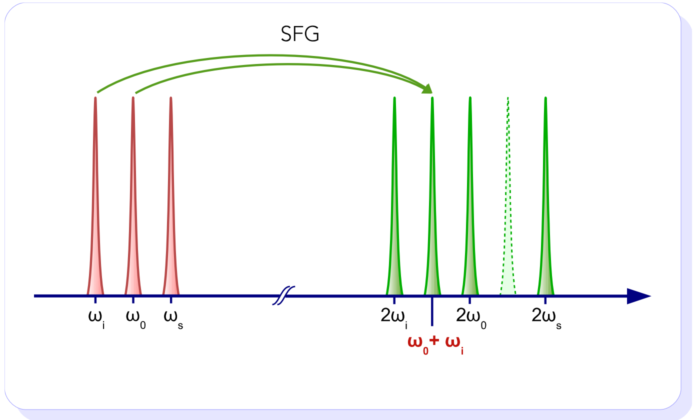

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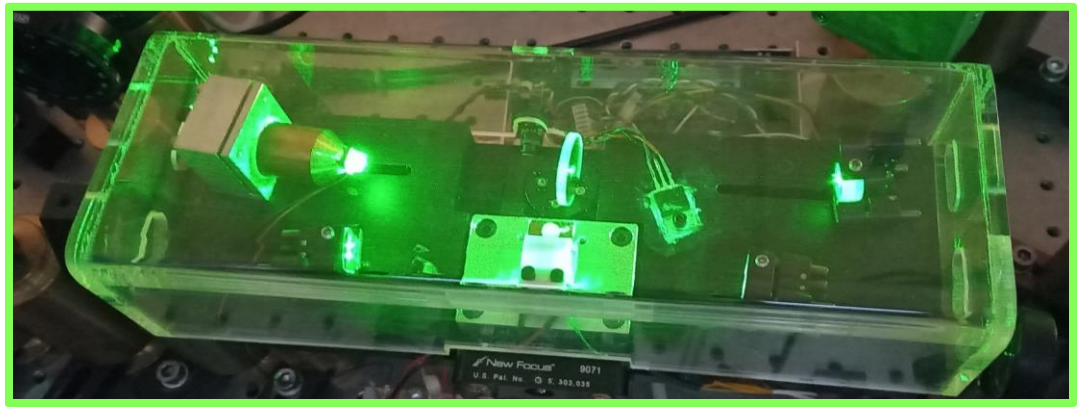

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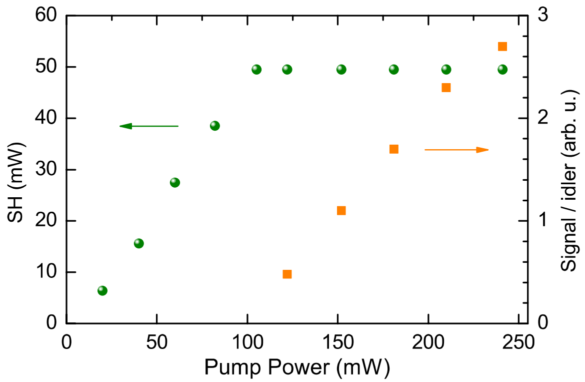

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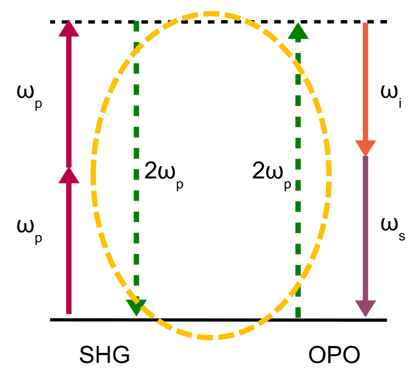

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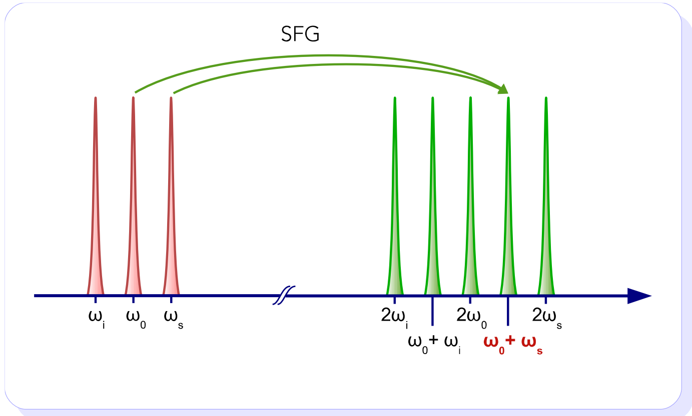

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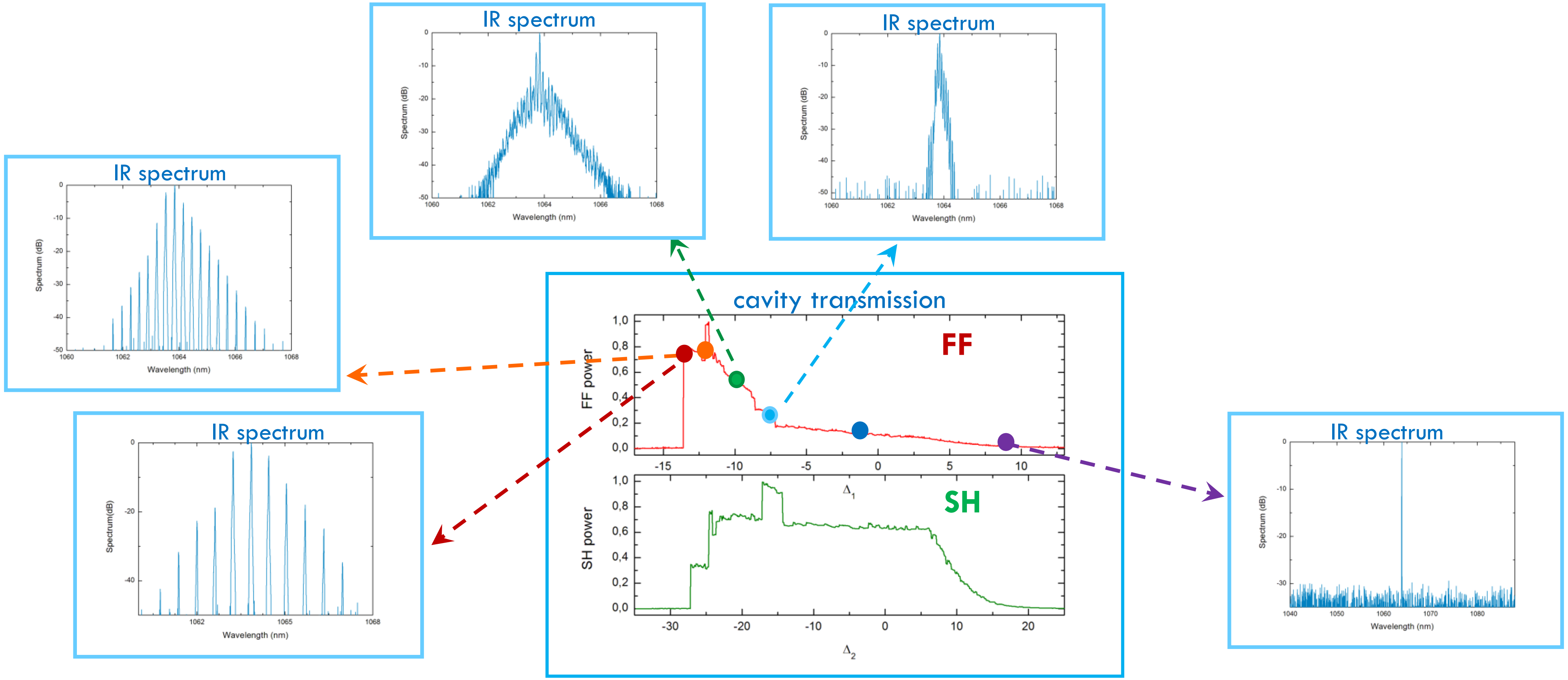
$\chi^{(2)}$- combs generation in DR cavity

P_{in}=300 mW

Different types of combs depending on the detuning



Iolanda Ricciardi *et al*, *Optics Express* 30 (2022)

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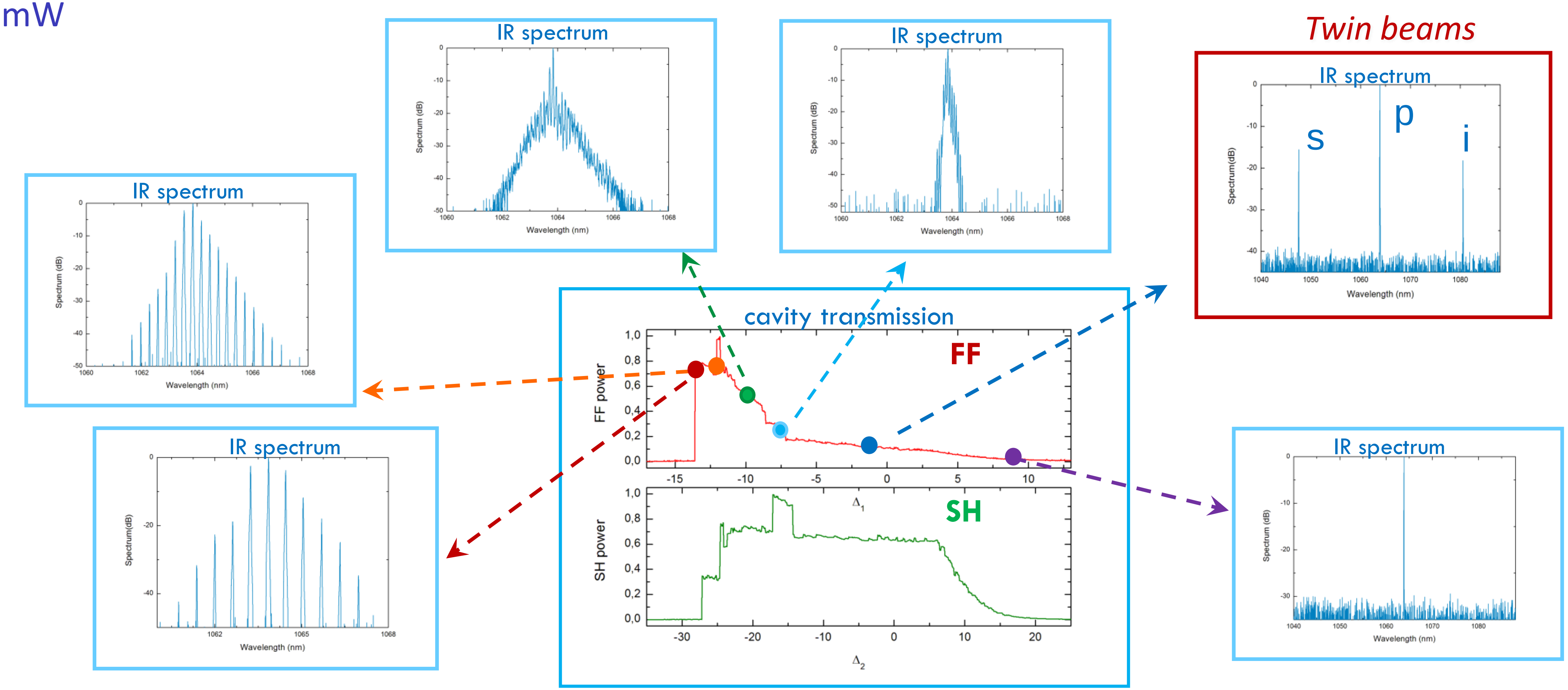

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Two-mode correlations

$\chi^{(2)}$ nonlinear processes: efficient sources of nonclassical light (SHG, OPO)

★ Cascaded SHG-OPO: Squeezing in the difference between the intensities of the two side modes

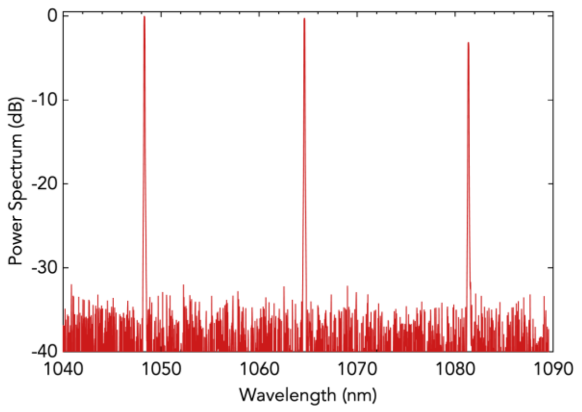
$$d = I_1 - I_2$$

Squeezing factor relative to shot noise

$$S_d(f) = 1 - \eta_e \eta_d \frac{\gamma^2}{f^2 + \gamma^2}$$

γ: cavity linewidth (HWHM)
$\eta_e = T/(T+L)$: escape efficiency
η_d: detection losses

M. Marte, Phys. Rev. Lett. 74, 4815 (1995)



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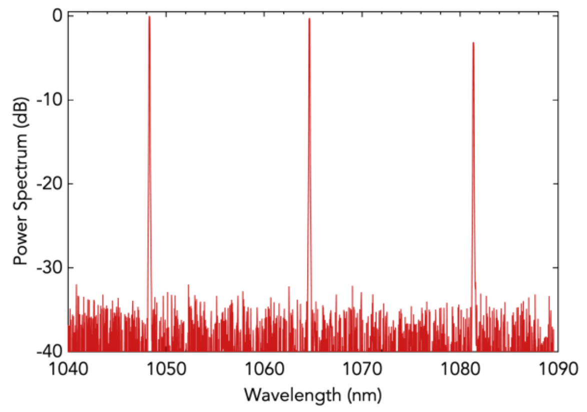
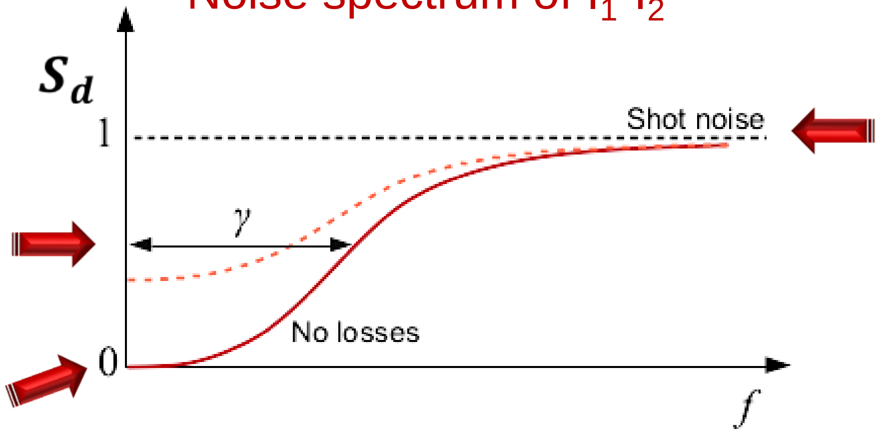


Noise spectrum of I_1-I_2

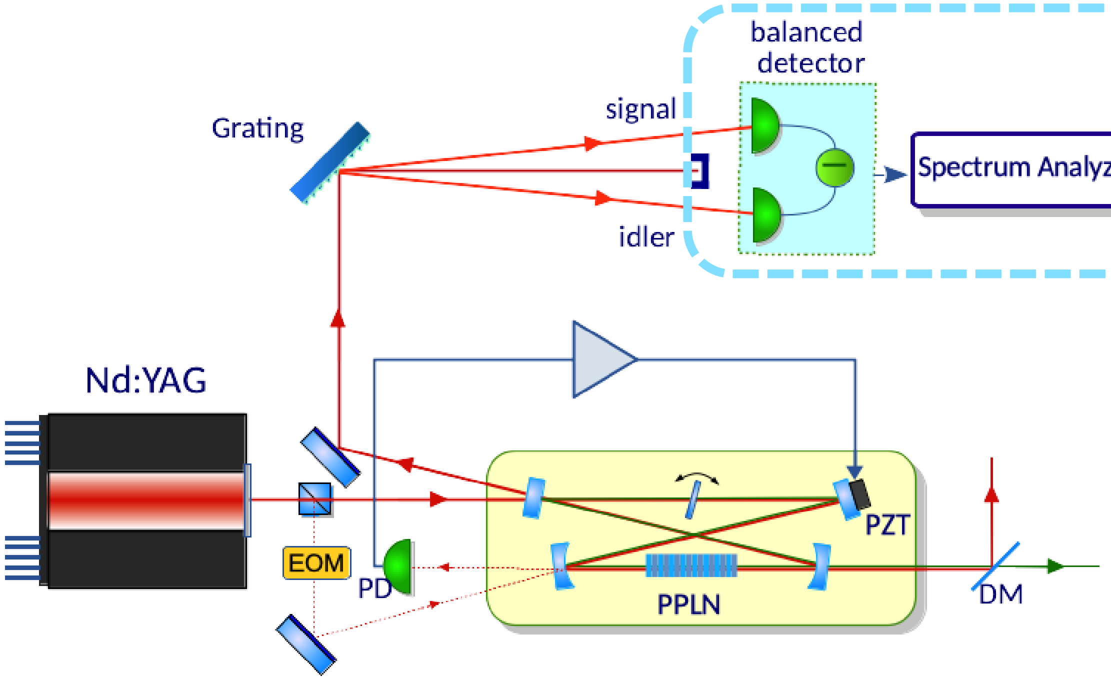


losses

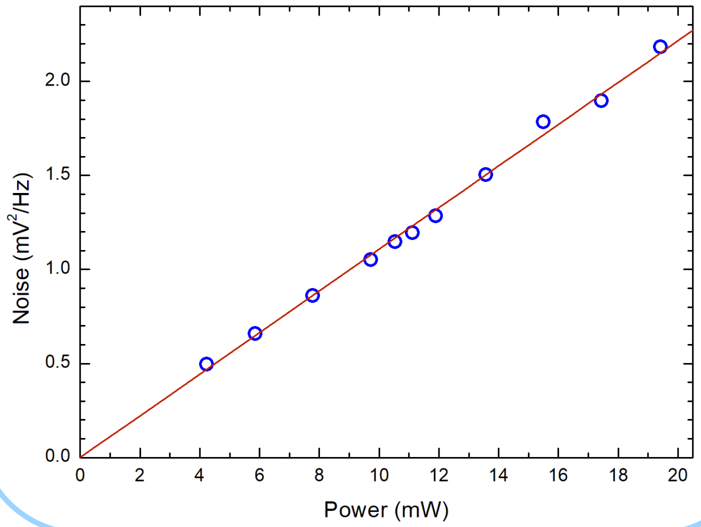
perfect quantum noise suppression

perfect quantum noise suppression

Experimental scheme



Shot noise characterization



Balanced detection

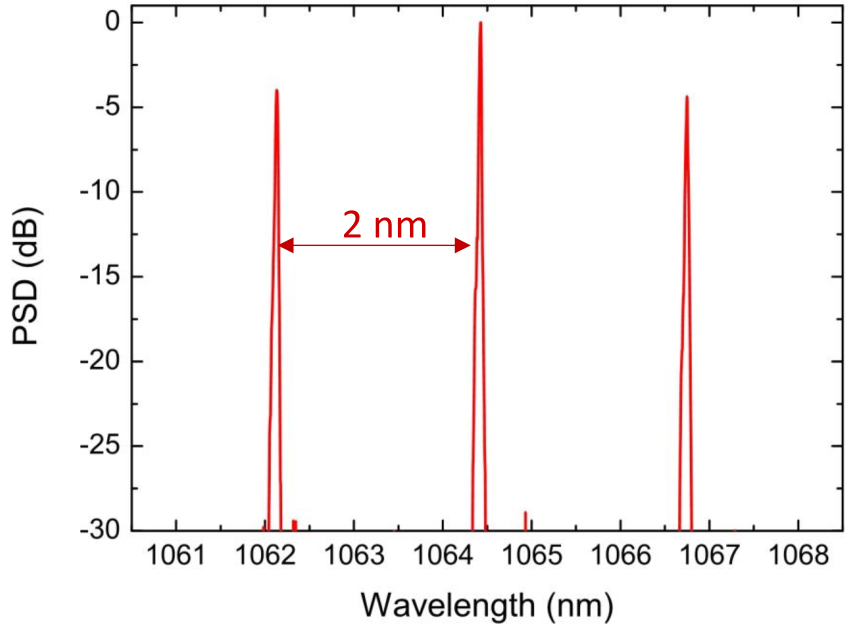
- InGaAs PD (ETX500)
- Detection bandwidth: 20 MHz
- Detection area: 0.25 mm^2
- Homemade electronics
- CMRR> 30 dB

Observation of twin beams squeezing

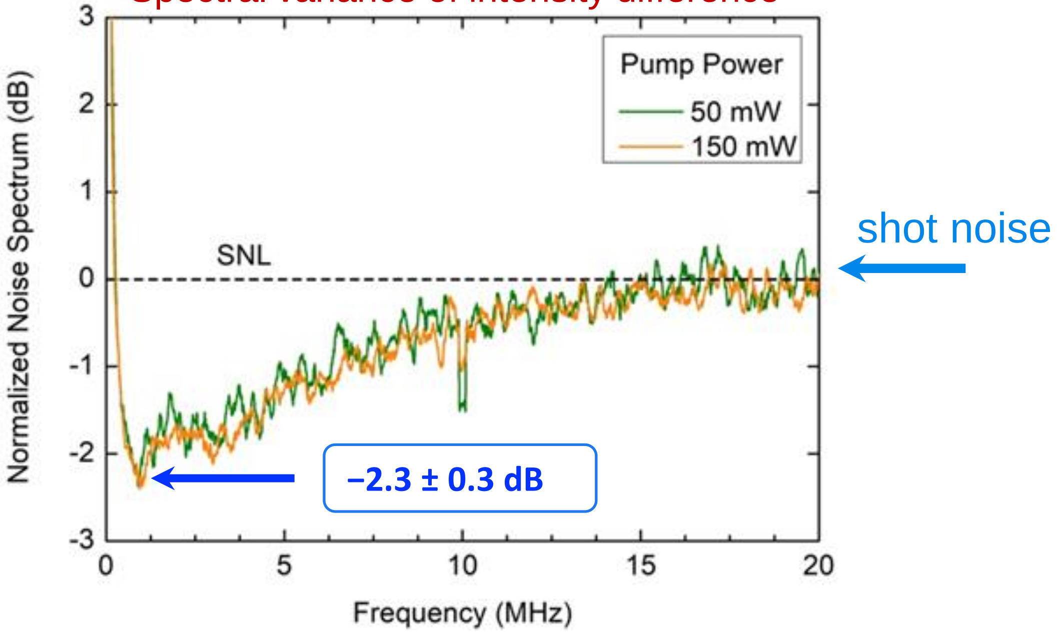
- Highly efficient nonlinear generation
- Very well balanced intensity signals

→ TBs power: 4 mW, 21 mW

Optical spectrum of TBs



Spectral variance of intensity difference



- Escape efficiency: 0.81
- Detection efficiency: 0.60

Corrected for detection losses
−5.0± 0.9 dB @ 900 kHz

Salvatore Castrignano *et al, Optics Letters* 49, 1733 (2024)

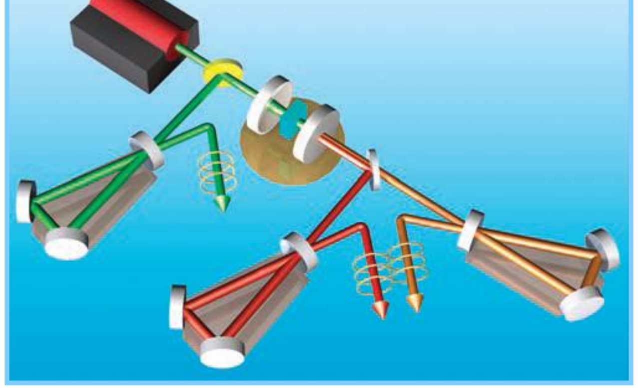
Work in progress..

- Twin beams: measurement of the degree of entanglement

Duan inseparability criterion: $\Delta^2(X_i - X_s) + \Delta^2(Y_i + Y_s) \geq 2$

phase quadrature variance measurement (*self-homodyne*)

Coelho et al., Science 2009



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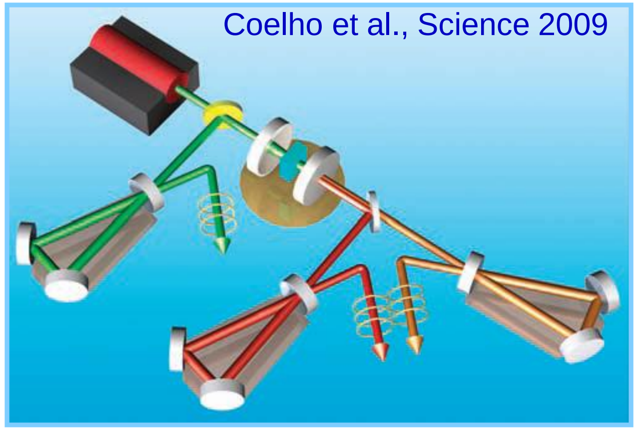

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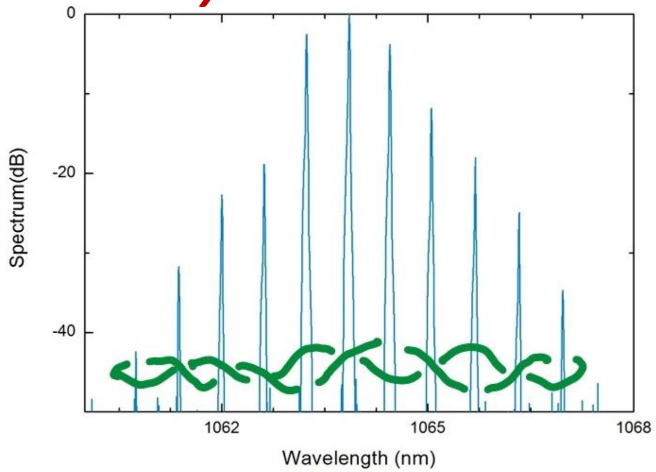
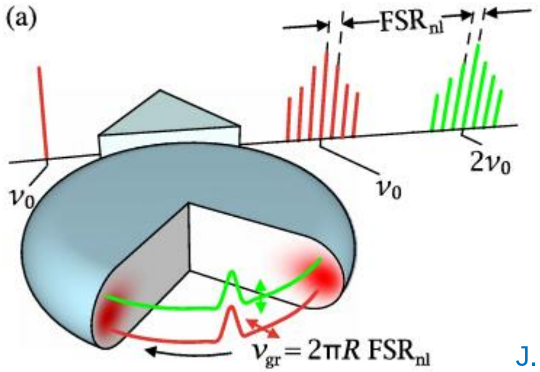
…towards

Many-mode correlations



Integration



quadratic microresonators

J. Szabados et al., Phys. Rev. Lett. 124, 203902 (2020)
I. Hendry et al., Opt. Lett. 45, 1024 (2020)

NQO Group

Pasquale Bosso

Salvatore Castrignano

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Paolo De Natale
Pasquale Maddaloni

Stefan Wabnitz

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Technical details

Resonator
Finesse = 60 @1064 nm
HWHM = 4.2 MHz
Coupling mirror reflectivity
91.5% @1064 nm
96% @532 nm

Nonlinear crystal
MgO-doped LiNbO3
Length 15 mm
Periodically poled p = 6.92 µm

Balanced detection
InGaAs PD (ETX500)
Detection area 0.25 mm^2
Homemade electronics
CMRR> 30 dB

Detection efficiency (nm-distant)

Diffraction grating efficiency	0.78 x
Other optics	0.98 x
Detector quantum efficiency	0.78 =
Total	**0.60 ±1**