Optical Combs in the mid-IR: Frequency Divide-and-Conquer Approach

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Beginning of the Laser Era in the USSR: 1939-1976

Early Soviet Papers on Quantum Electronics

Beginning of the Laser Era in the USSR

a special reprint collection for LaserFest

The 50th anniversary of the laser has stimulated worldwide interest in the history of quantum electronics. This special collection, "Beginning of the Laser Era in the USSR," presents early Soviet pioneering works that had a significant impact on laser science and quantum electronics. Several of the papers have never been published in English and were not generally available outside the USSR.

http://www.opticsinfobase.org/laserfest/laserfest-soviet.cfm

Contents

Anti -second harmonic generation

ω -> 2ω second harmonic generation

ω -> $\omega/2$ sub-harmonic generation

Standing on shoulders of giants

Sergei Akhmanov
(Moscow State Univ.)

Prior work on *microwave* degenerate parametric oscillators

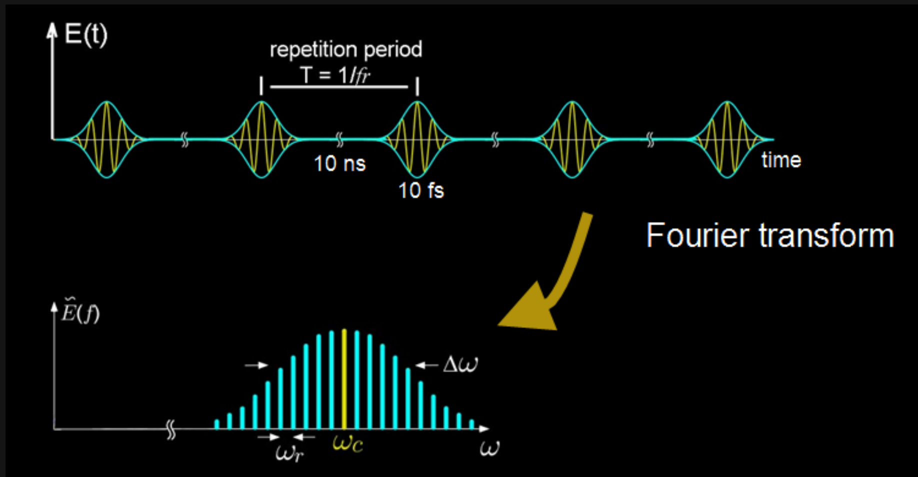
Lev Kulevsky
(Lebedev Inst. Moscow)

Introduced me to nonlinear optics

Robert Byer
(Stanford University)

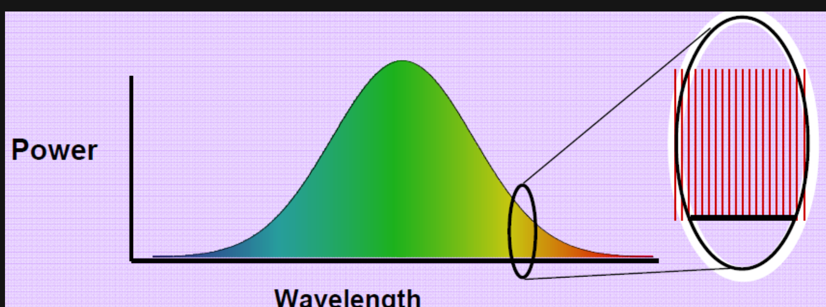
Prior work on CW degenerate OPO

What are frequency combs ?

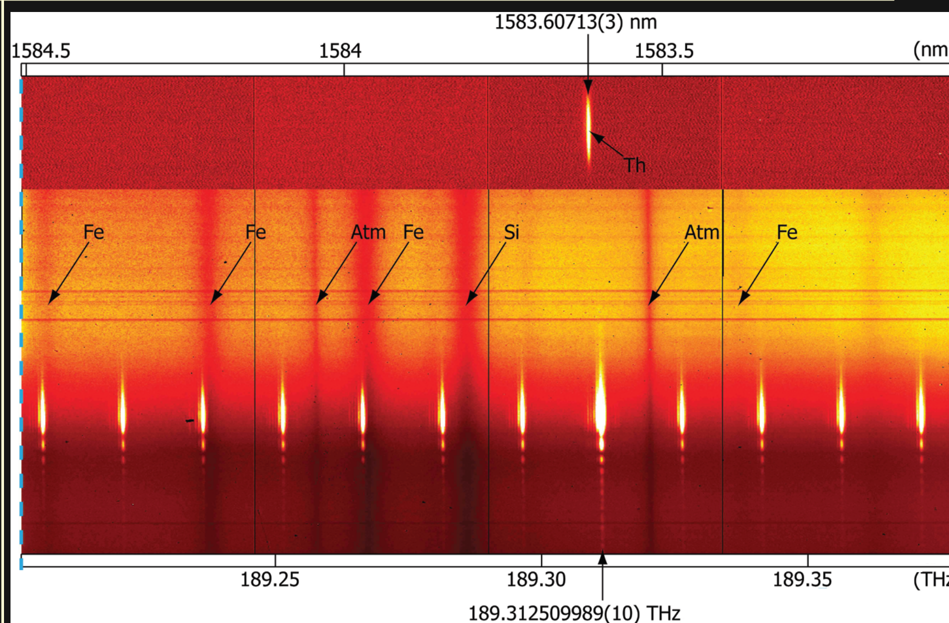


Regularly spaced train of short (fs) pulses corresponds to a comb in the frequency domain

Theodor W. Hänsch and John L. Hall
2005 Nobel Prize in Physics

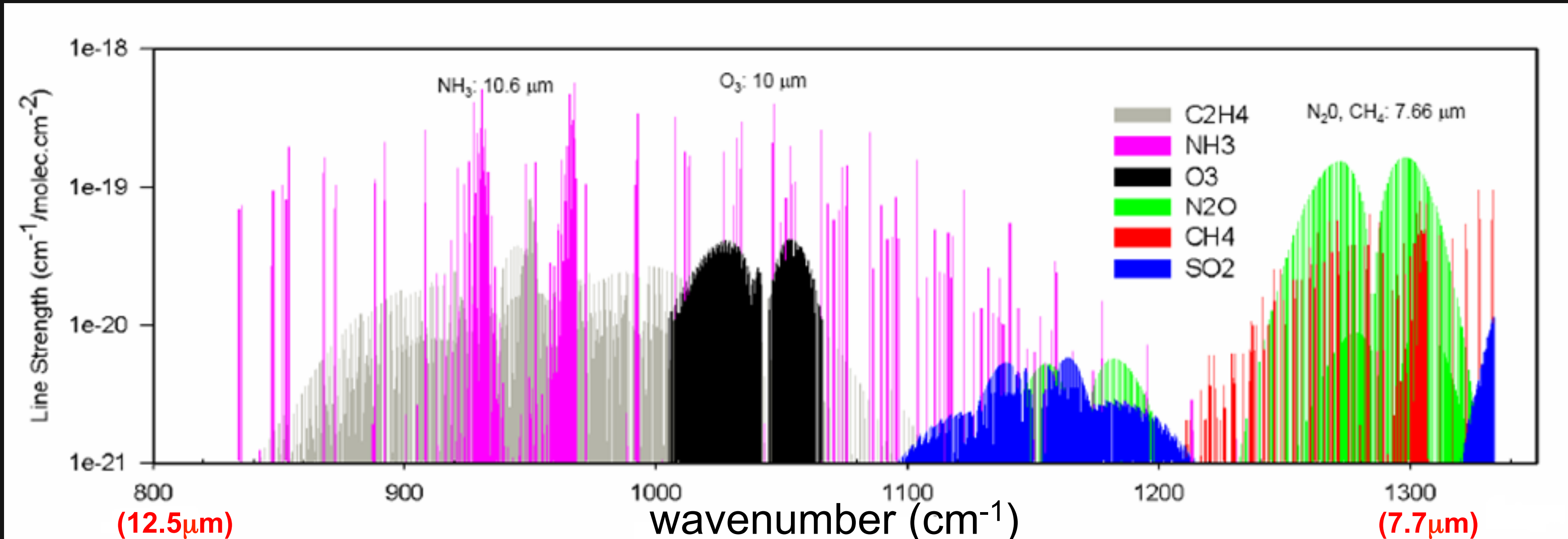


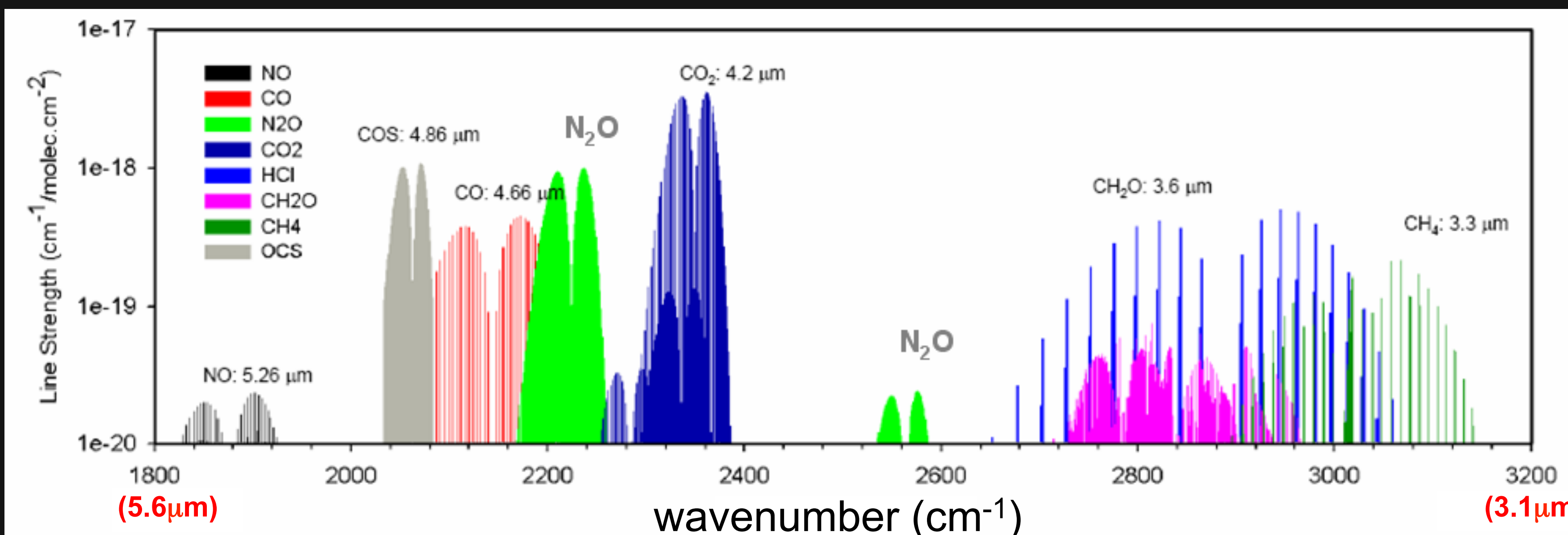
Spectra of the solar photosphere near 1.5μm overlaid by a Laser Frequency Comb with 15-GHz mode spacing →



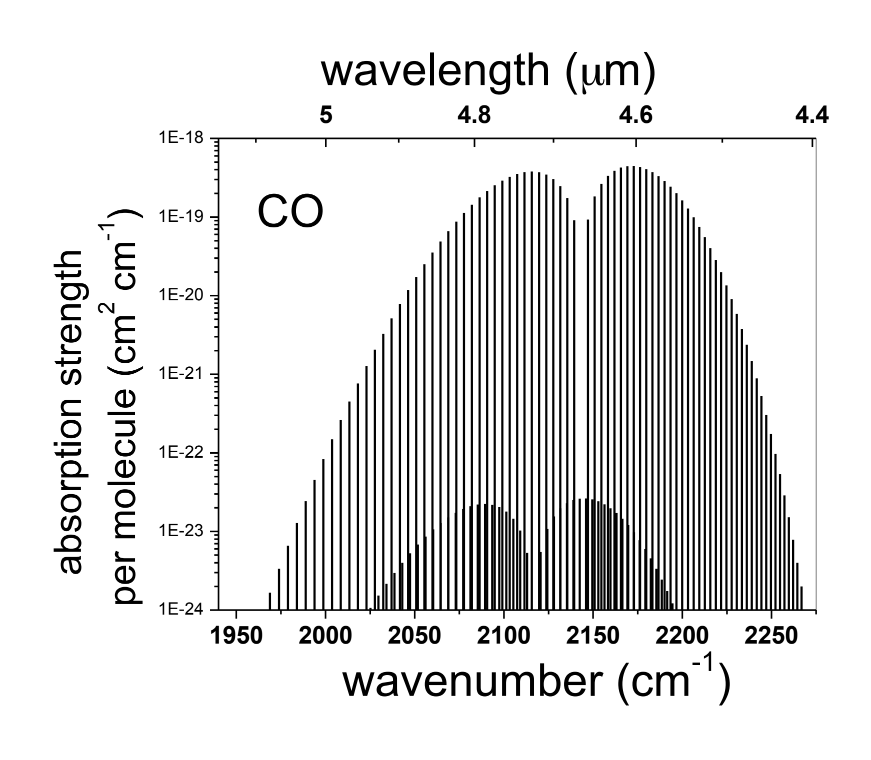
Steinmetz et al. *Science* **321**, 1335 (2008)

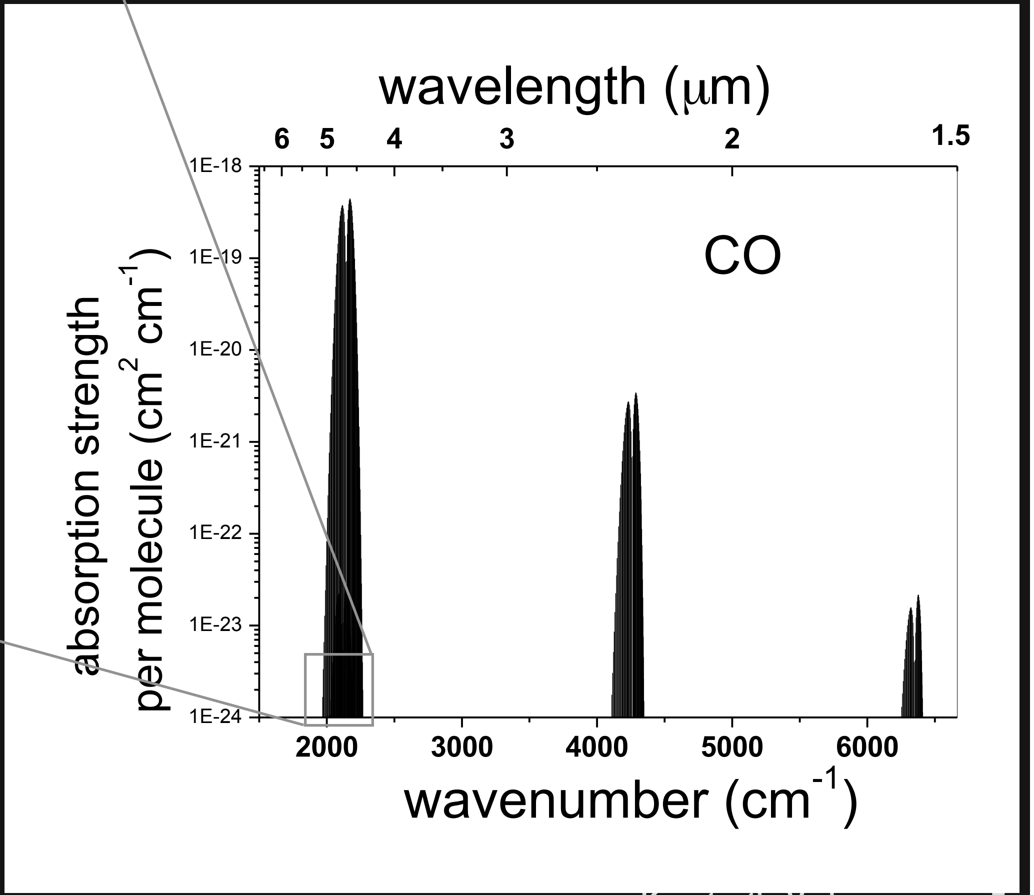
Molecular spectra in the "signature" mid-IR spectral range (3-12 μm)



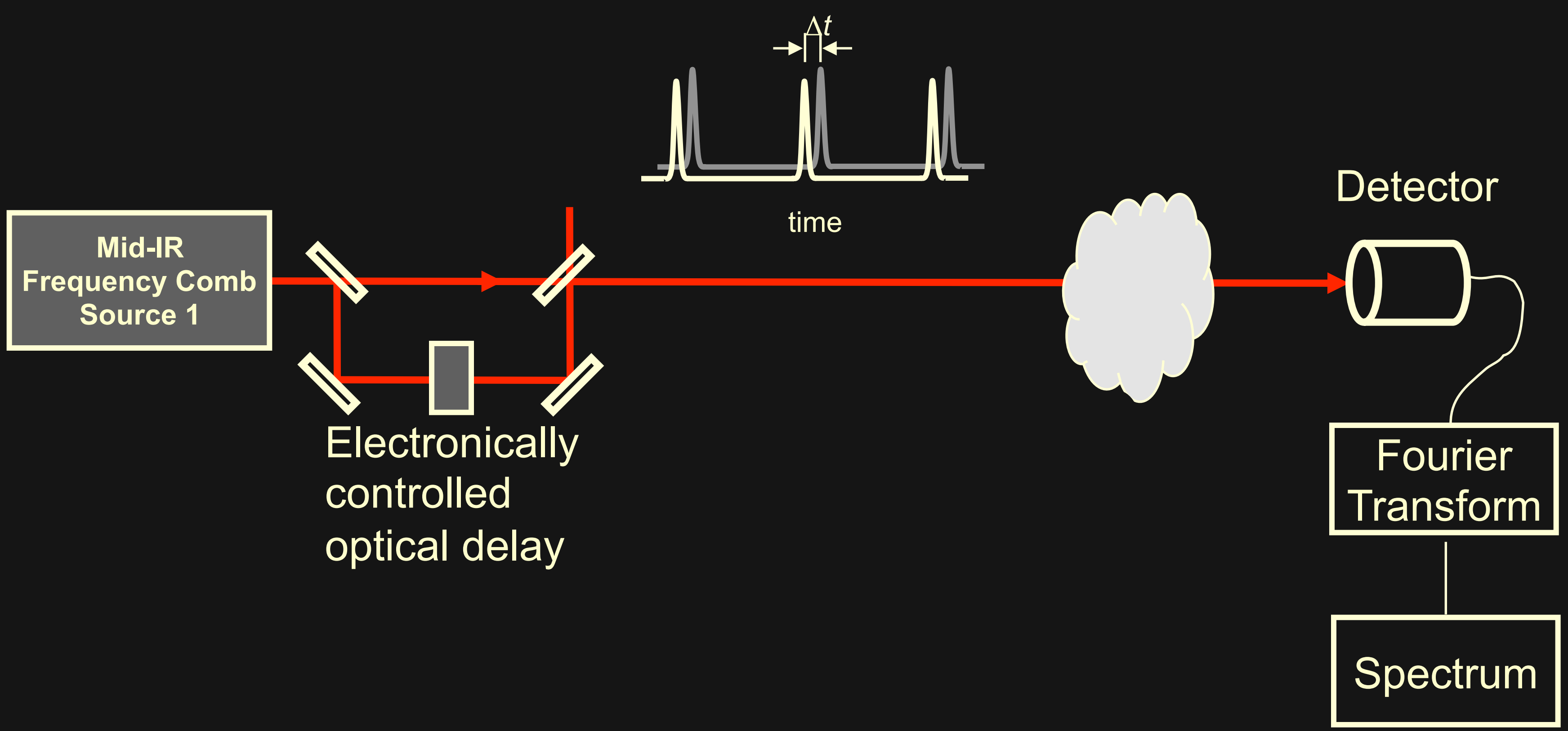


CO molecule spectrum



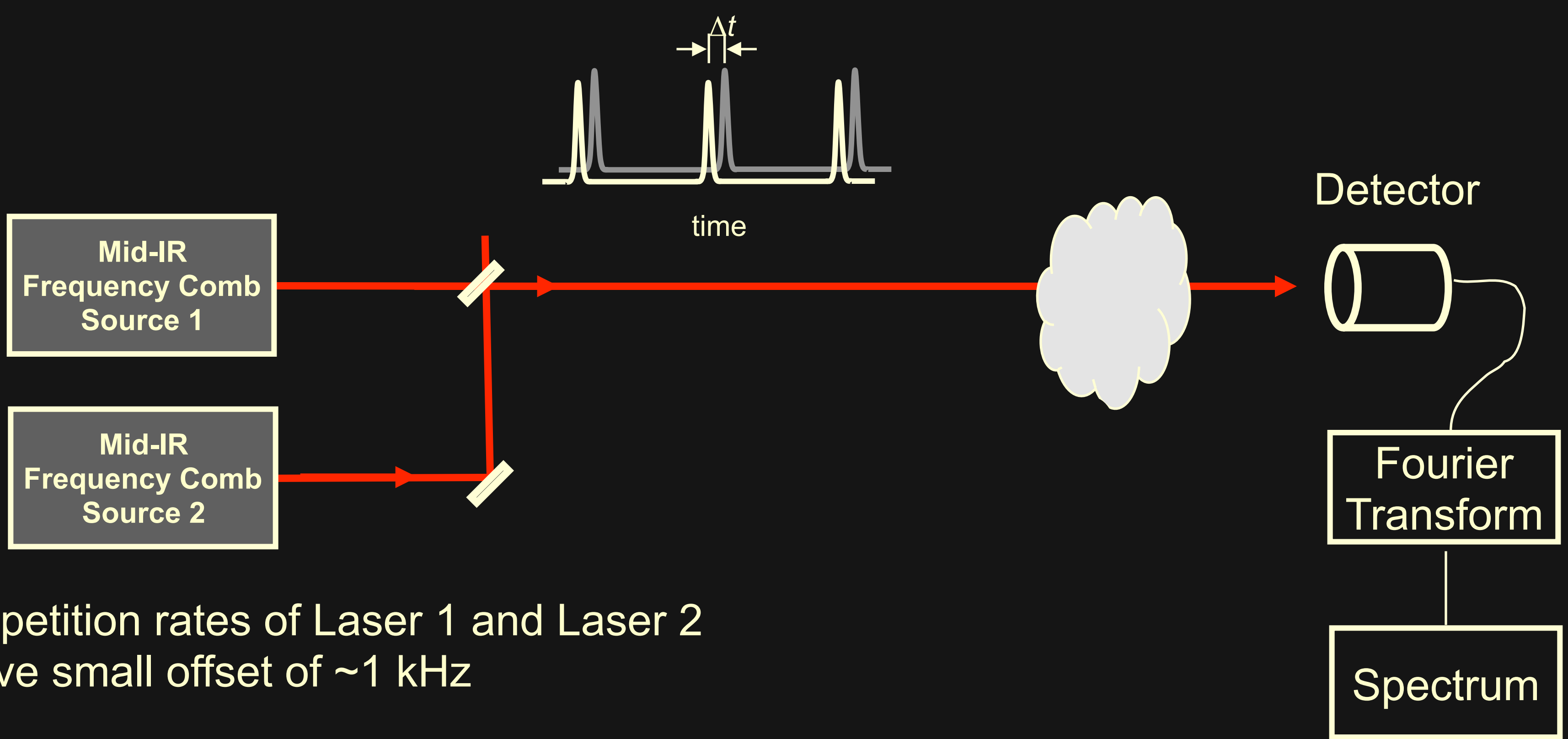


Comb Fourier Transform Spectroscopy



Dual-Comb Fourier Transform Spectroscopy

Schliesser, Brehm, Keilmann, Opt. Express 13, 9029 (2005)



Repetition rates of Laser 1 and Laser 2 have small offset of ~1 kHz

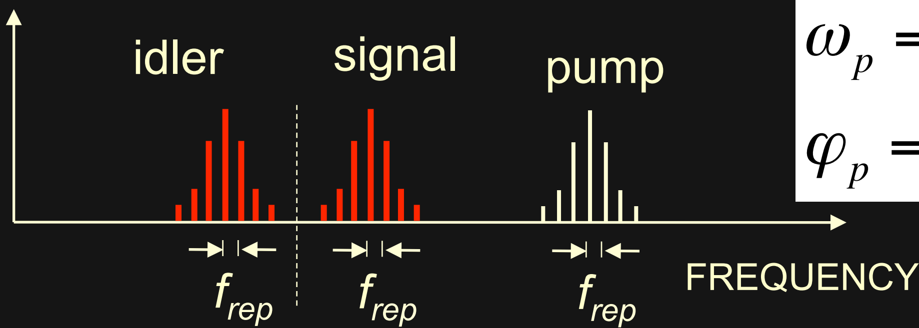
Up to 1000 spectra/sec
Resolution ~ 100 MHz (0.003 cm^{-1})

Frequency combs in the mid-IR

- Direct laser sources, e.g. Cr^{2+}: ZnSe
  Sorokin et al., Opt. Express 15, 16540 (2007)
- Supercontinuum from optical fibers
  Washburn et al., Opt. Lett. 29, 250-252 (2004)
- Optical parametric oscillators
  Sun, Gale, Reid. Opt. Lett. 32, 1414-1416 (2007).
  Adler et al. Opt. Lett. 34, 1330-1332 (2009).
- Difference frequency generation
  Erny, Moutzouris, Biegert, Kühlke, Adler, Leitenstorfer, Keller, Opt. Lett. 32, 1138-1140 (2007)
- Optical rectification
  Keilmann, Gohle, Holzwarth, Opt. Lett. 29, 1542-1544 (2004)
- Microresonators
  Wang, Herr, Pascal Del'Haye, Schliesser, Holzwarth, Haensch, Picque, Kippenberg, Post-Deadline, CLEO -2011

Degenerate $\chi^{(2)}$ sync-pumped OPO

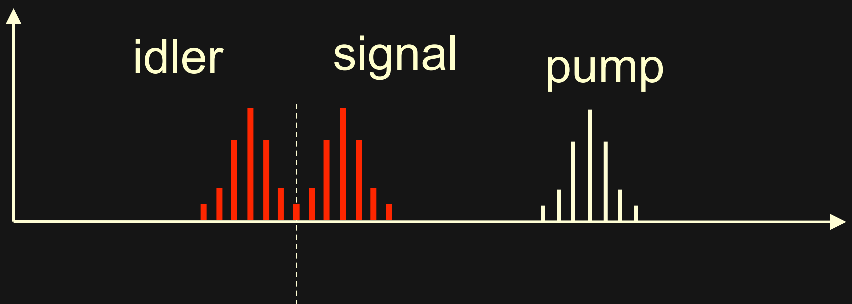
non-degenerate OPO



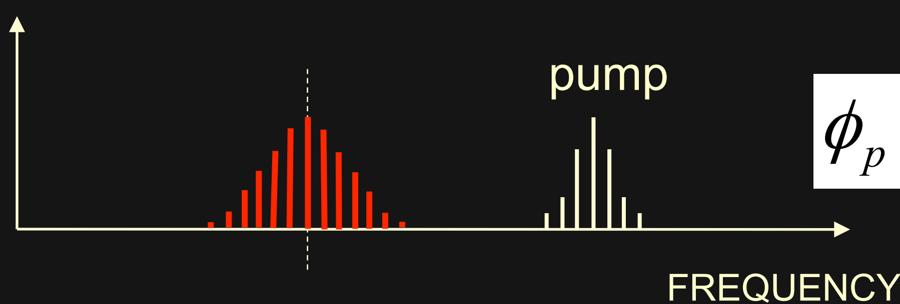
$$\omega_p = \omega_s + \omega_i$$

$$\varphi_p = \varphi_s + \varphi_i + \pi / 2$$

partly degenerate OPO



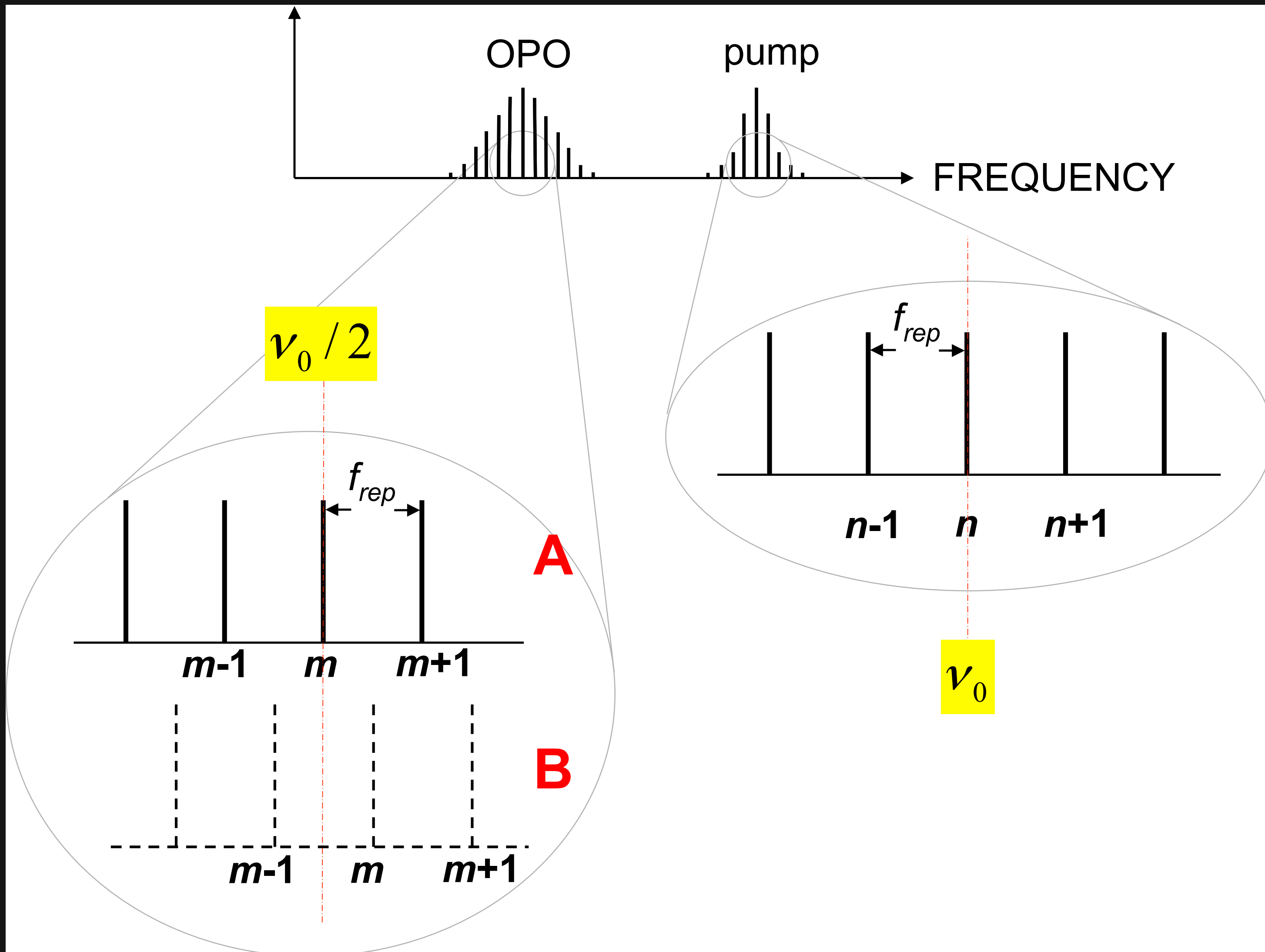
degenerate OPO



$$\phi_p = 2\phi_{s,i} + \pi / 2$$

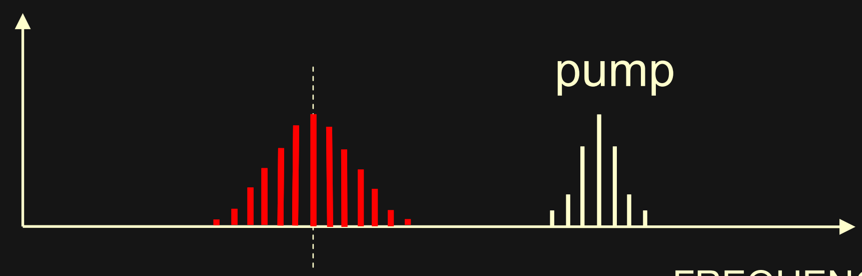
Wong, Vodopyanov, Byer, *JOSA* **B 27**, 876 (2010)

Longitudinal modes of the sync-pumped degenerate OPO



Wong, Vodopyanov, Byer, *JOSA* **B 27**, 876 (2010)

Degenerate synch-pumped OPO



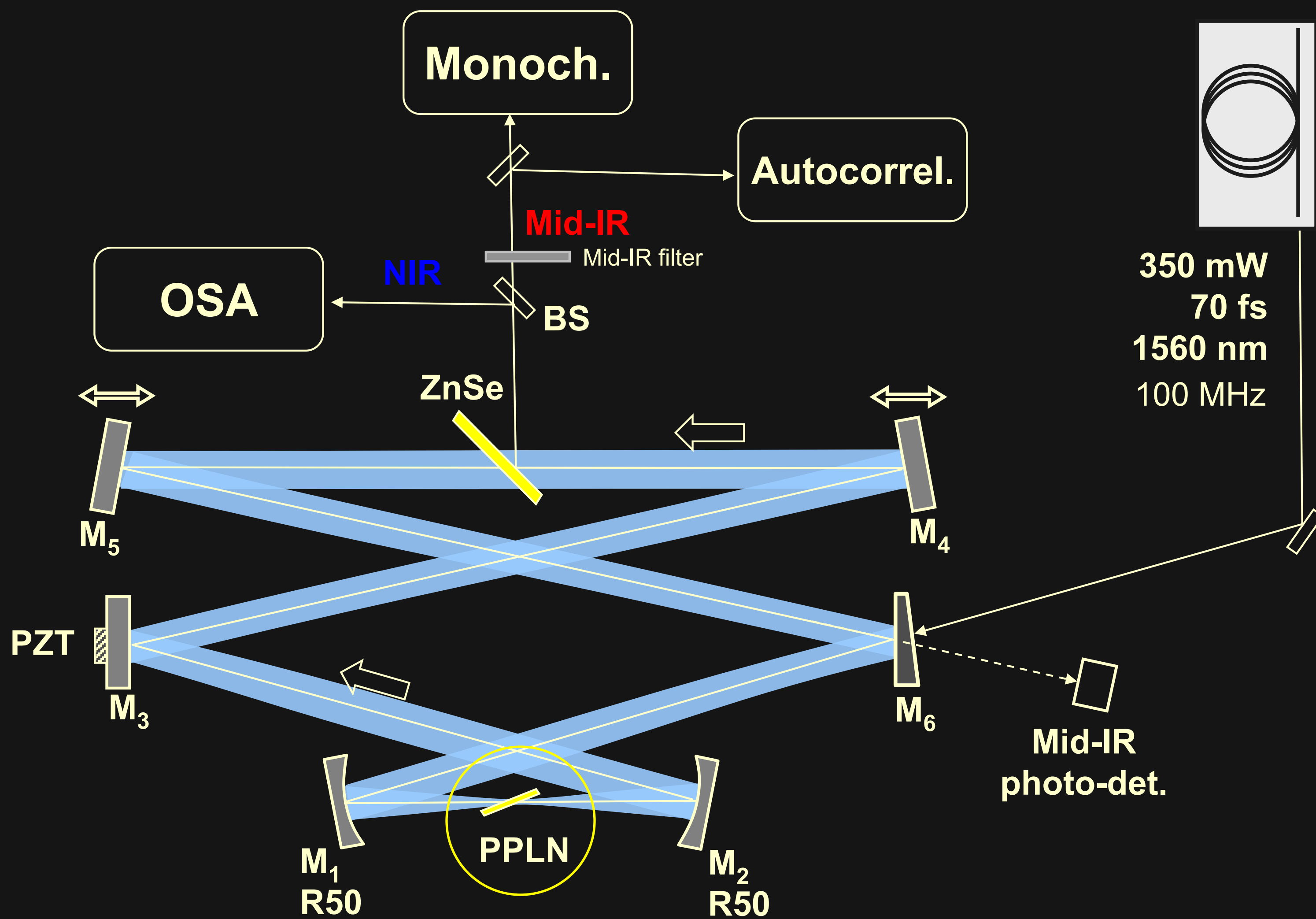
1. **Large acceptance bandwidth at degeneracy**

   $\sim \beta_2^{-1/2}$ ($\beta_2 = d^2 k / d\omega^2$)

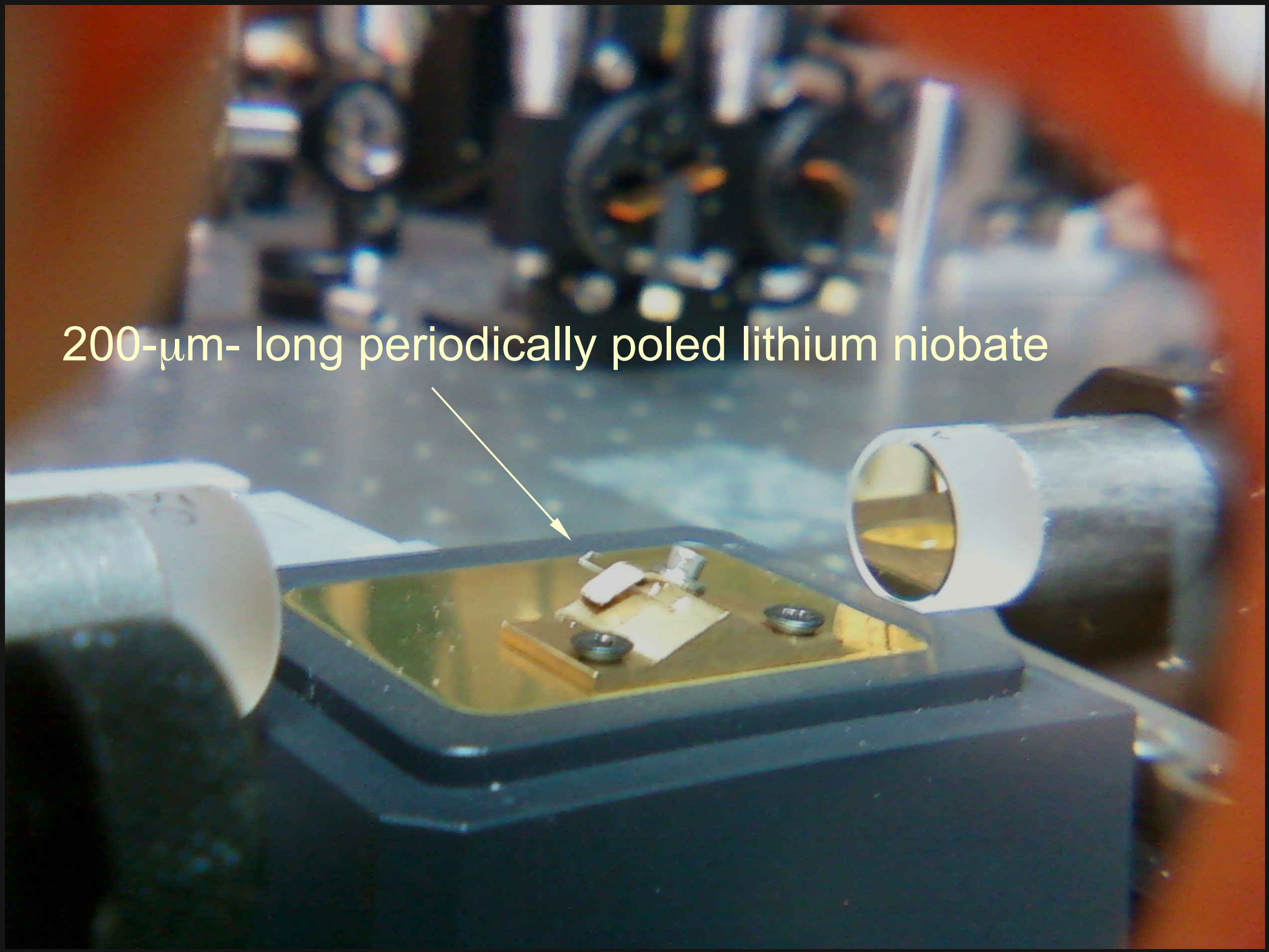
   $\sim \beta_4^{-1/4}$, if $\beta_2 = 0$ ($\beta_4 = d^4 k / d\omega^4$)

2. **Double resonance -> low pump threshold**
3. **OPO is phase- and frequency locked to the pump laser**

Mid-IR subharmonic OPO setup



“OPO engine”

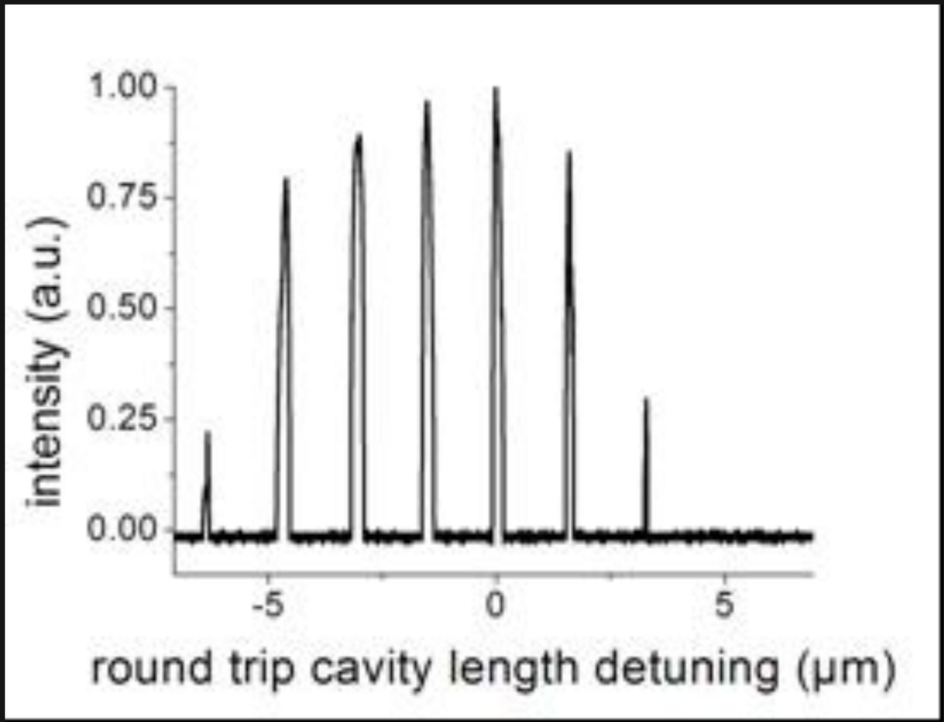


PPLN crystal:

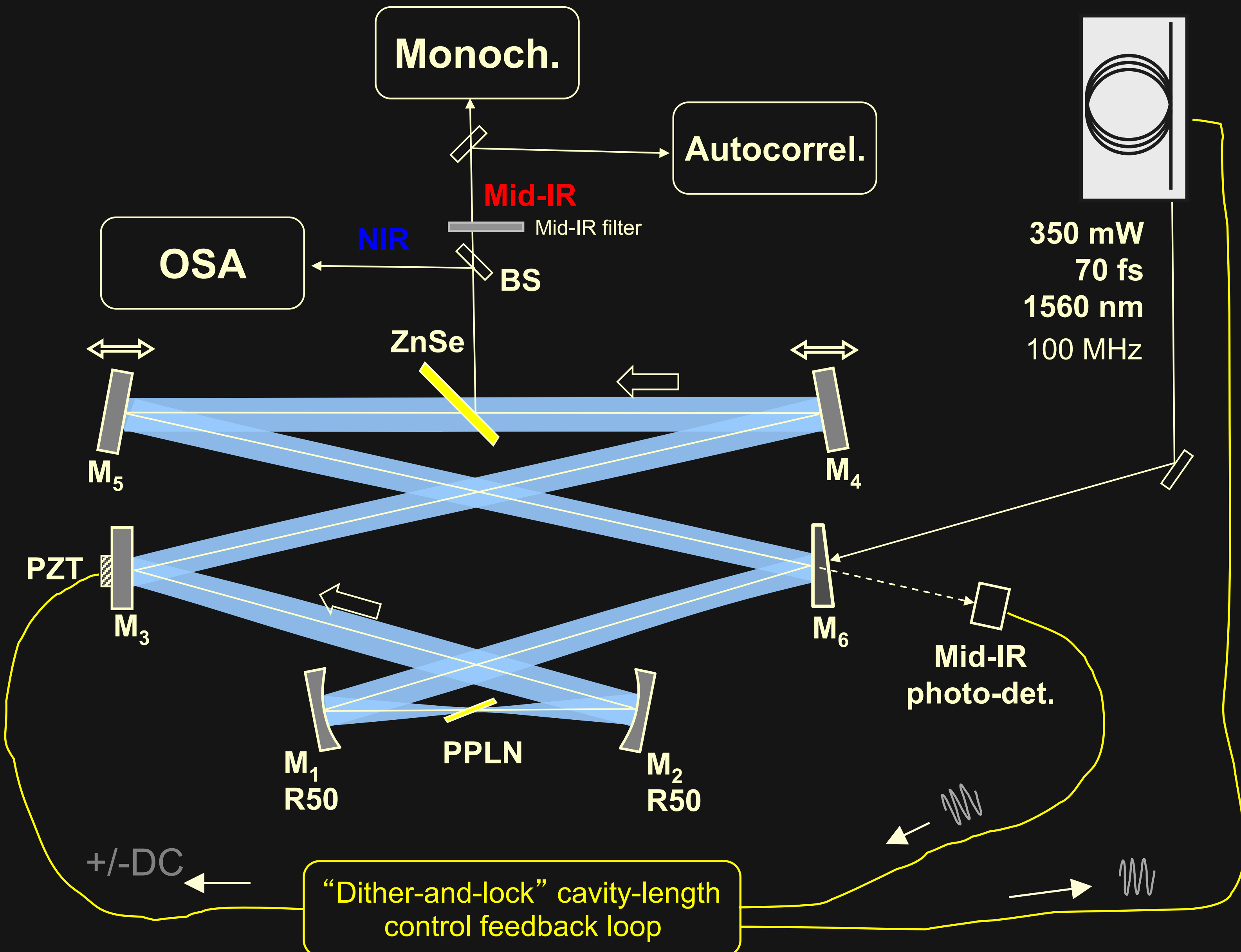
500 μm (14 periods)
or
200 μm (6 periods)

Brewster-cut

OPO oscillation occurs at several discrete cavity lengths
Can be stabilized at each of those peaks

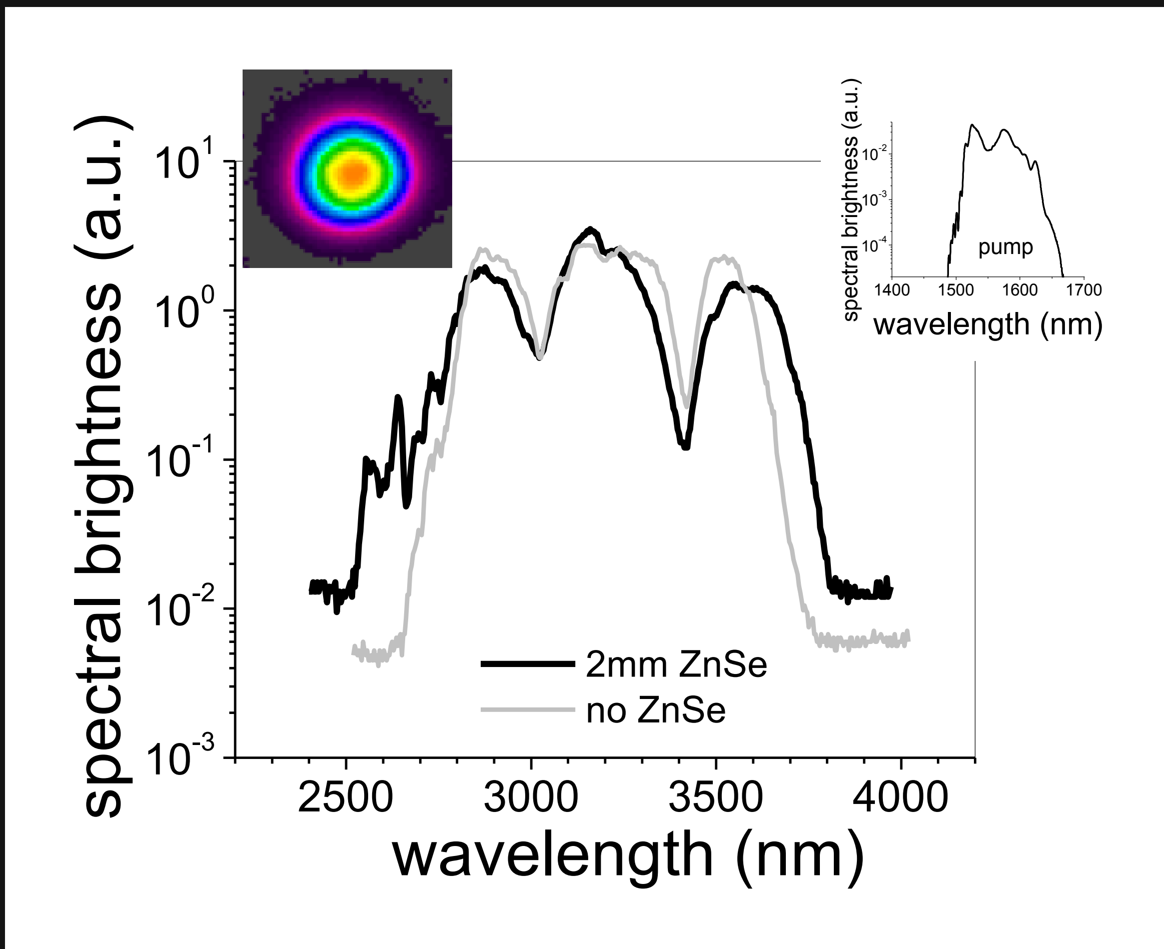


Mid-IR subharmonic OPO setup

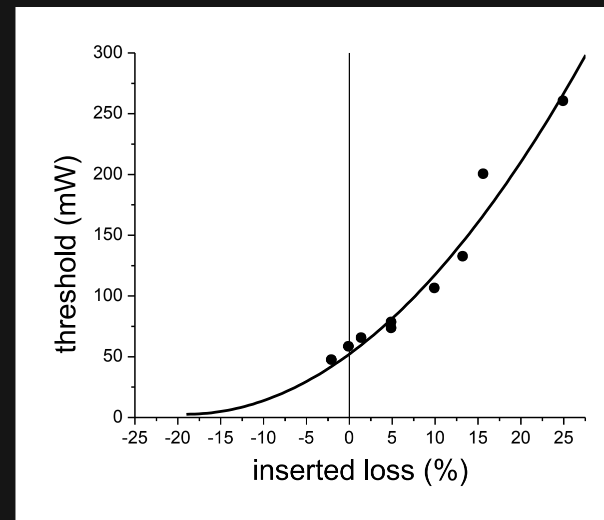


OPO main features

Spectrum: Monochromator



Threshold ~ $(loss)^2$



Pump threshold 9 mW

Pump depletion 80-83%

Outcoupled power 60 mW

Bandwith 2500-3900 nm (2/3 octaves)

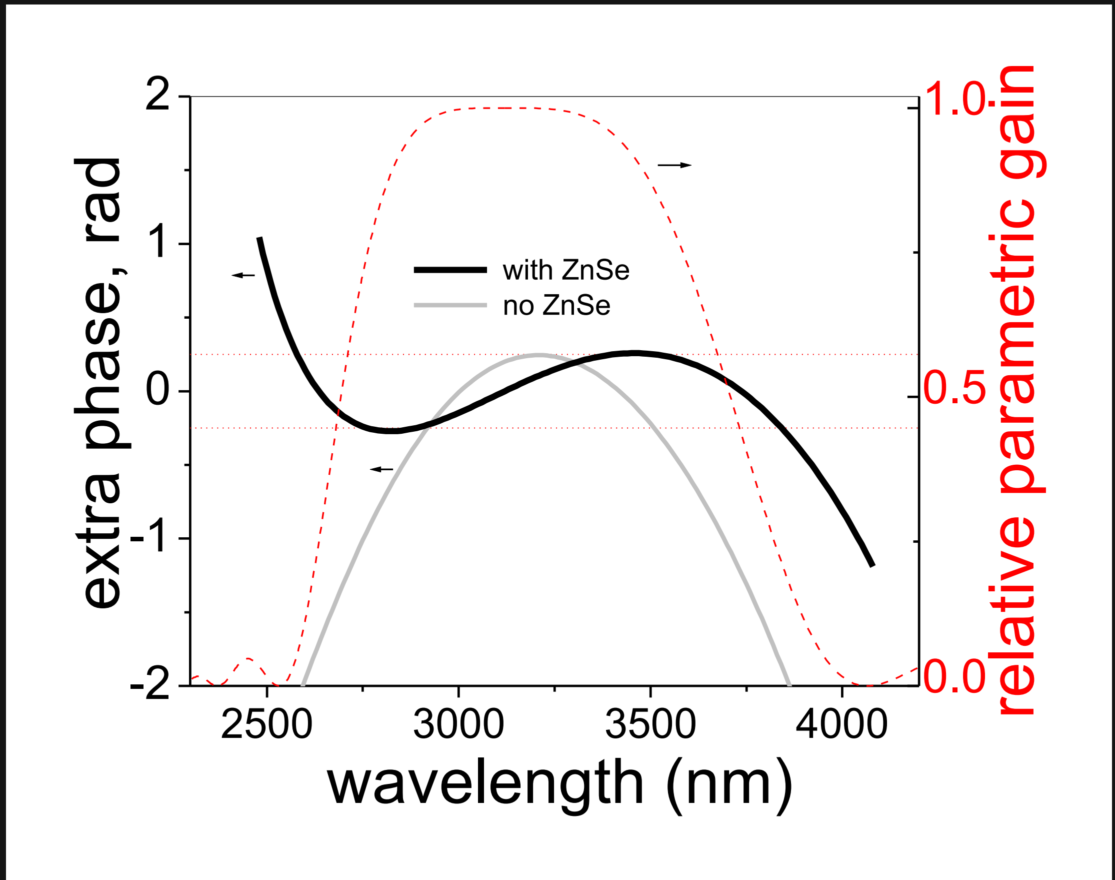
Can support 3-cycle pulses

at ~ 3 μm

Intracavity power 1.2W

Leindecker, Marandi, Byer, Vodopyanov, *Opt. Express* **19**, 6296 (2011)

What limits the comb spectral width ?



Computed extra phase accumulated per cavity roundtrip due to the dispersion of 0.5-mm PPLN plus mirrors (gray curve) and (black curve) with ZnSe added for dispersion compensation.

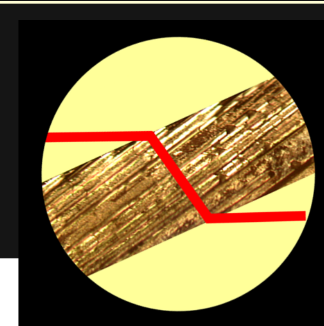
Leindecker, Marandi, Byer, Vodopyanov, *Opt. Express* **19**, 6296 (2011)

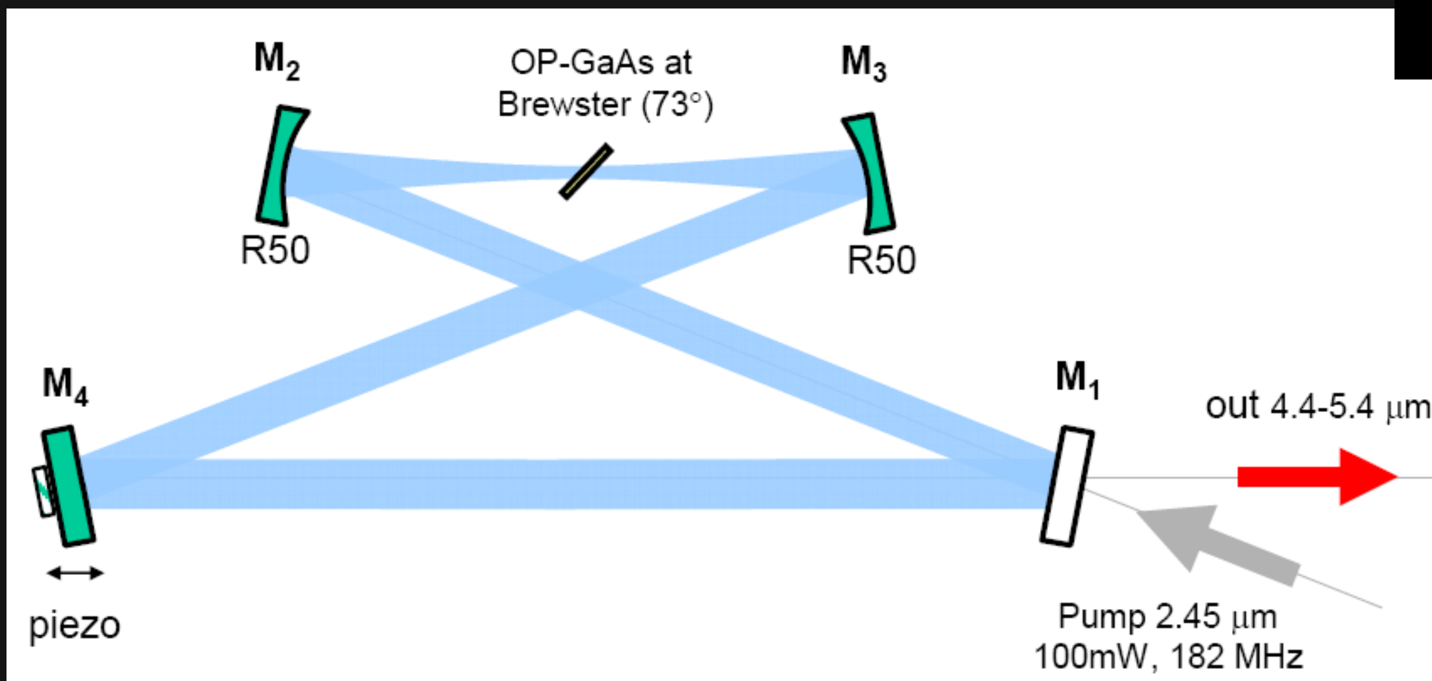
Results with orientation-patterned GaAs pumped at 2.45 μm

4.4-5.4 μm frequency comb was produced in a subharmonic OP-GaAs OPO pumped by a femtosecond Cr^{2+}:ZnSe laser at 2.45 μm

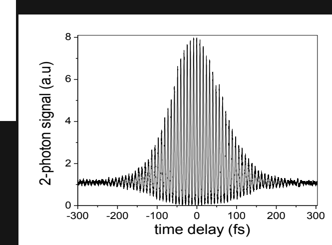
Pump threshold 40mW

OP-GaAs : 500-μm-long
QPM period: 92 μm
Beam *k*-vector: along [110]
Polarization: along [111]





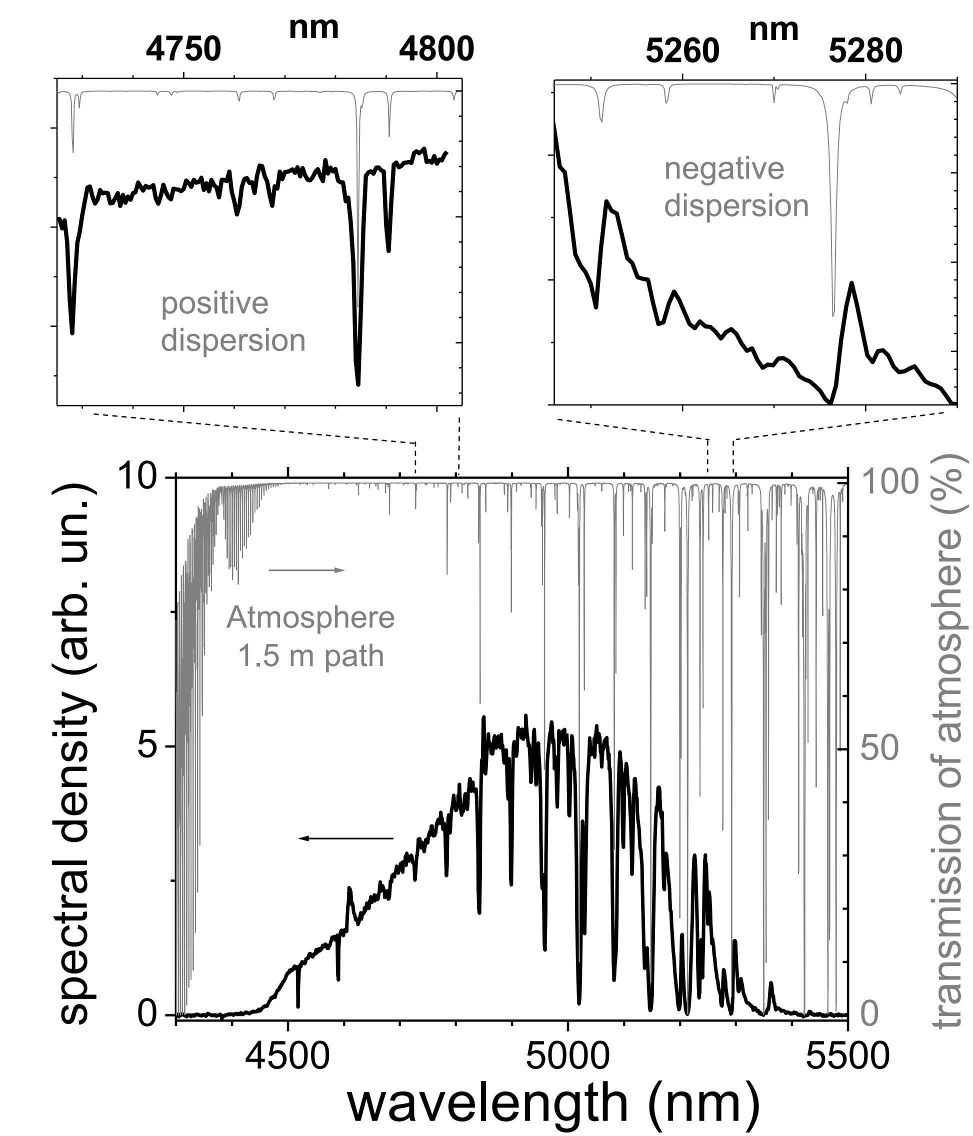
τ≈100fs



Vodopyanov, Sorokin, Sorokina, Schunemann, *Opt. Lett.* **36**, 2275 (2011)

Results with orientation-patterned GaAs

Monochromator spectrum



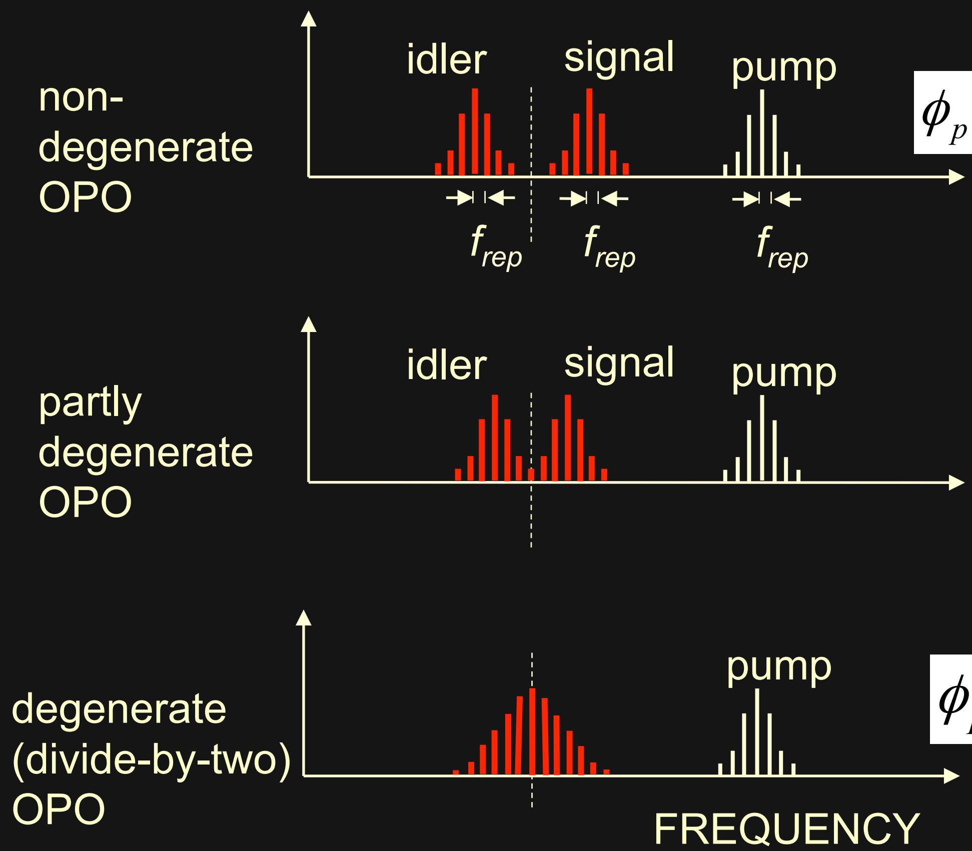
The spectrum is affected by intracavity absorption (water and CO_2)

Vodopyanov, Sorokin, Sorokina, Schunemann, *Opt. Lett.* **36**, 2275 (2011)

Most recently 3.5-5.5 μm frequency comb was produced in a subharmonic OP-GaAs OPO pumped by a femtosecond Tm^{3+} - fiber laser at λ=2 μm

Coherence properties of divide-by-two OPO

Divide-by-two synch-pumped OPO



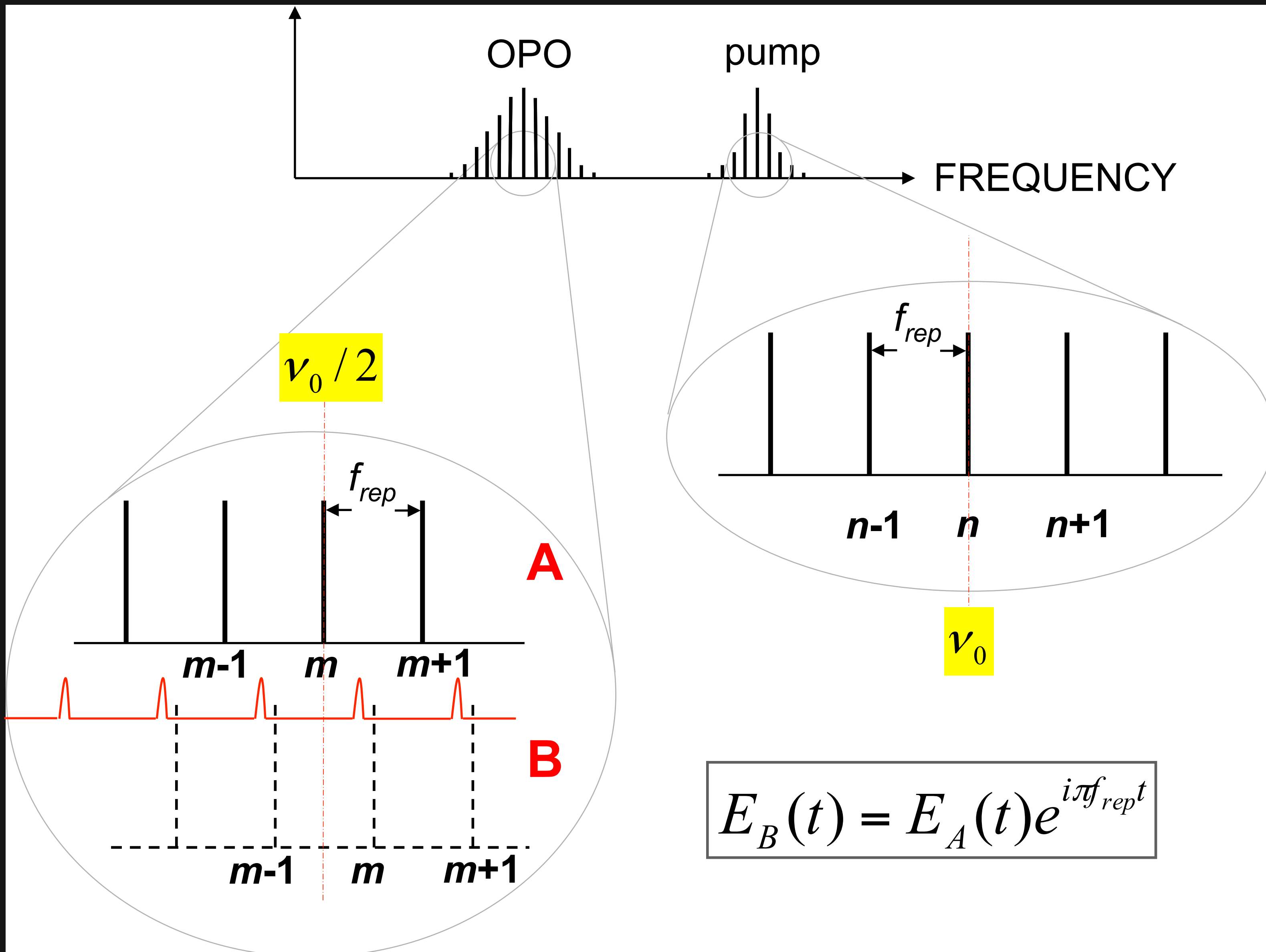
$$\phi_p = \phi_s + \phi_i + \pi/2$$

$$\phi_p = 2\phi_{s,i} + \pi/2$$

- OPO is phase locked to the pump laser
- adding π to the signal and idler does not change phase relation

Wong, Vodopyanov, Byer, *JOSA* **B 27**, 876 (2010)

Longitudinal modes of the sync-pumped degenerate OPO

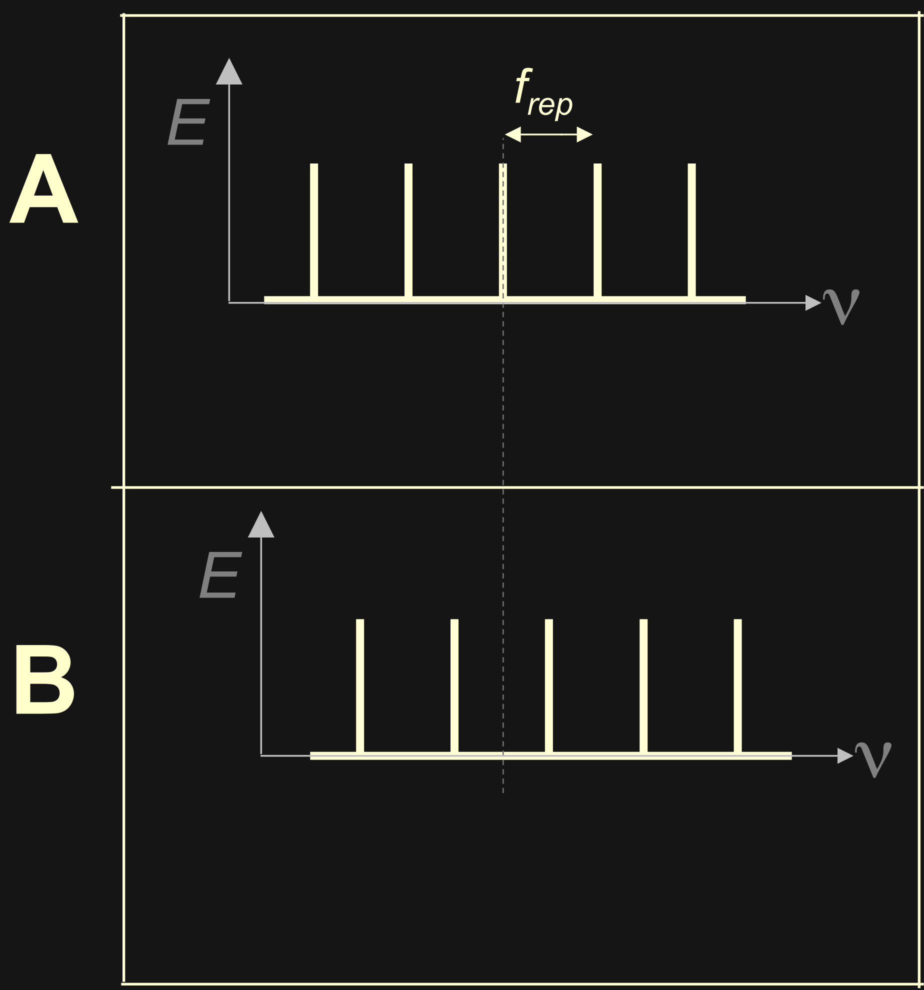


$$E_B(t) = E_A(t)e^{i\pi f_{rep}t}$$

Wong, Vodopyanov, Byer, *JOSA* **B 27**, 876 (2010)

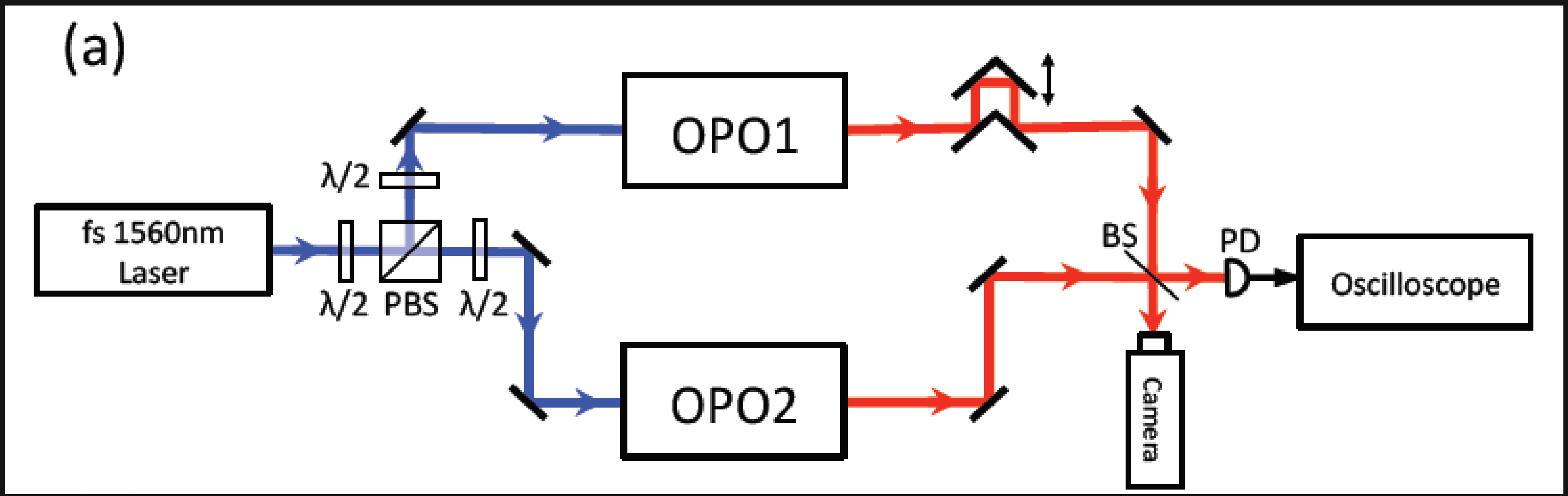
Four possibilities for the OPO mode phases

$\phi = 0$



Experiment

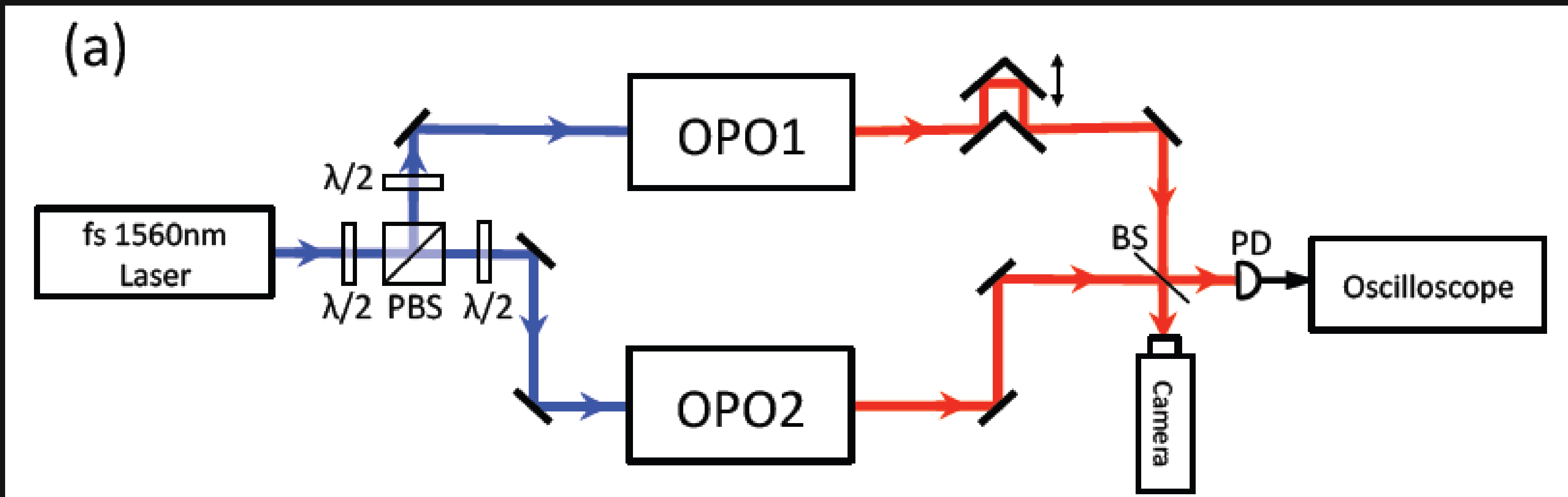
A twin OPO system



1) **AA** or **BB**
 interfere constructively or destructively, depending on the "0" or "π" state

2) **AB or BA**
 do not interfere, but give $f_{rep}/2$ (50 MHz) beats

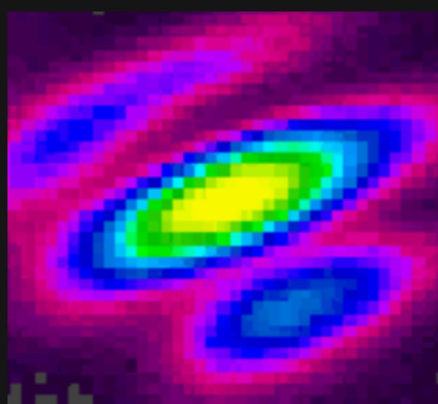
A twin OPO system

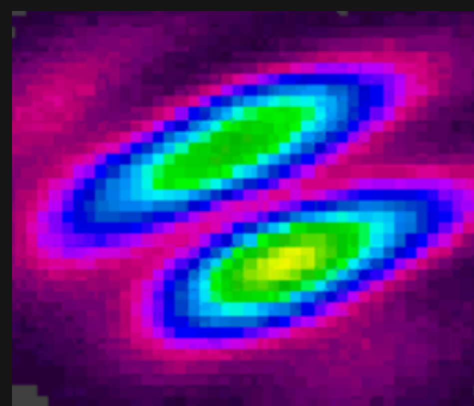


AA

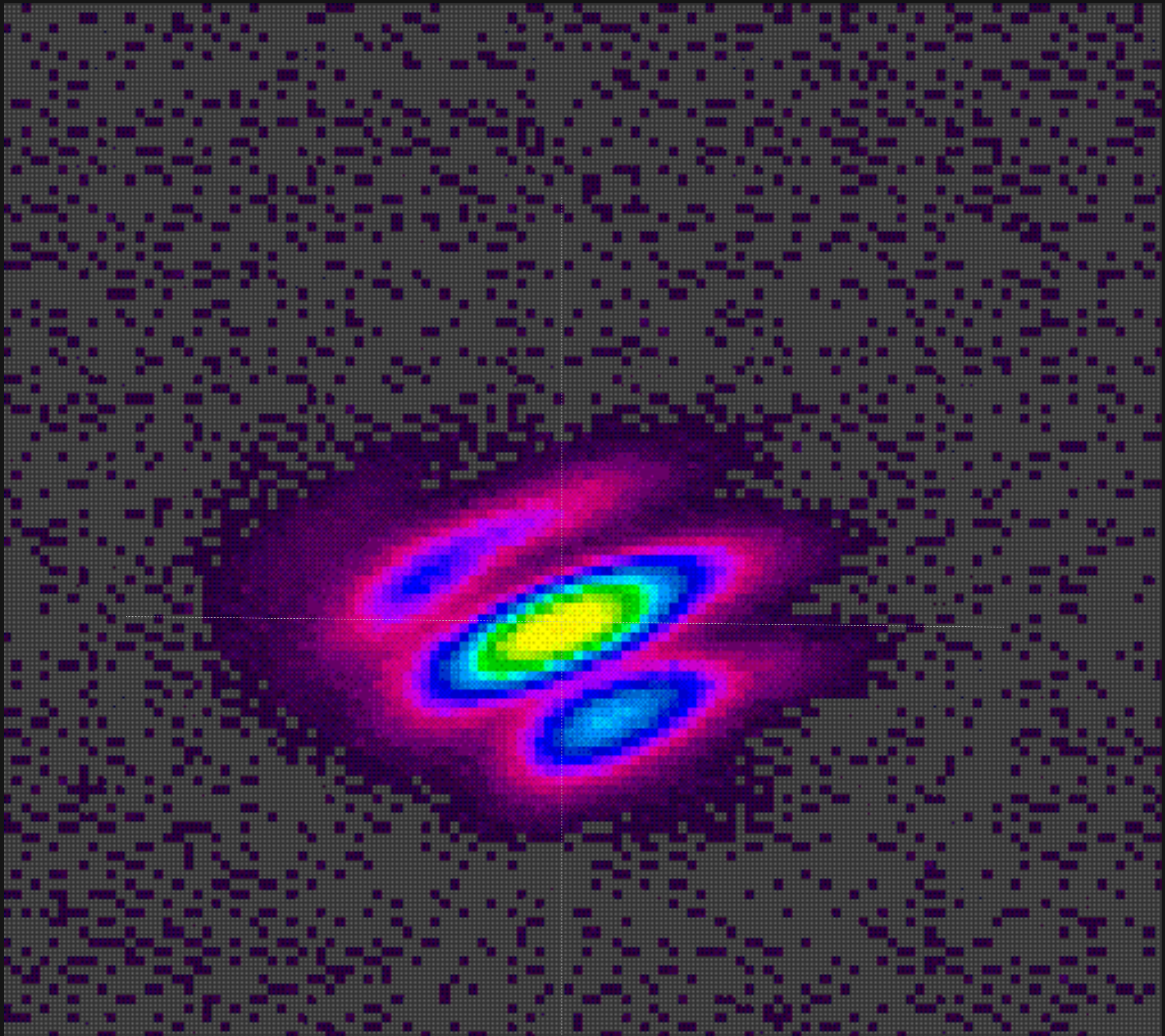
or

BB



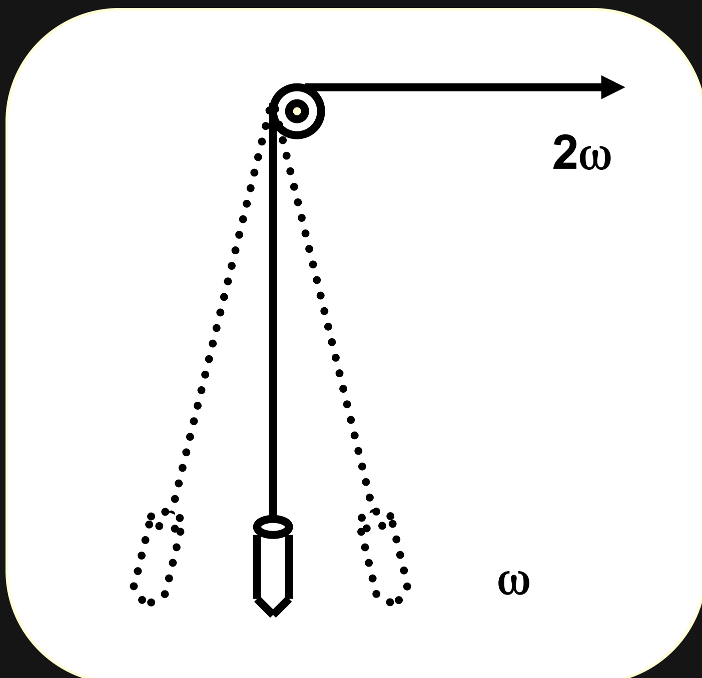


Observed spatial interference patterns



Every ~ 5 seconds OPO2 is briefly terminated
Phase randomly flips from “0” to “π” state

Mechanical analogy: parametrically driven pendulum



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

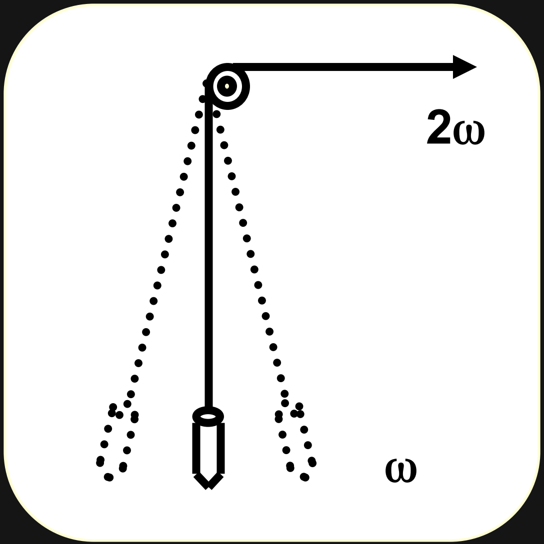
[FIFTH SERIES.]

APRIL 1883.

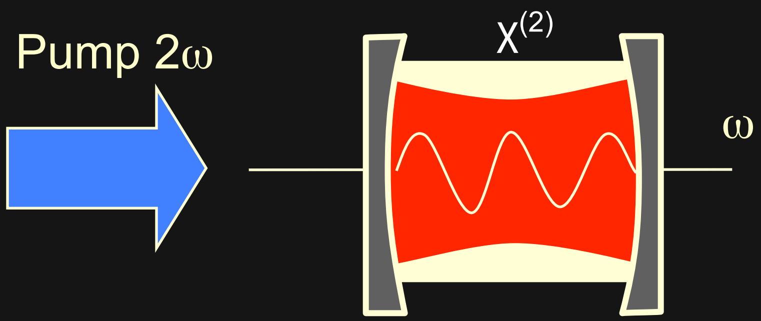
XXXIII. *On Maintained Vibrations. By* Lord RAYLEIGH, *F.R.S., Professor of Experimental Physics in the University of Cambridge**.

$$\ddot{\theta} + \omega^2 (1 - 2\alpha \sin 2\omega t)\theta = 0$$

Mechanical and optical parametric oscillators are described by the same equation



$$\ddot{\theta} + \omega^2 (1 - \alpha \sin 2\omega t)\theta = 0$$



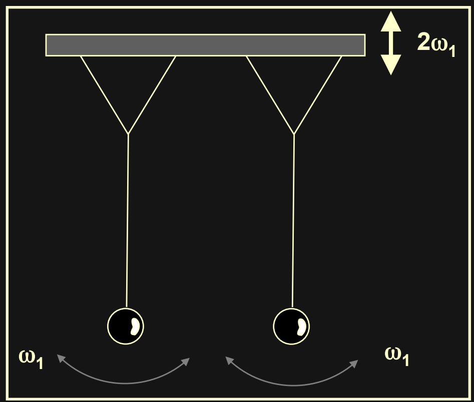
E-field in a cavity mode:

$$E(\mathbf{r},t) = p_l(t) E_l(\mathbf{r})$$

$$\ddot{p}_l + \omega^2 p_l = 0; \qquad \omega = \frac{k_l}{\sqrt{\mu\varepsilon}}$$

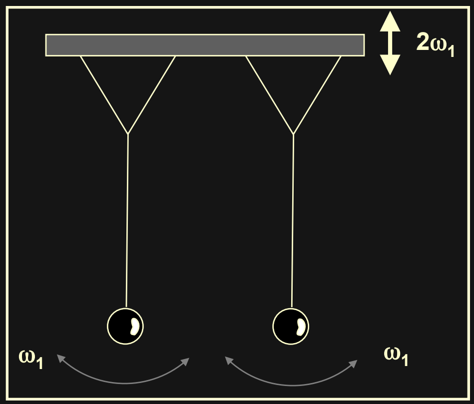
$$\Delta\varepsilon \sim \chi^{(2)} E_{pump}$$

Mechanical analogy: parametrically driven pendulum



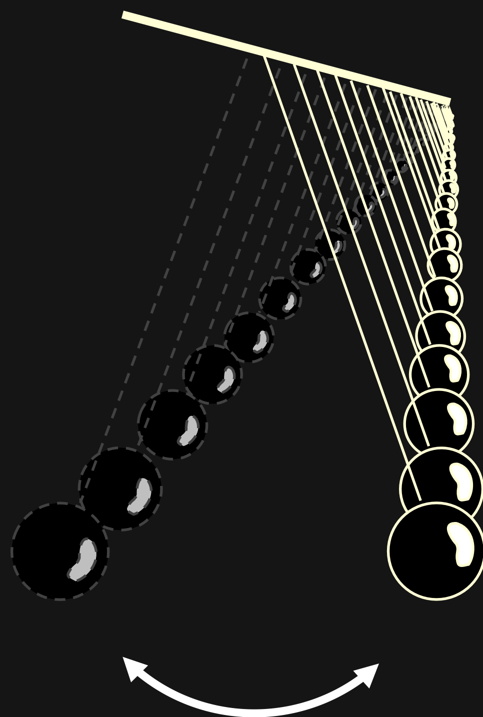
Two independent parametrically driven pendulums start randomly in-phase or out-of-phase

Mechanical analogy: parametrically driven pendulum



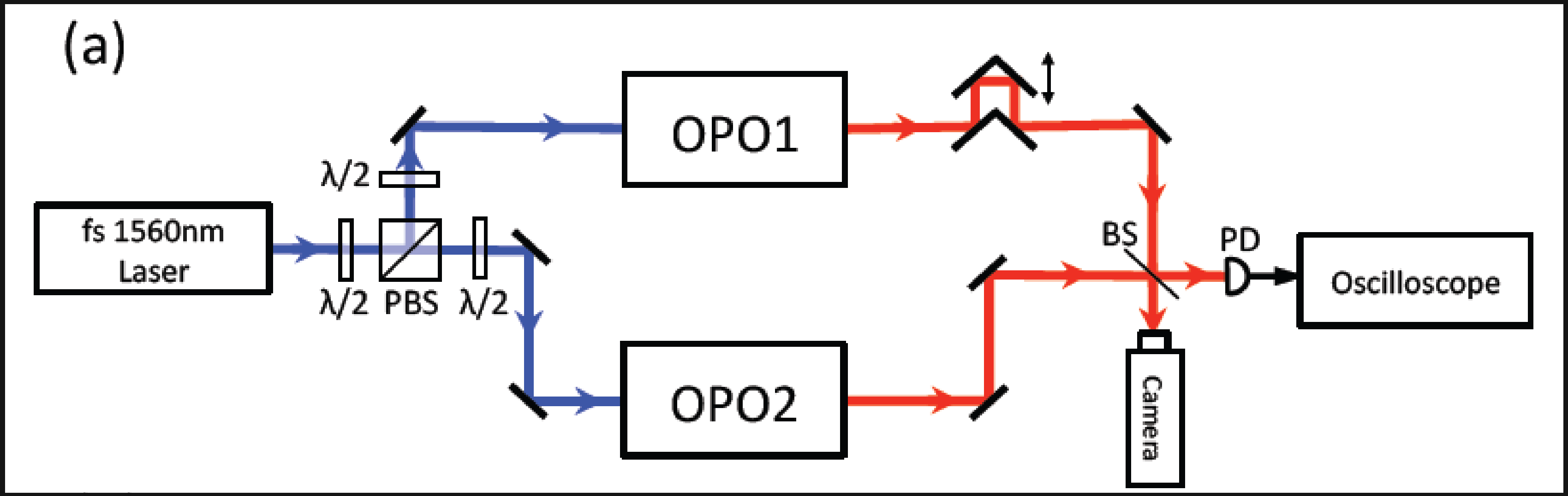
Two independent parametrically driven pendulums start randomly in-phase or out-of-phase

300 000 oscillators in phase

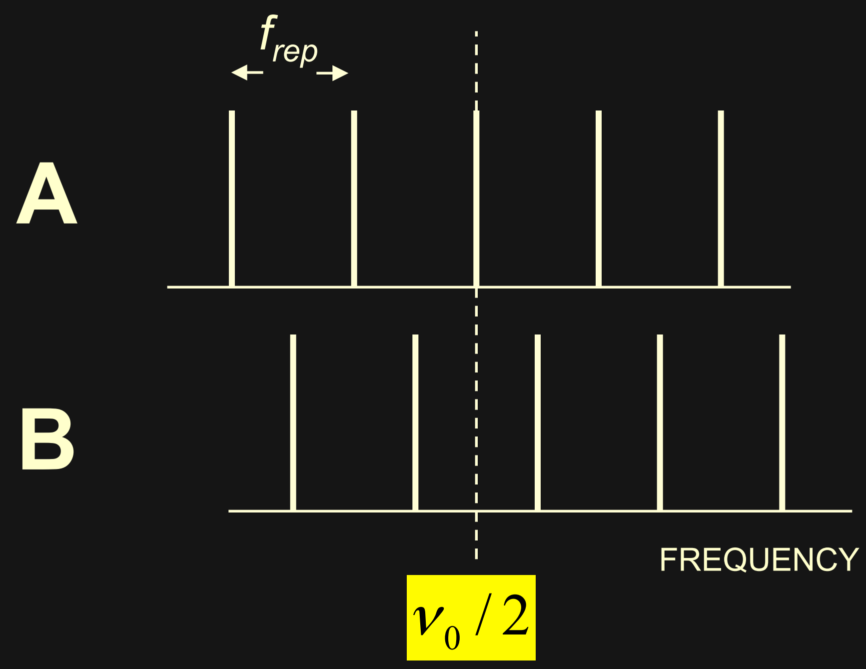


Some 300 000 pendulums oscillate with the same phase “0” or “π”

A twin OPO system: beat note study



Two possible states: ‘odd’ and ‘even’

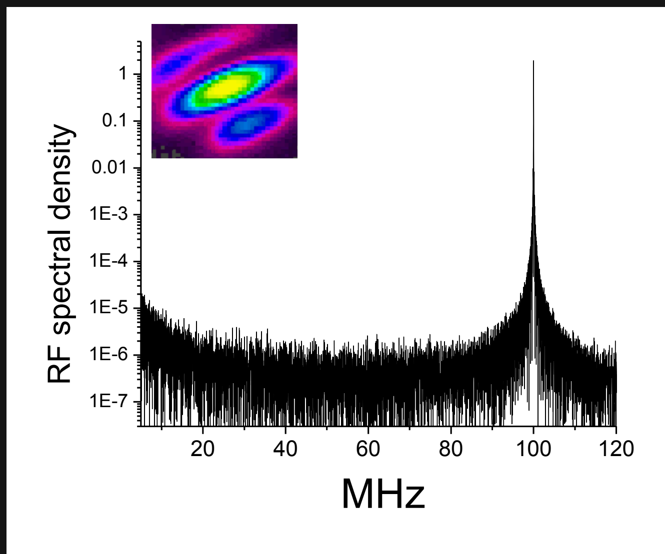


Switching between A and B is totally deterministic !
(by adjusting cavity length)

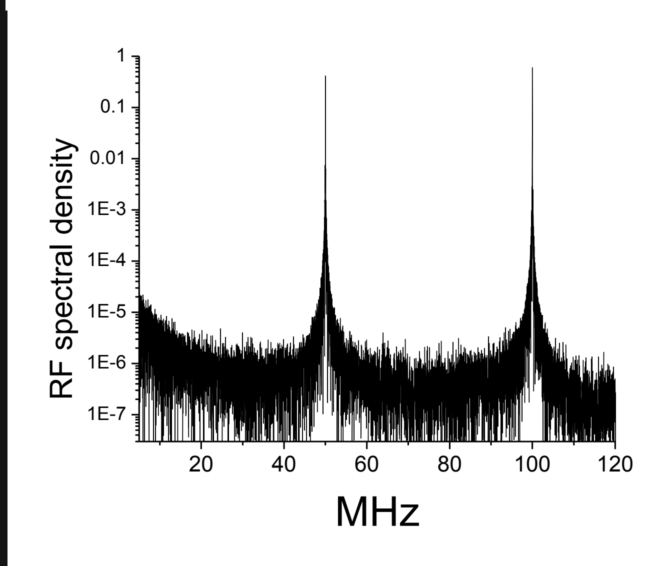
Observation of beats at $f_{rep}/2$

RF spectrum

AA

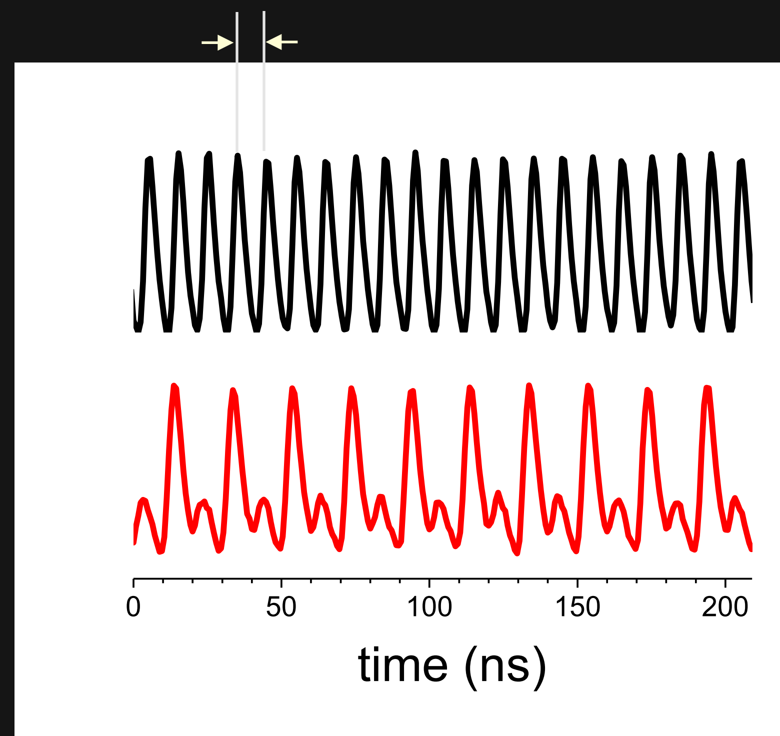


AB

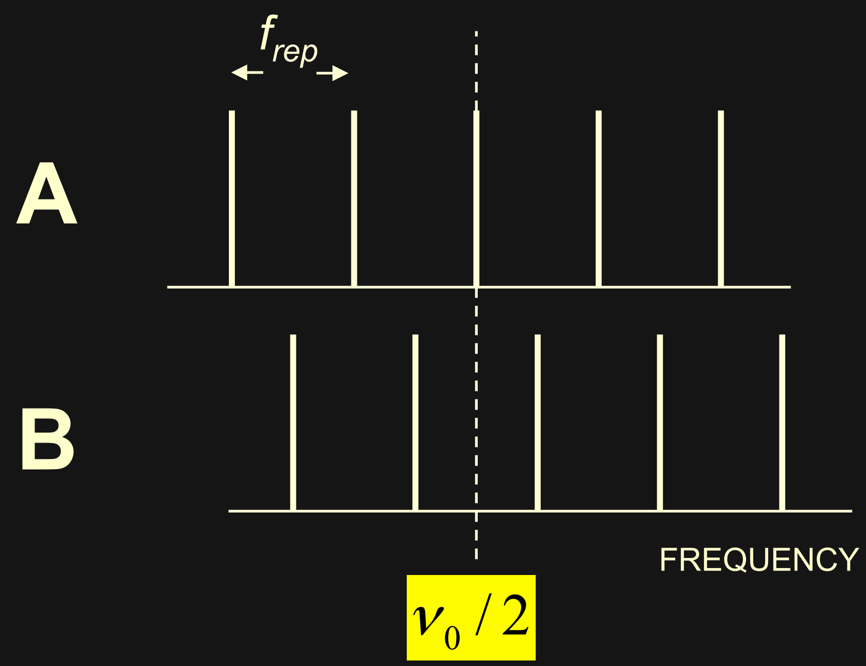


Time-domain signal

$1/f_{rep}$ = 10ns



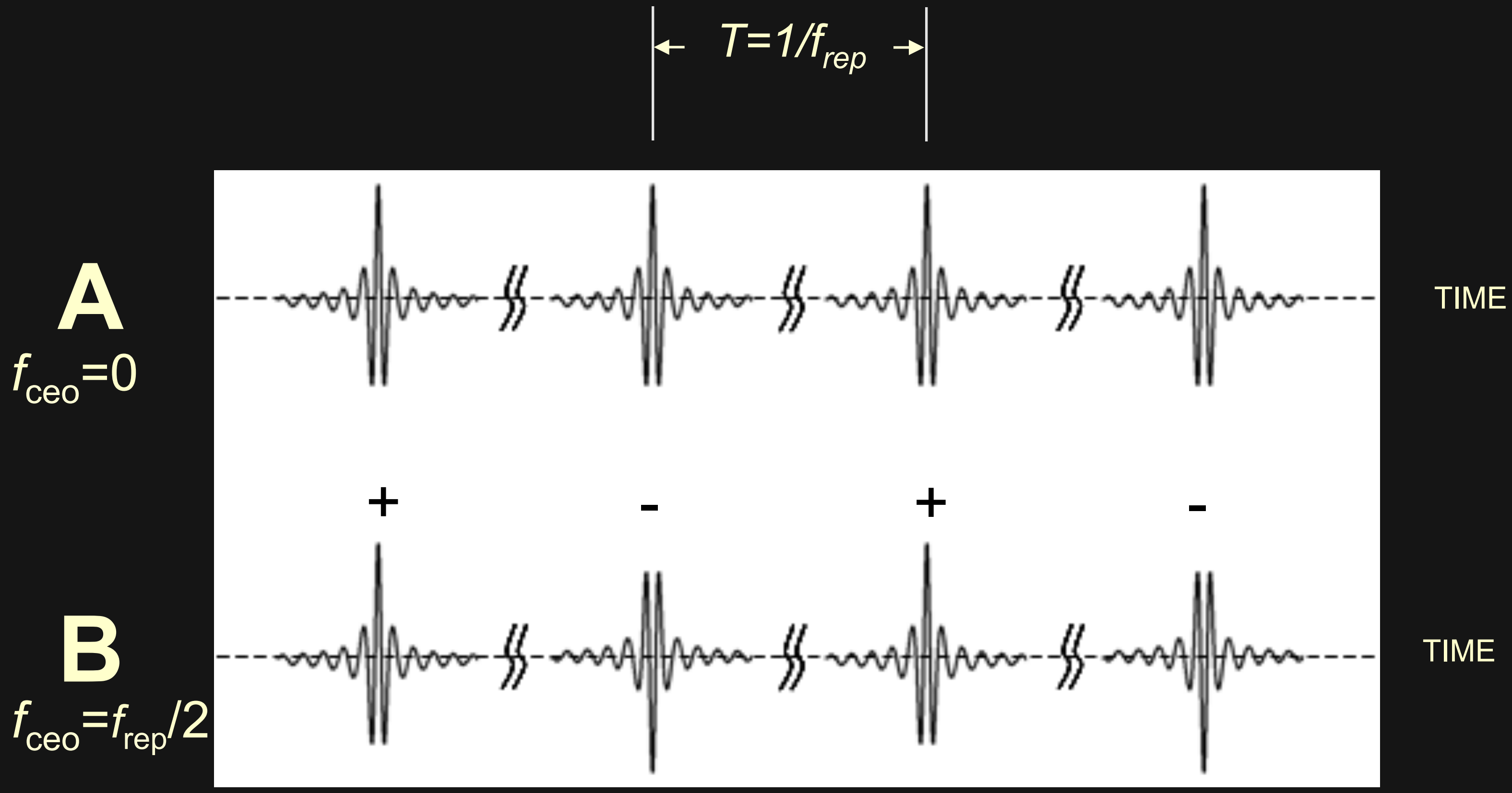
Two possible states: 'odd' and 'even'



$$E_B(t) = E_A(t) e^{i 2\pi \frac{f_{rep}}{2} t}$$

Switching between A and B is totally deterministic !
(adjust cavity length)

In time domain



$$E_B(t) = E_A(t)e^{i\pi f_{rep}t}$$

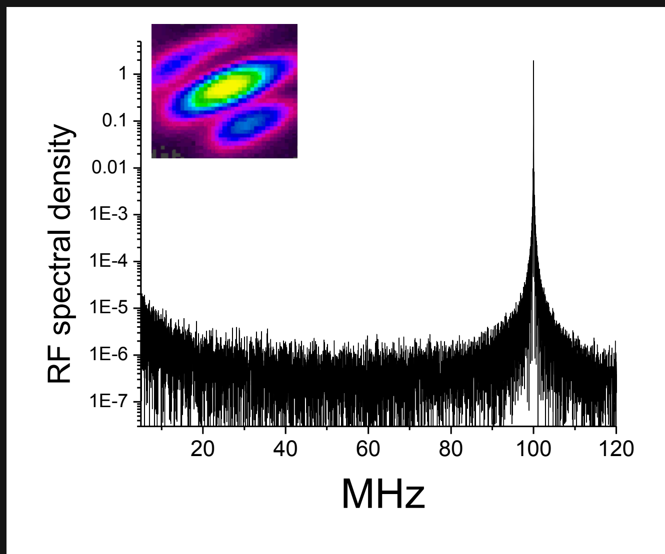
$$e^{i\pi f_{rep}t} = 1 \quad \text{for even pulses}$$

$$e^{i\pi f_{rep}t} = -1 \quad \text{for odd pulses}$$

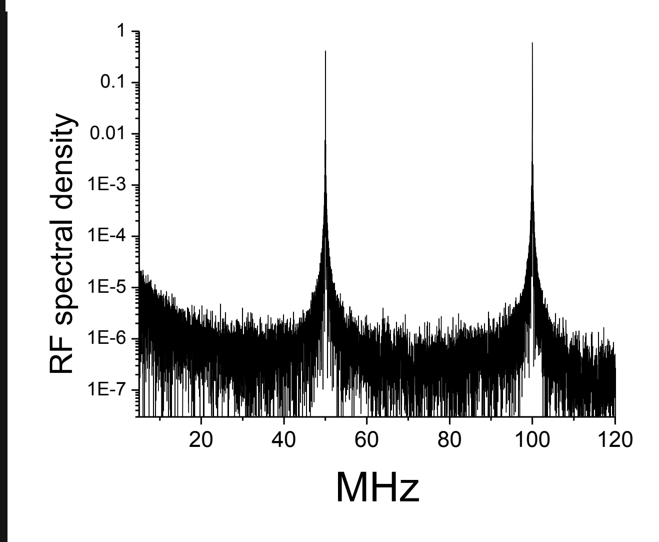
Observation of beats at $f_{rep}/2$

RF spectrum

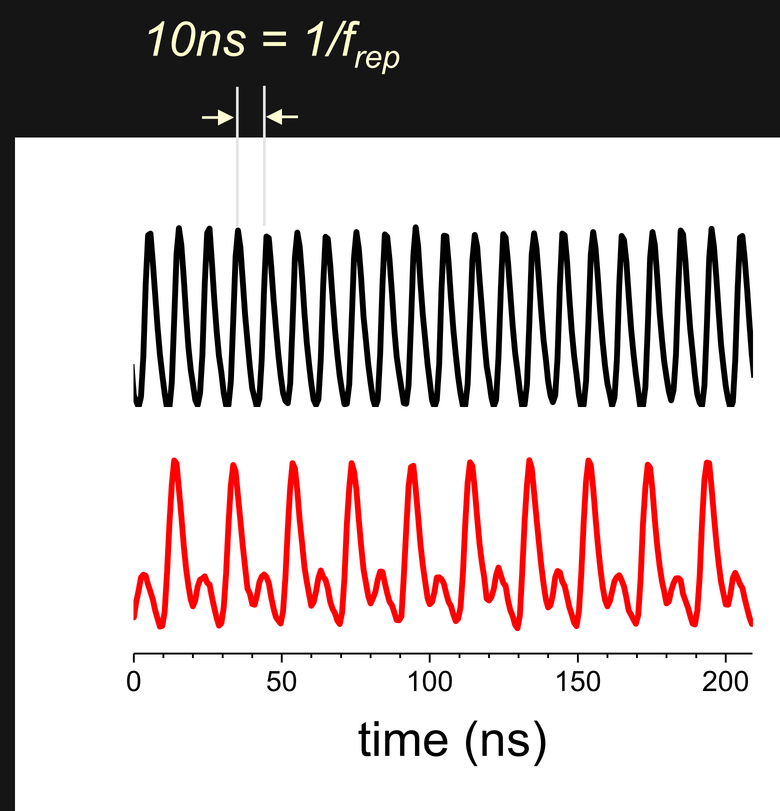
AA



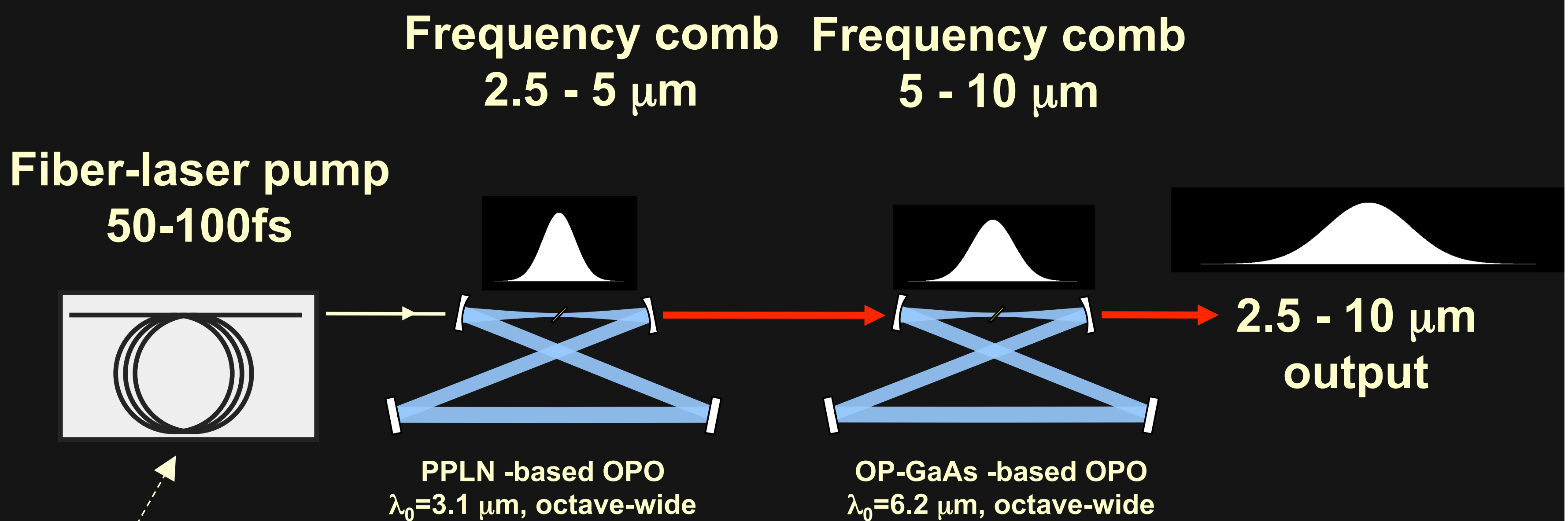
AB



Time-domain signal



Divide-and-conquer approach: ultimate concept of a cascaded OPO setup



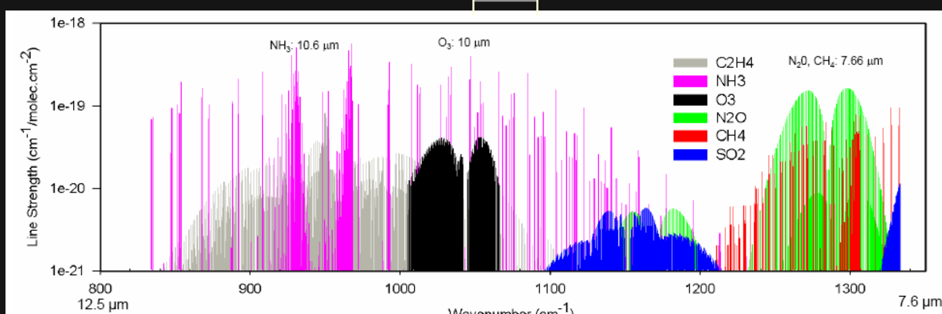
Broad-bandwidth (2.5 - 10 μm) mid-IR frequency comb source consisting of two consecutive subharmonic OPOs.

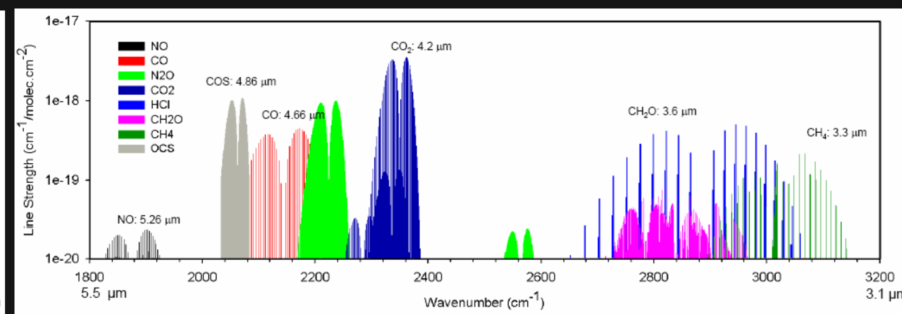
Nonlinear crystals can be ~ one coherence length long !

Desired mid-IR comb spectral coverage

Frequency comb spectral coverage: 2 octaves
Resolution: ~ 0.003 cm^{-1}

QCL tuning range

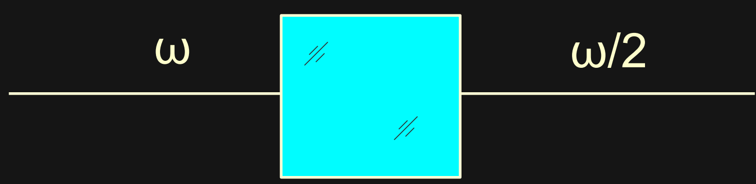




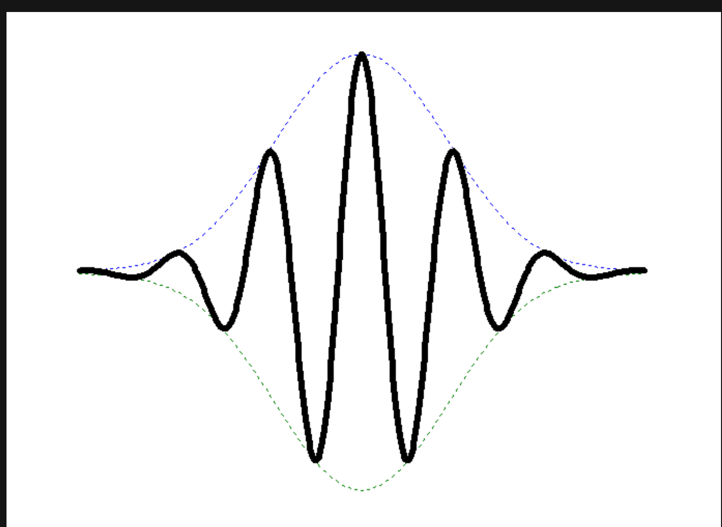
12.5µm λ=7.6µm 5.5µm 3µm

Is the assumption that pulses consist of modes necessary ?

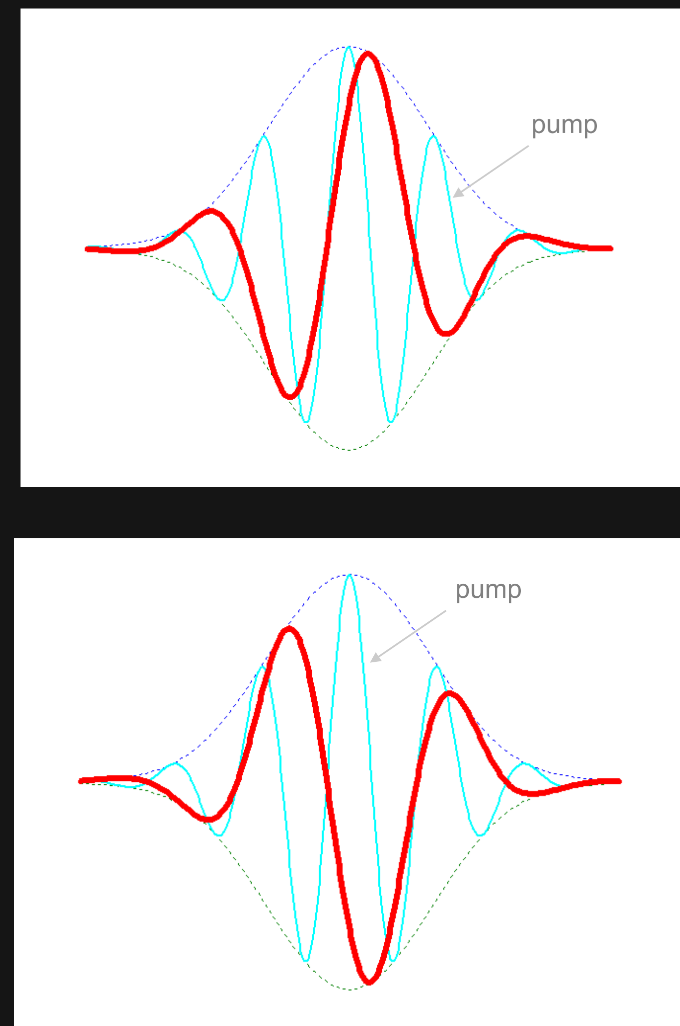
Implementation for the single pass subharmonic generation



Pump



Subharmonic

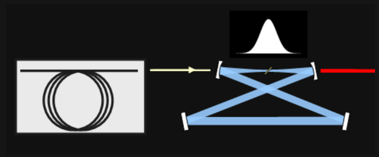


0 -state

π -state

$$\sqrt{1} = \pm 1$$

Conclusion



- 'Frequency-divide-by-two' approach allows to jump right into mid-IR region and broaden the pump comb
- 9 mW threshold, 60 mW output
- Wavelength span: close to an octave in the mid-IR
- Phase- and frequency locked to the pump, other interesting coherence properties
- Frequency comb coherence – inherited from the pump
- Applications: molecular spectroscopy, trace detection, quantum optics, random number generation …

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