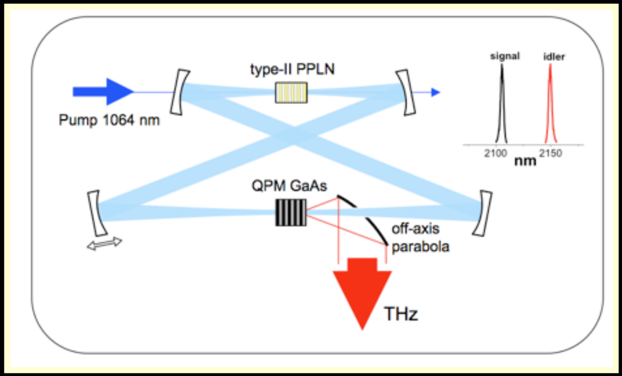
# Resonantly-enhanced photonic generation of monochromatic 0.5-5 THz radiation using periodically-inverted GaAs




Konstantin Vodopyanov

*Stanford University / CREOL, College of Optics and Photonics, Univ. Central Florida, Orlando, USA*

7th Terahertz Days and GDR-I Workshop, March 25-27, 2013
Cargèse, Corsica, France

**Goal : create efficient room temperature optical-to-THz converter with quantum conversion efficiency exceeding (!) unity.**

**Quasi- monochromatic THz output**
**Scalable to 100 mW of average power**

# why THz via photonics ?

## PRO

1) Small and efficient pump sources available

2) THz power scales as optical power squared


Ultrafast fiber laser

## CONTRA

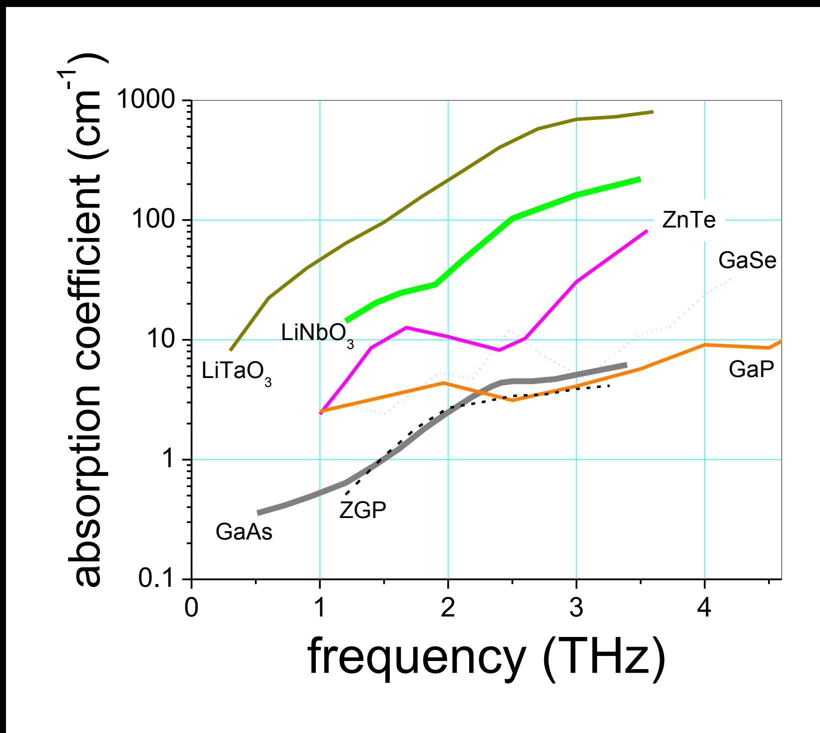
1) Conversion efficiency ~ $\Omega_{THz}^{3}$

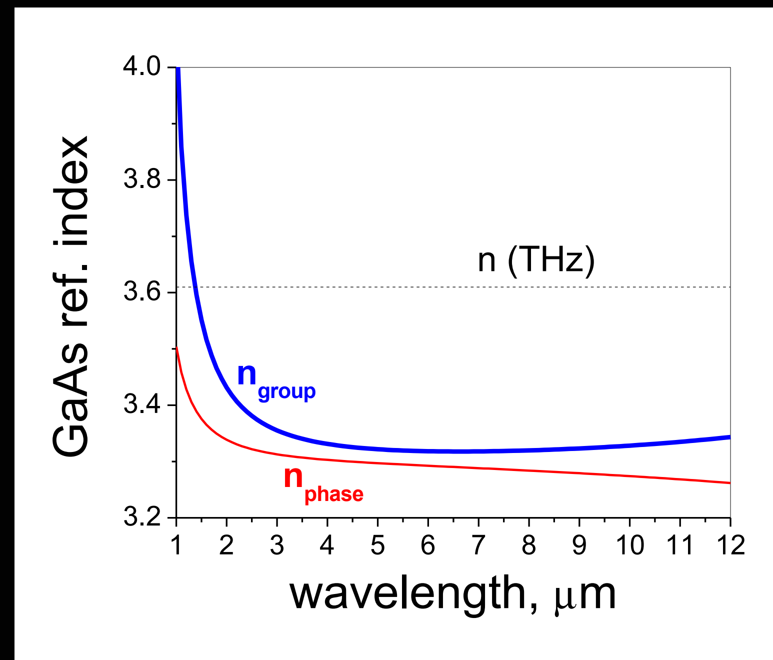
2) Manley-Rowe limit:
can not get more than one THz photon per one optical photon

**Is it possible to overcome these limitations ?**

# Why GaAs ?

# THz properties of GaAs

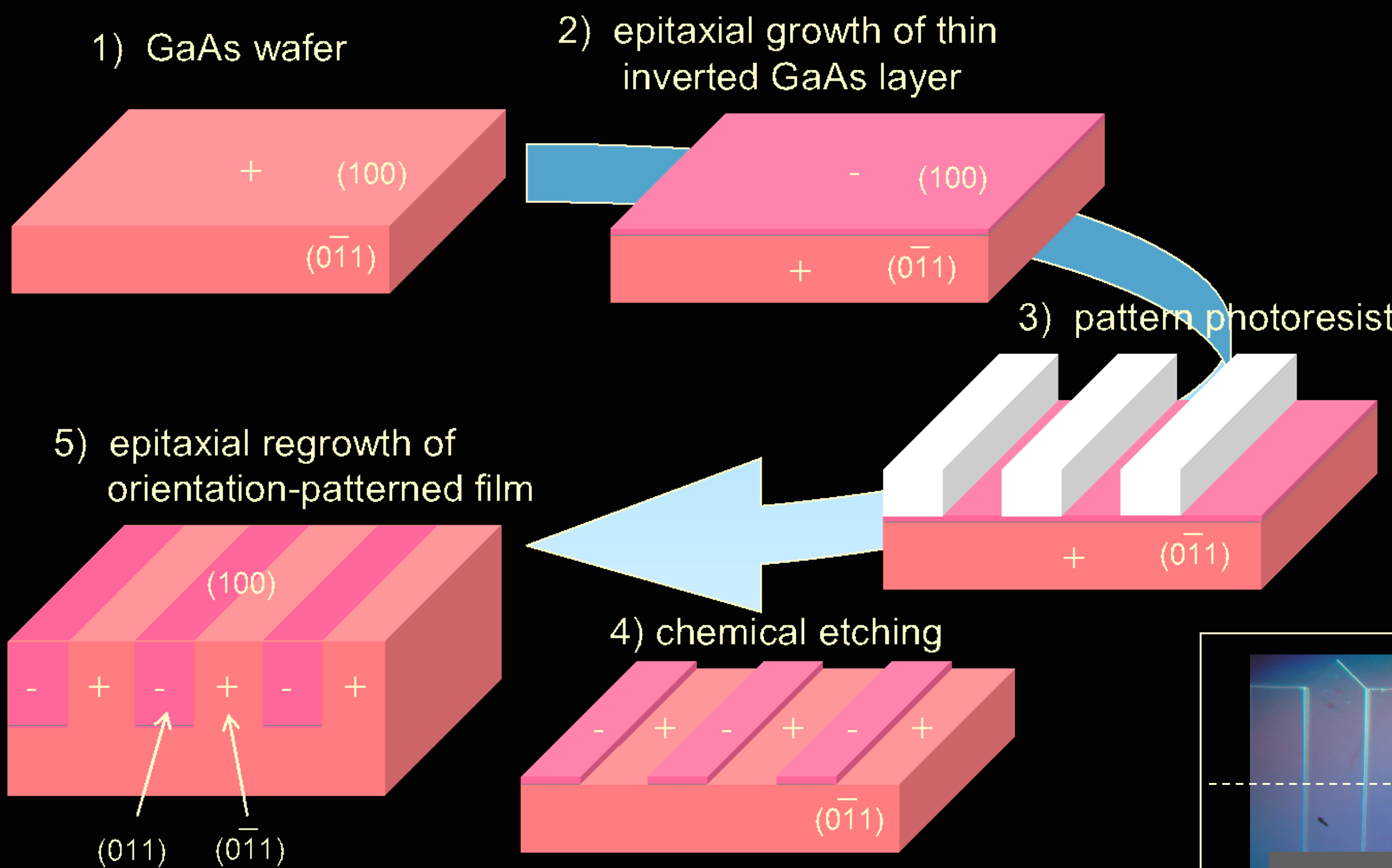


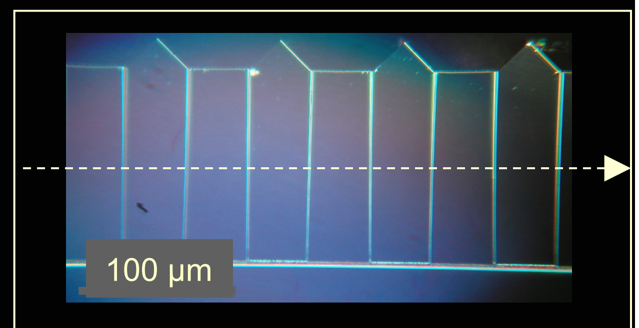




- **Low THz absorption (~ 20 times less than in $LiNbO_3$)**
- **Small ref. index mismatch between optical and THz waves (Δn~0.2)**
- **Pretty high EO coefficient -> NLO coefficient**

Vodopyanov, *Laser & Phot. Reviews* **2**, 11 (2008)

# All-epitaxial fabrication process of orientation-patterned GaAs (OP-GaAs)




APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 7 13 AUGUST 2001

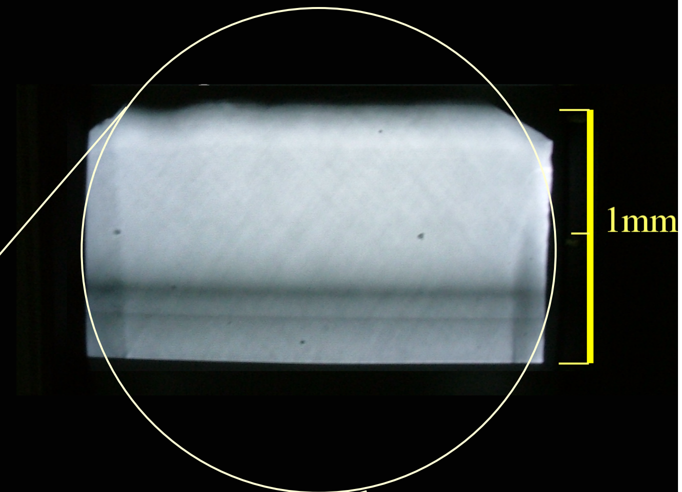
**All-epitaxial fabrication of thick, orientation-patterned GaAs films for nonlinear optical frequency conversion**

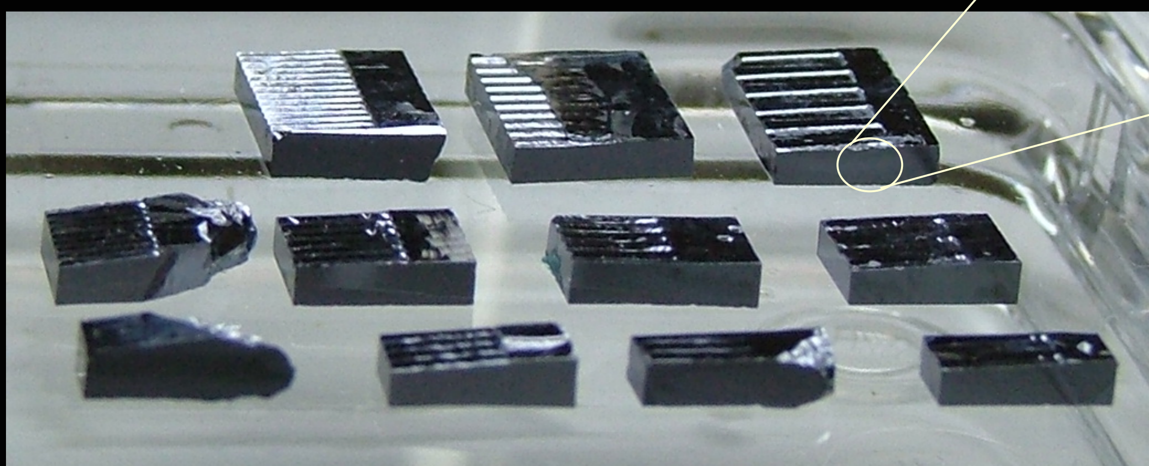
L. A. Eyres,[a] P. J. Tourreau,[b] T. J. Pinguet, C. B. Ebert,[c] J. S. Harris, and M. M. Fejer
*Center for Nonlinear Optical Materials, Stanford University, Stanford, California 94305-4090*

L. Becouarn,[d] B. Gerard, and E. Lallier
*Laboratoire Central de Recherches, THALES, Domaine de Corbeville-91404 Orsay Cedex, France*

# Orientation-patterned GaAs samples

Height: 0.4-1.2 mm
Length: 3-10 mm
Reversal period Λ: 500-2300 μm

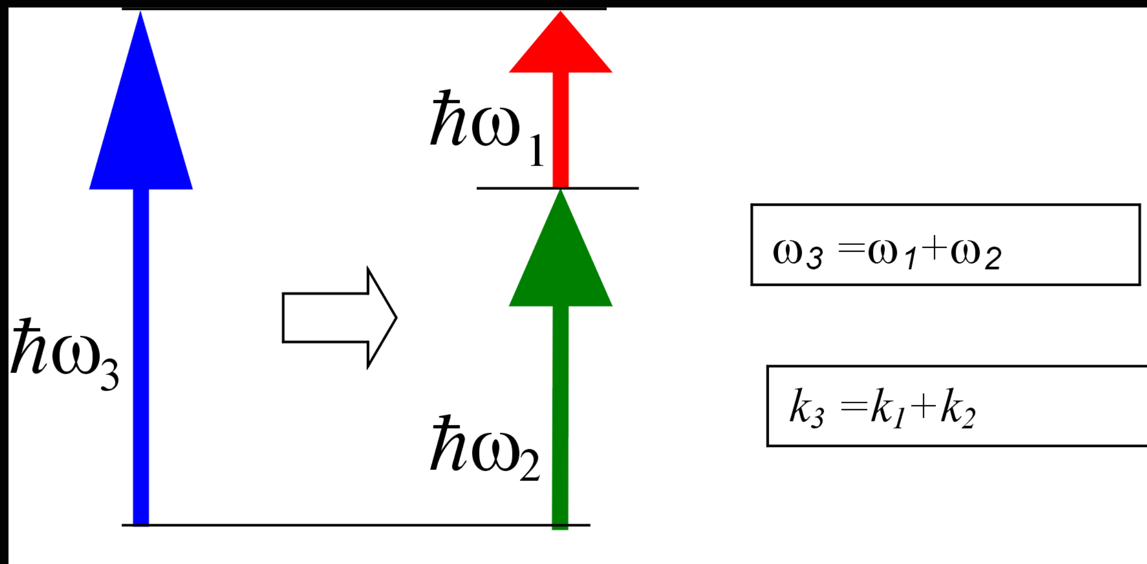



Optical transmission loss at optical (λ~2 μm) frequencies < 1 % per cm

# approach

# 3 – wave process: optical parametric oscillator OPO



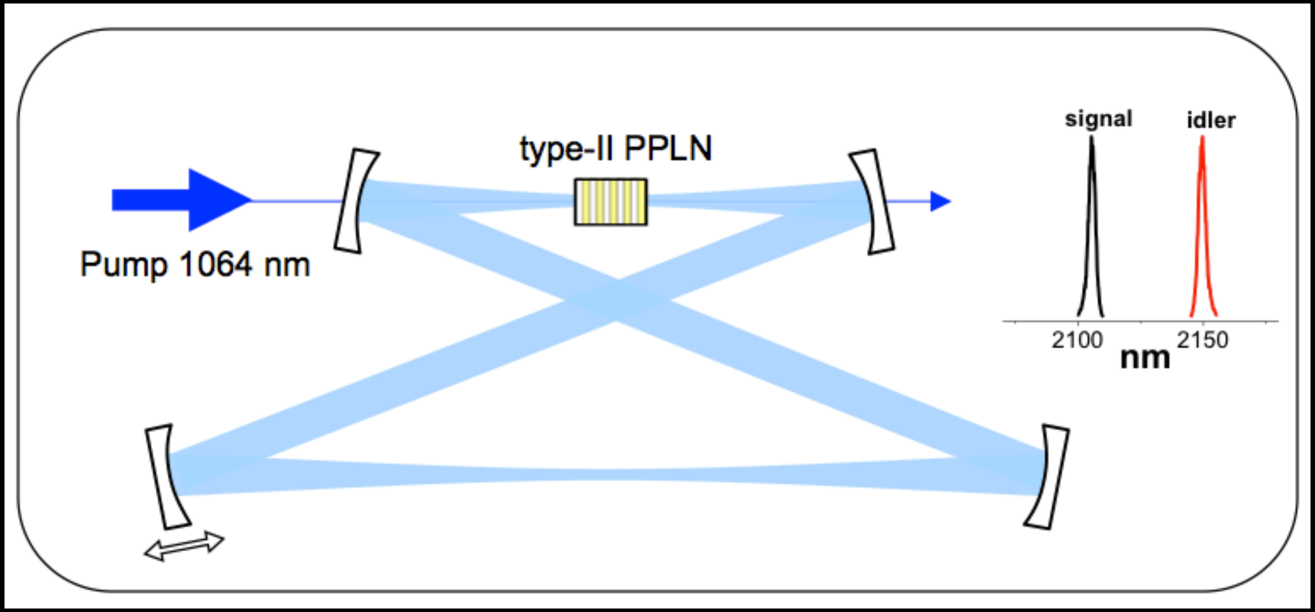

**Near-degenerate OPO:**

$\omega_3 = \omega_1 + \omega_2$

$\omega_1 = \omega_3/2 - \Delta$; $\omega_2 = \omega_3/2 + \Delta$; $\Delta$ - small

# Conceptual design

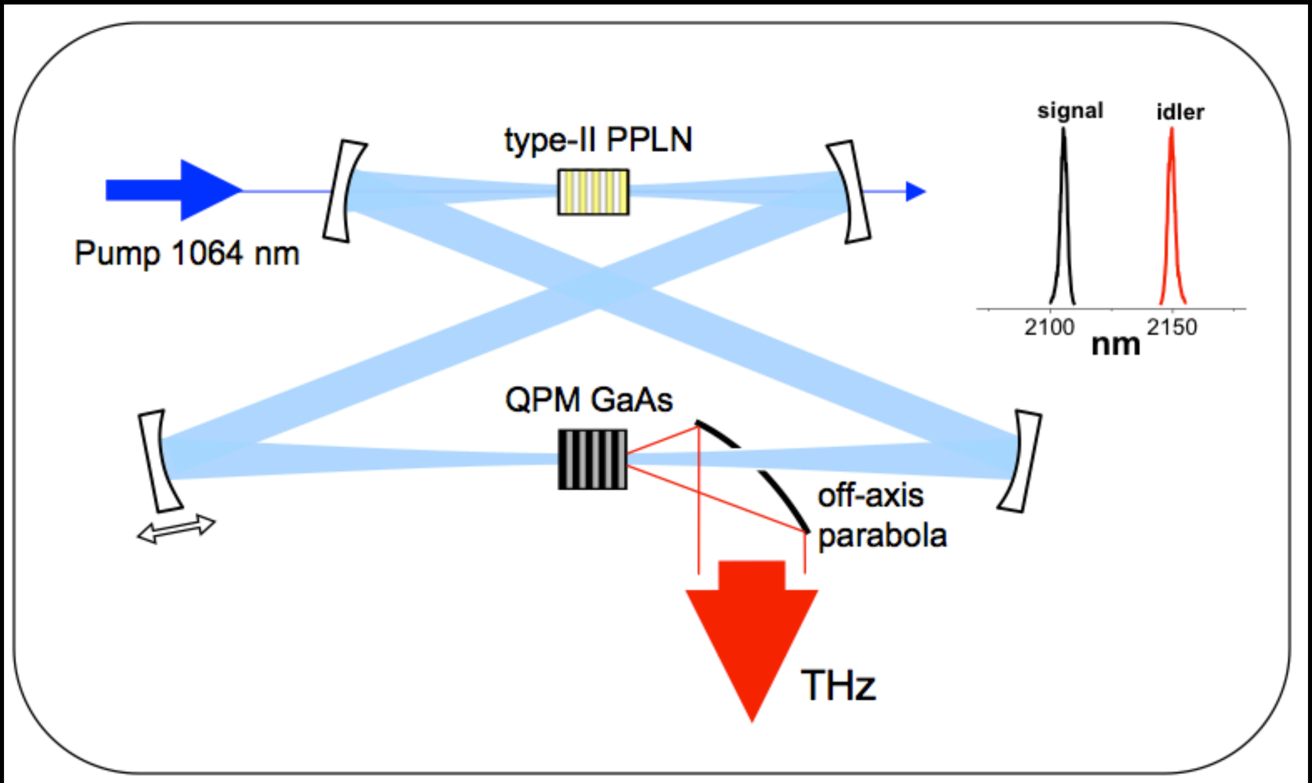
• Through parametric process, create two closely spaced <u>resonating</u> waves at $\omega_2$ & $\omega_3$




Vodopyanov, Laser & Phot. Reviews, 2, 11-25, 2008

# Conceptual design

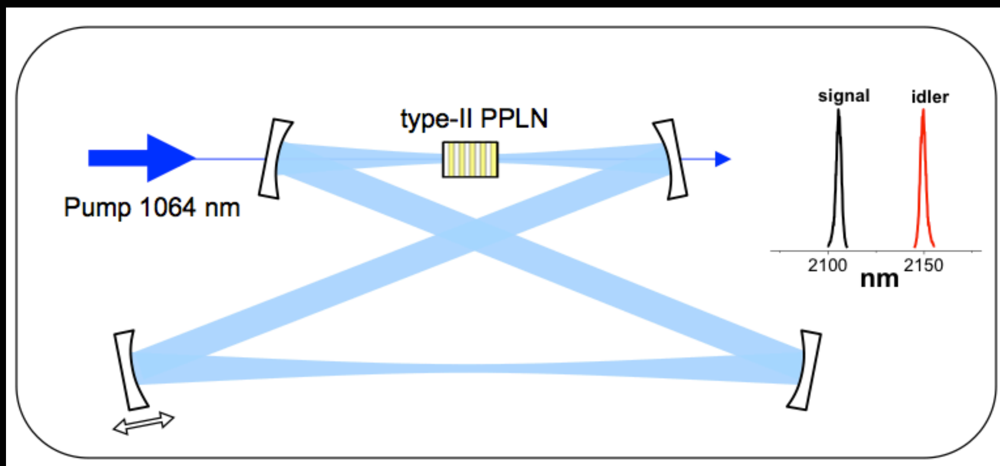
- Through parametric process, create two closely spaced resonating waves at $\omega_2$ & $\omega_3$
- Generate THz at their beat frequency $\omega_1 = \omega_3 - \omega_2$
- Use periodically inverted GaAs crystal

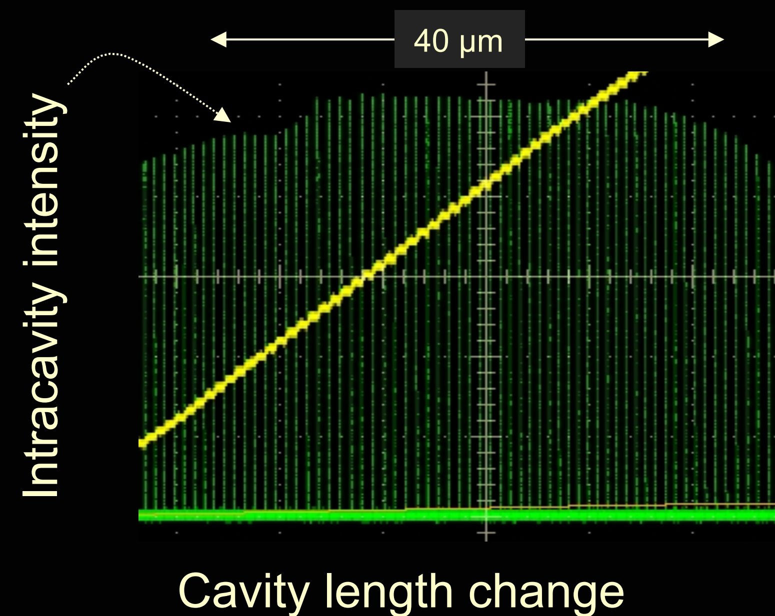



THz power increases as $1/loss^2$
Can easily get $1000^x$ increase at 3% cavity loss

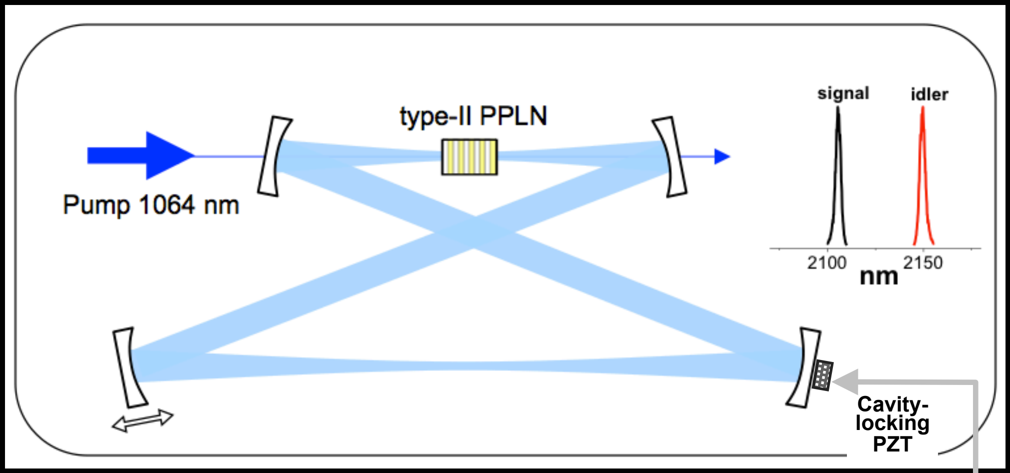
Vodopyanov, Laser & Phot. Reviews, 2, 11-25, 2008

# Doubly-resonant type-II OPO



# Doubly-resonant type-II OPO

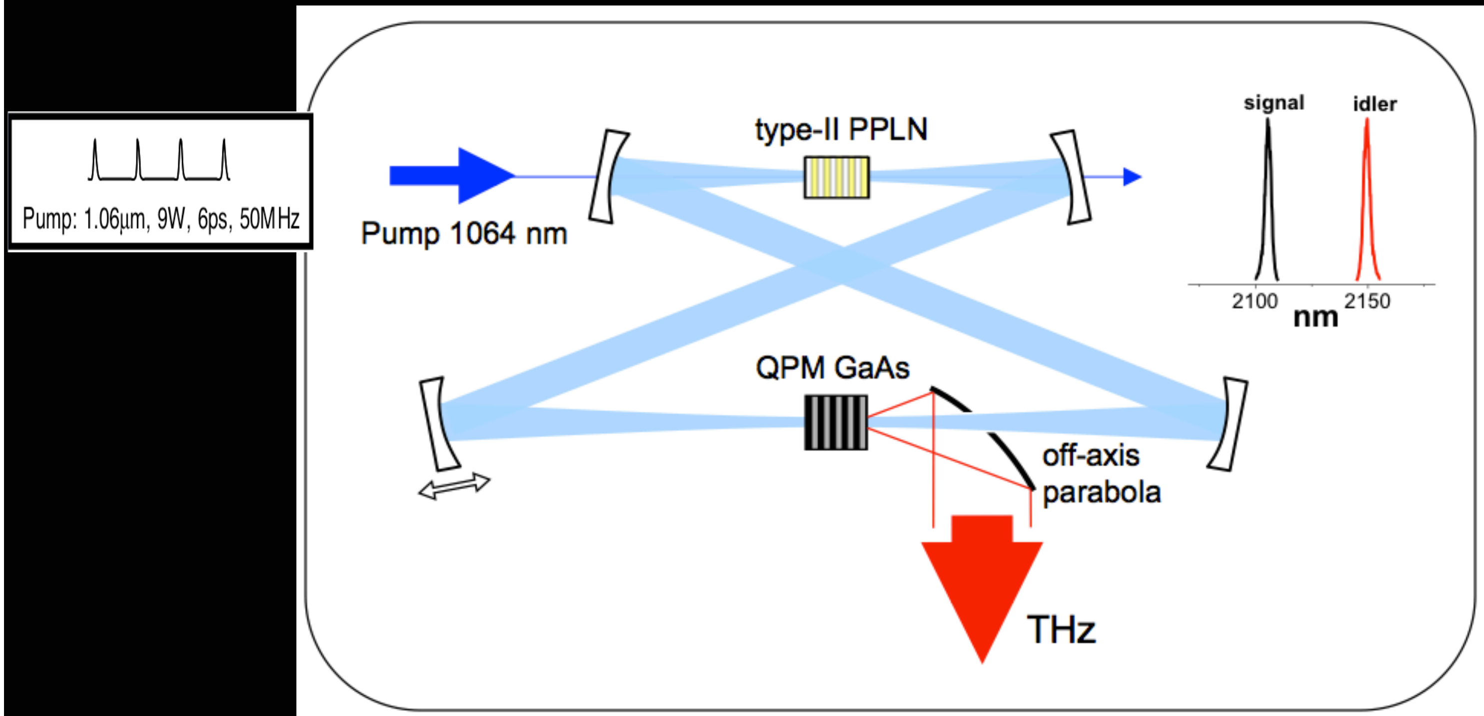



Piezo control loop
"dither-and-lock"

Intracavity OPO power:
150 W @ 2 µm (signal + idler)

Pump depletion: 90%
Pump threshold: 30 mW

# Intracavity THz generation, doubly-resonant OPO




Roundtrip loss 5-20%

Pump: 9 W @ 1064 nm

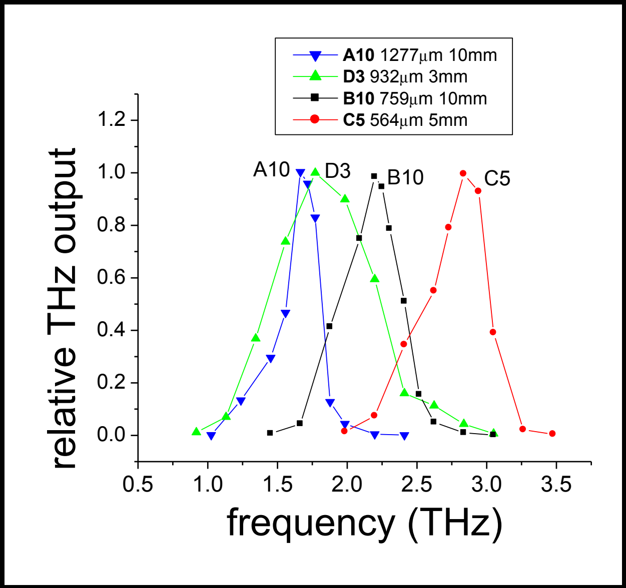
Intracavity OPO power :
~ 25 W @ 2 μm

Average THz power: **1 mW**
Range: 0.5-3.5 THz

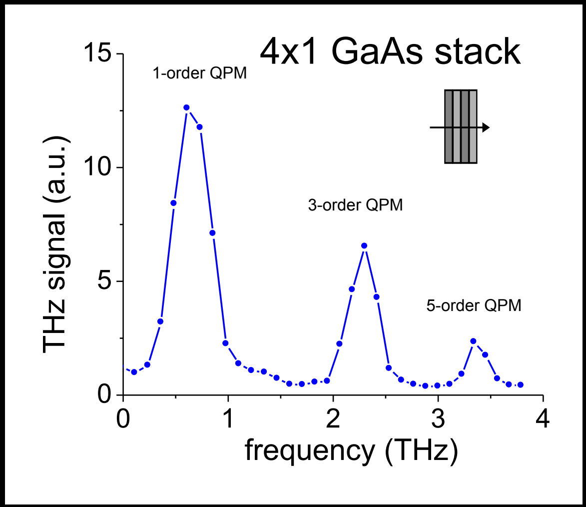
Schaar et al. Opt. Lett. 32,1284 (2007)

# Tuning of THz frequency

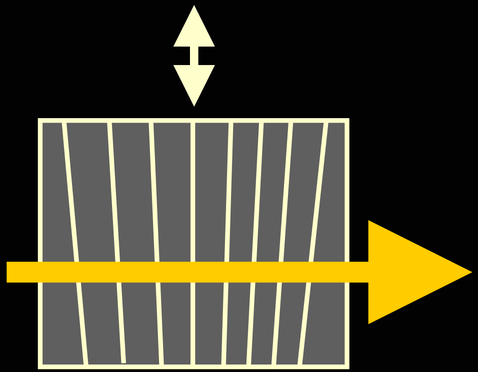
**1) Use tunability within acceptance band**




**2) Use higher order QPM peaks**



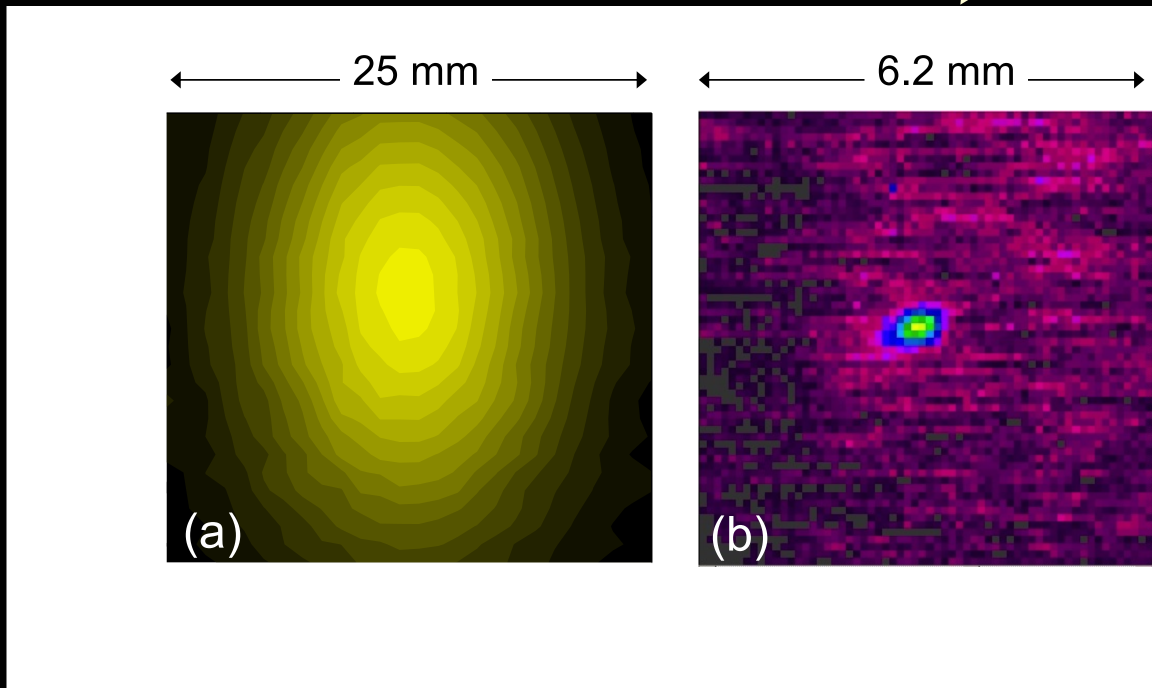

**3) Make 'fanned' GaAs structure**



# THz beam quality

**Collimated THz beam: reconstructed from knife edge scan**

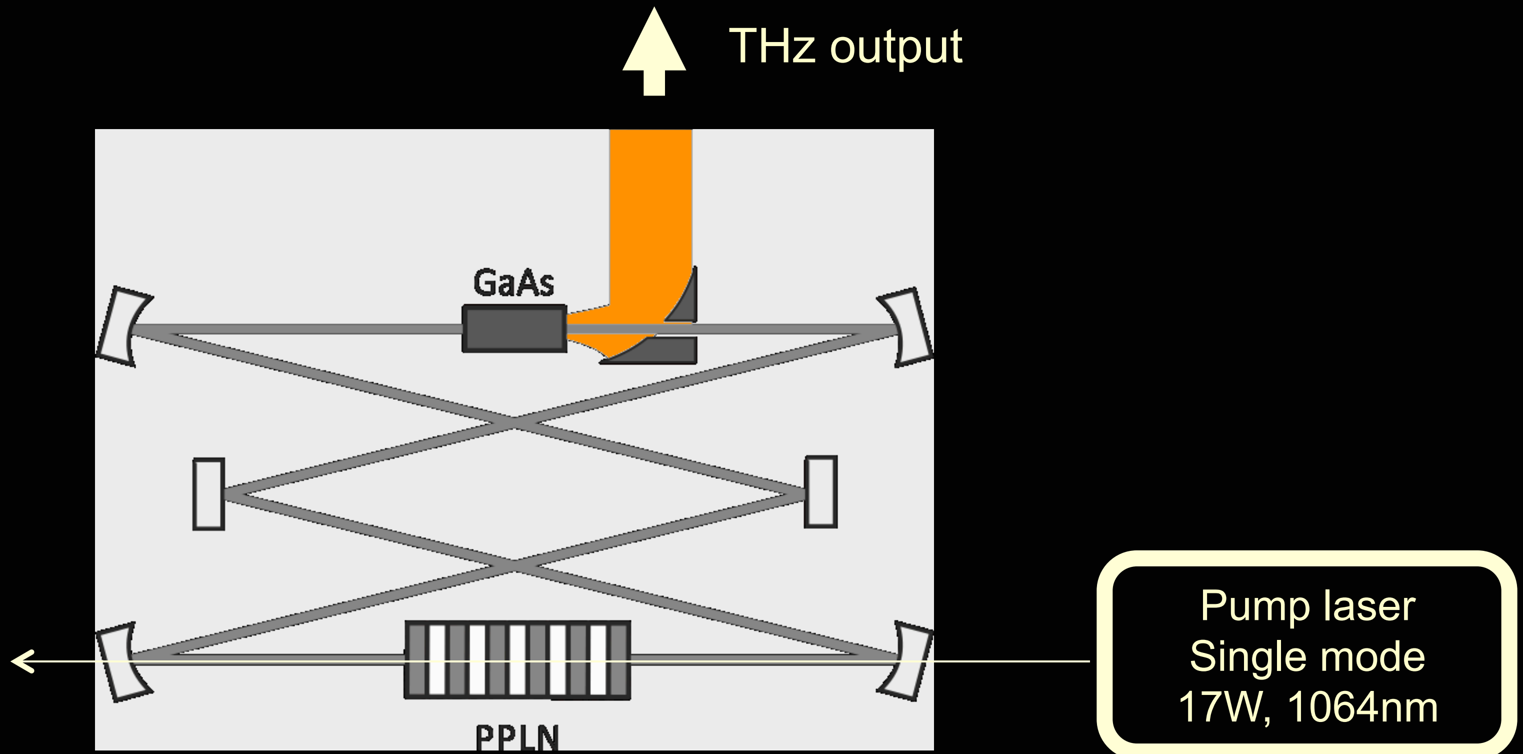
**Focussed THz beam, picarin lens, f=50mm (Spiricon, Pyrocam-III)**




Schaar et al. Opt. Lett. 32,1284 (2007)

# CW regime

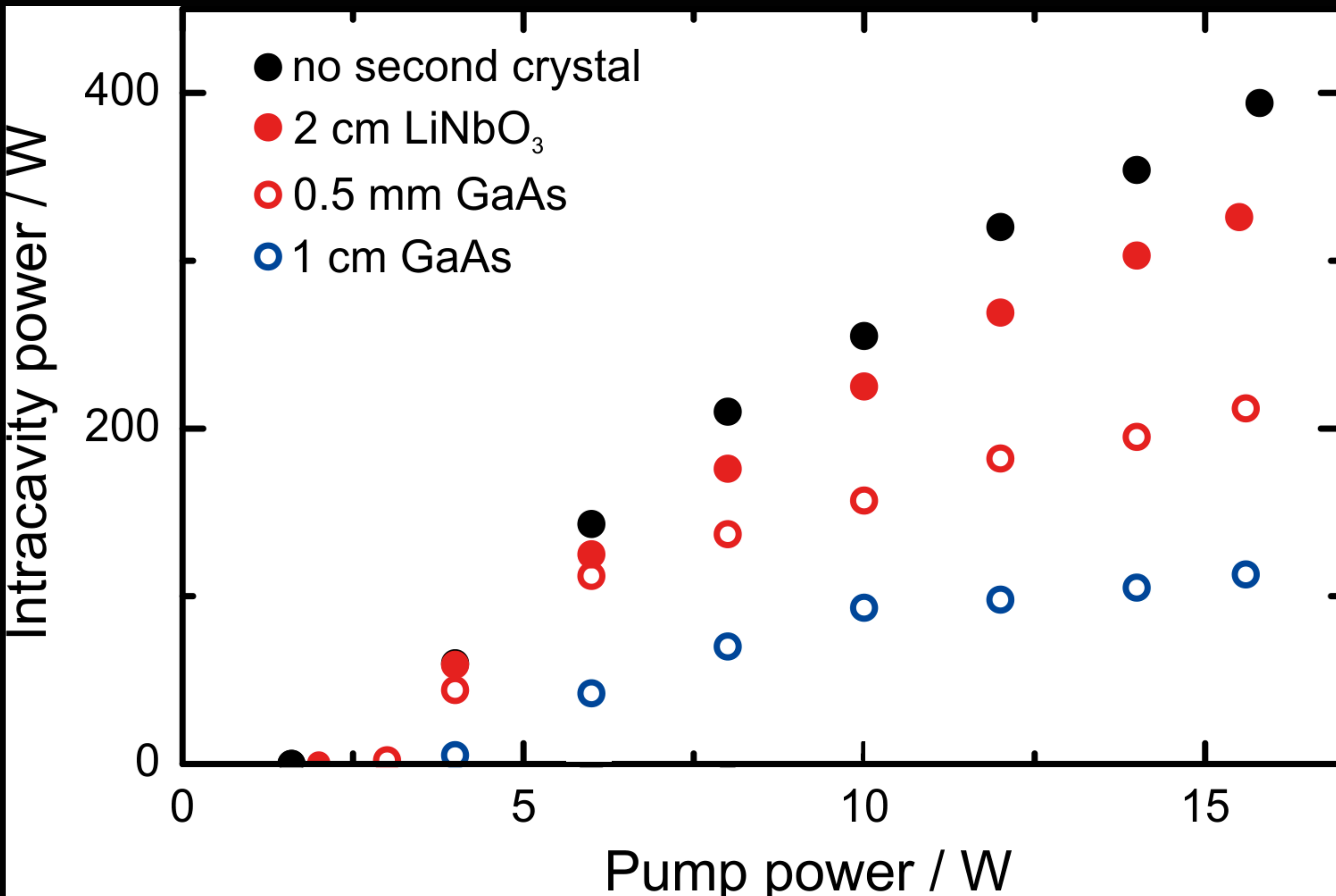
# THz, continuous wave regime



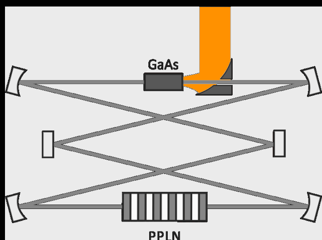

in collaboration with:
Jens Kießling and Ingo Breinig (University of Freiburg)

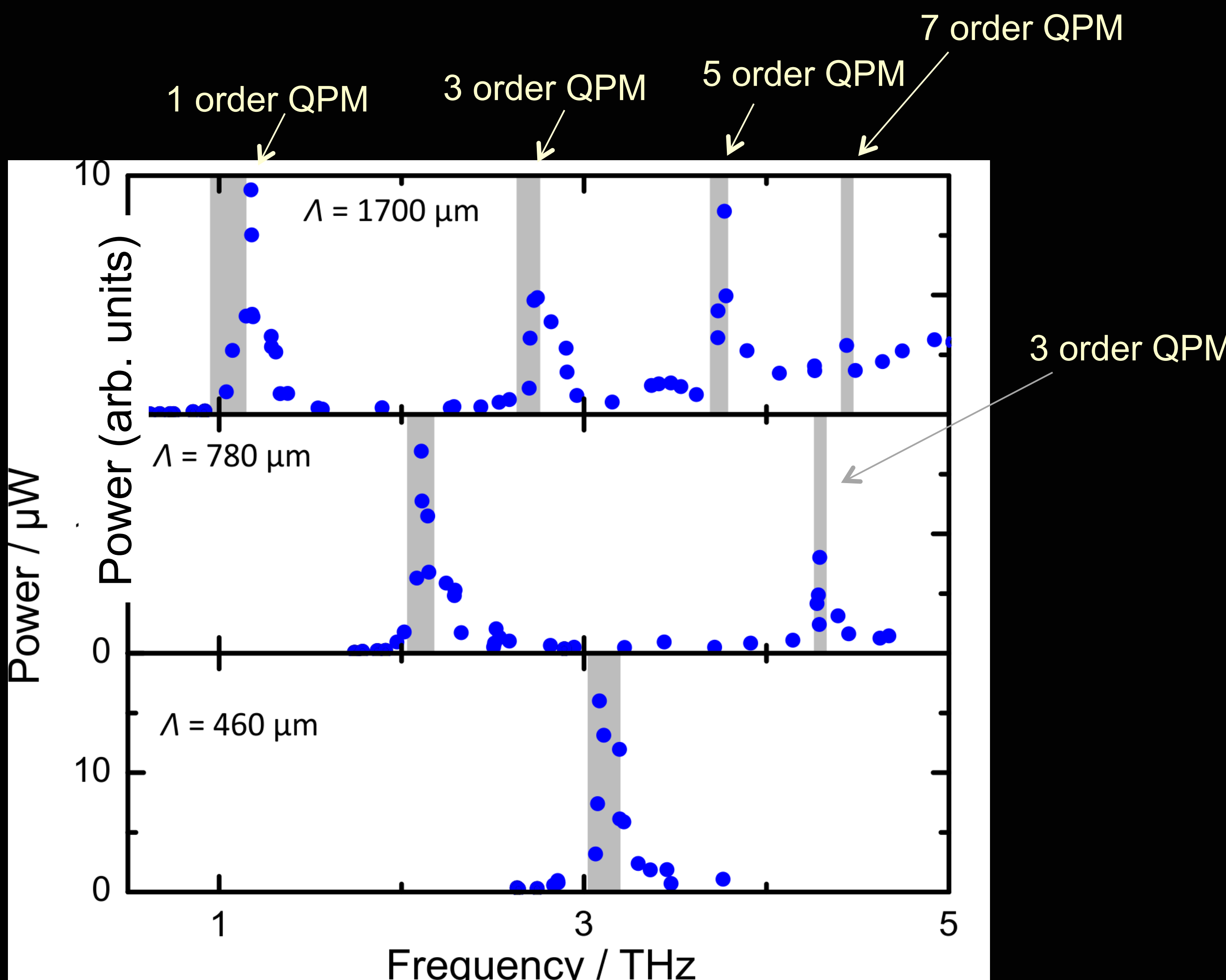
# Intracavity optical power

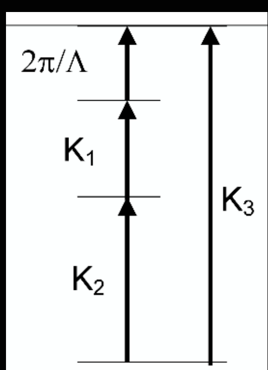
($P_{pump}$ ~20 W)



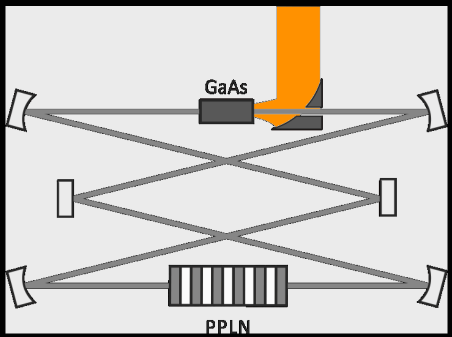
# THz generation, continuous wave regime



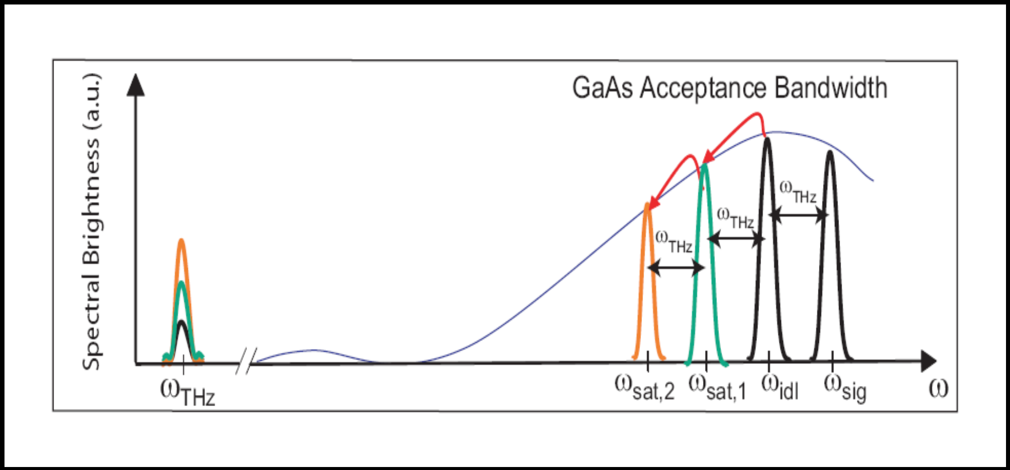
# THz, continuous wave regime

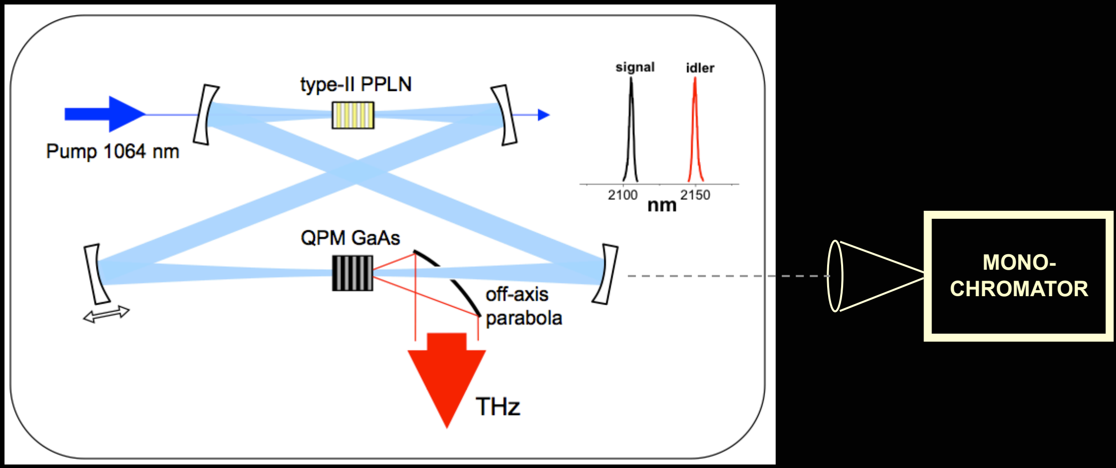


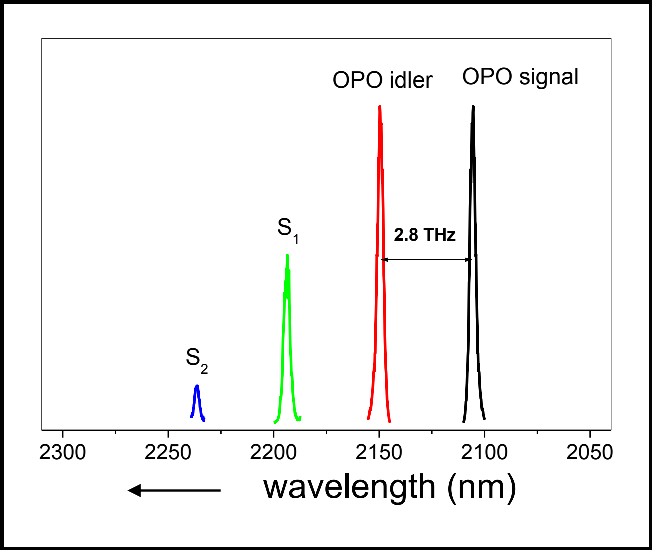

THz tunability 0.5-4.5
THz linewidth < 1 MHz
Output power 100 μW

# Recycling of the optical photons

# Recycling of optical photons in a DFG process



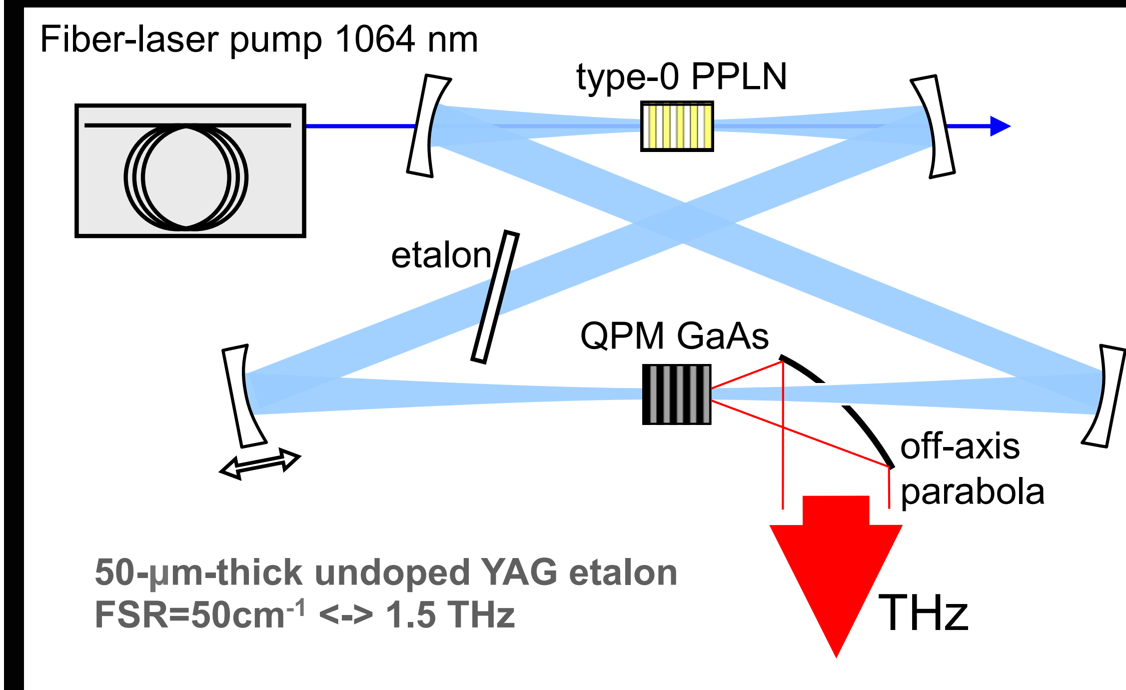



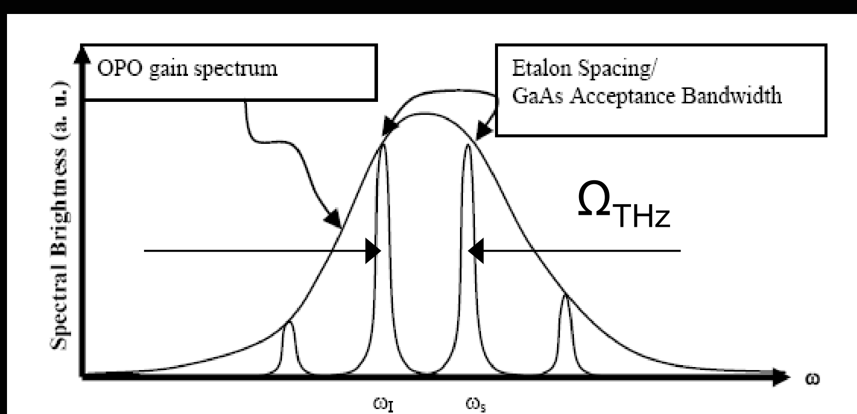

Optical photons can be recycled !

Schaar et al. Opt. Lett. 32,1284 (2007)

# Another design with fiber-pumped type 0 OPO

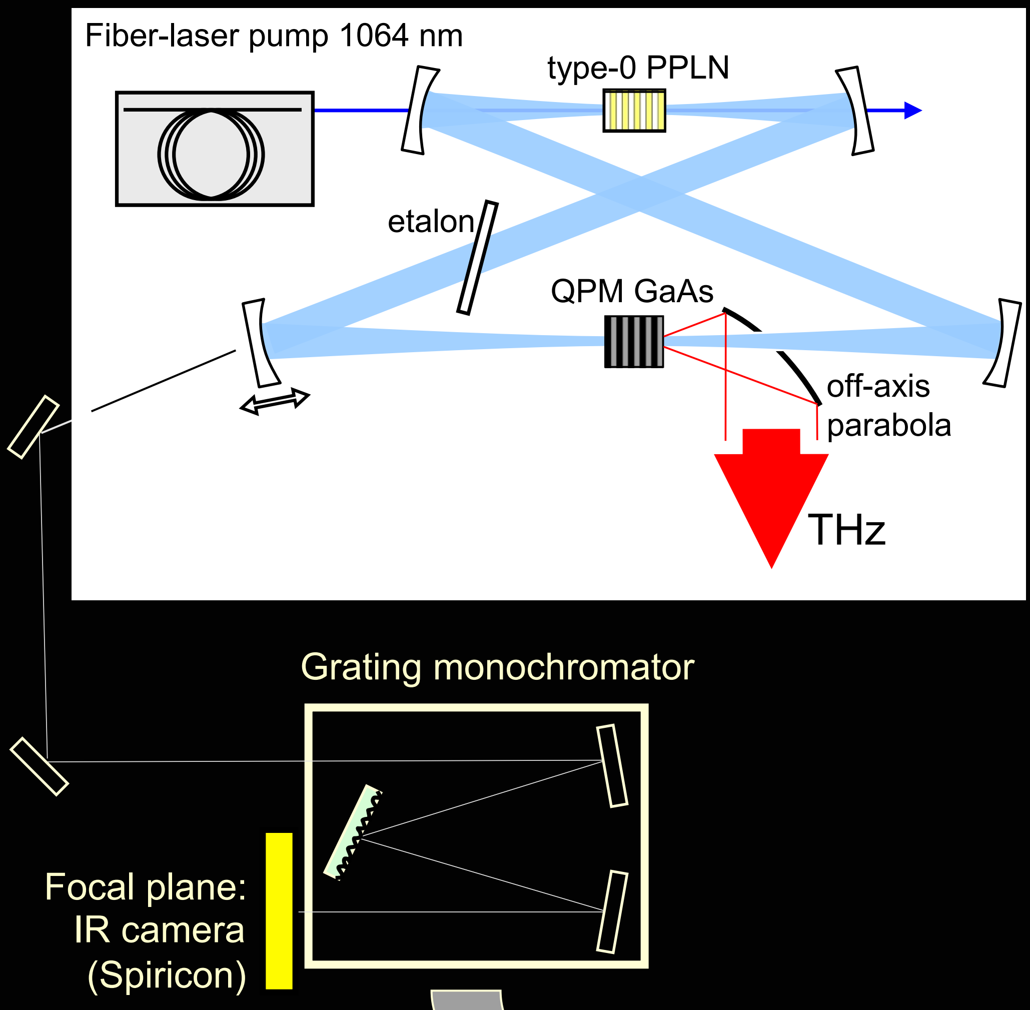
# New design with type 0 PPLN and GaAs

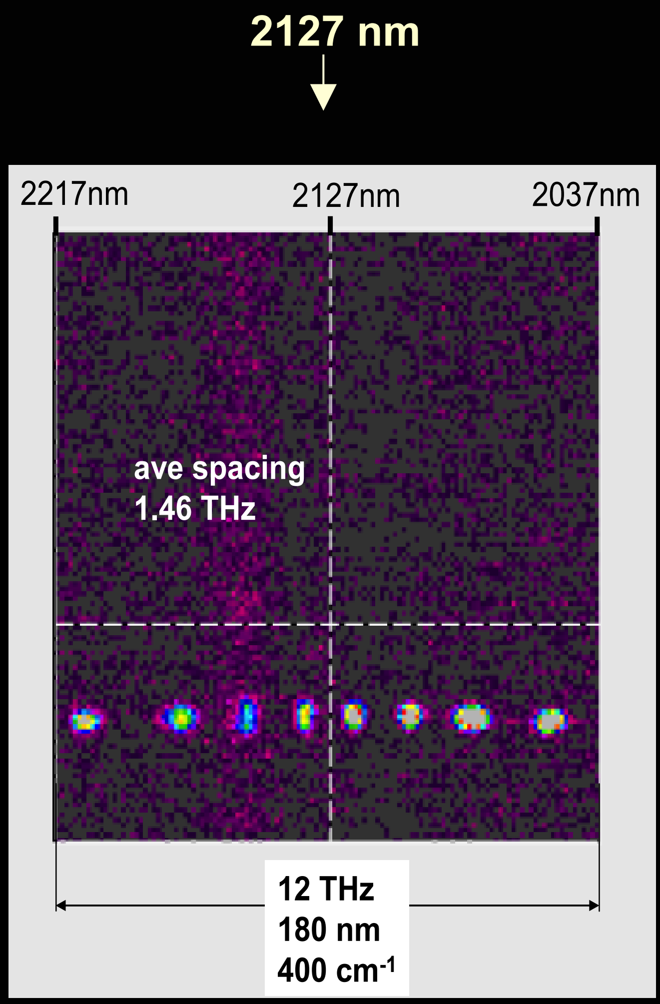



- $((N-1)/N)^2$ enhancement with N peaks
- Type-0, instead of type-II-phase-matched PPLN crystal
- Compact fiber laser (Fianium, FP1060-10 Yb-fiber laser, 10ps, 1063.5nm, 100 MHz, 10W) as a pump source
- Thin intracavity etalon with a free spectral range equal to the desired THz frequency.

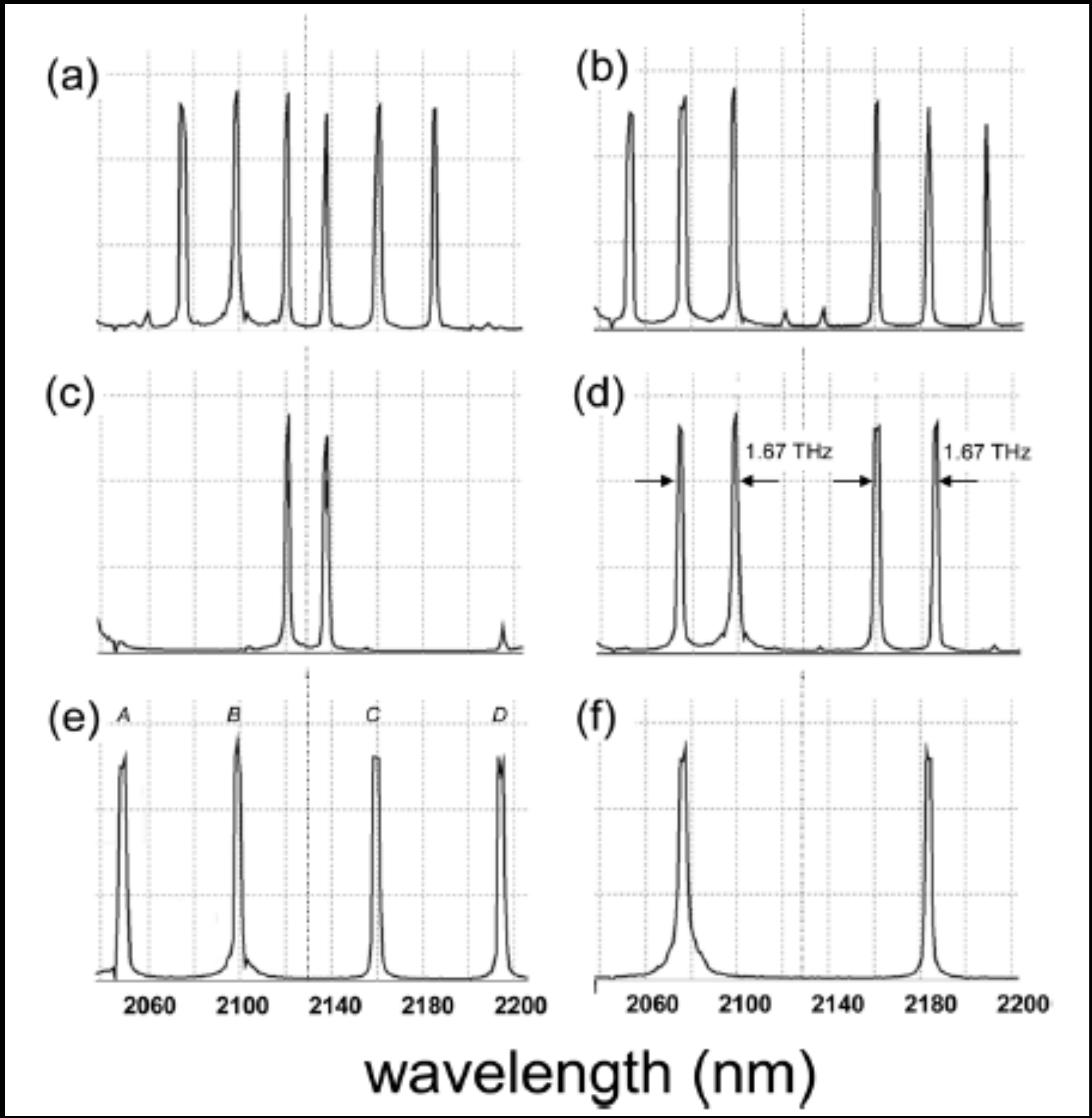
# New design with type 0 PPLN and GaAs



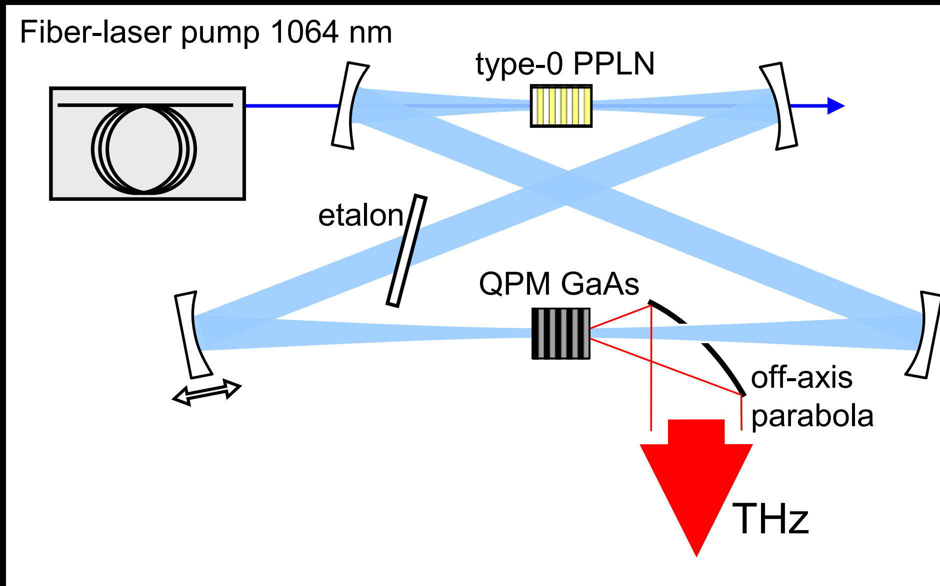




Spectrum: cavity length is dithered.

# OPO spectrum: NIRQuest



# THz system with multispectral mixing




Pump threshold: 20 mW

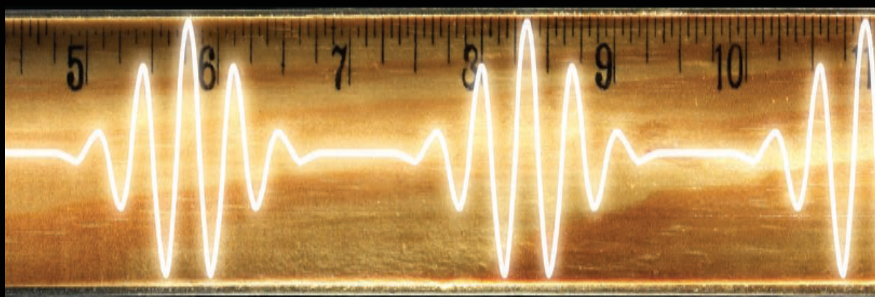
Optical intracavity average power exceeds 100 W at 6 W of pump power

250 μW of THz power at 1.4 - 3 THz

Vodopyanov, Hurlbut, Kozlov Appl. Phys. Lett. 99, 041104 (2011)

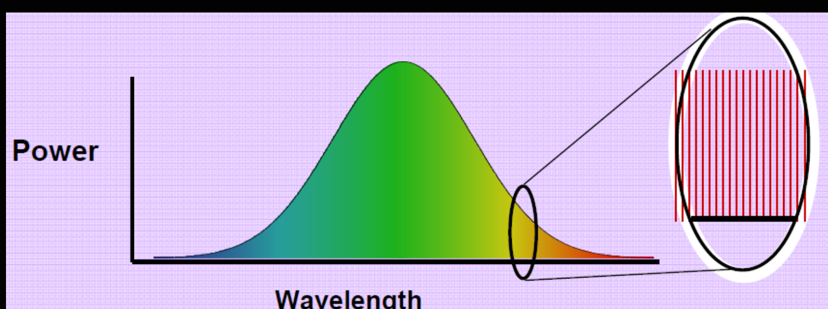
# frequency combs

# What are frequency combs ?



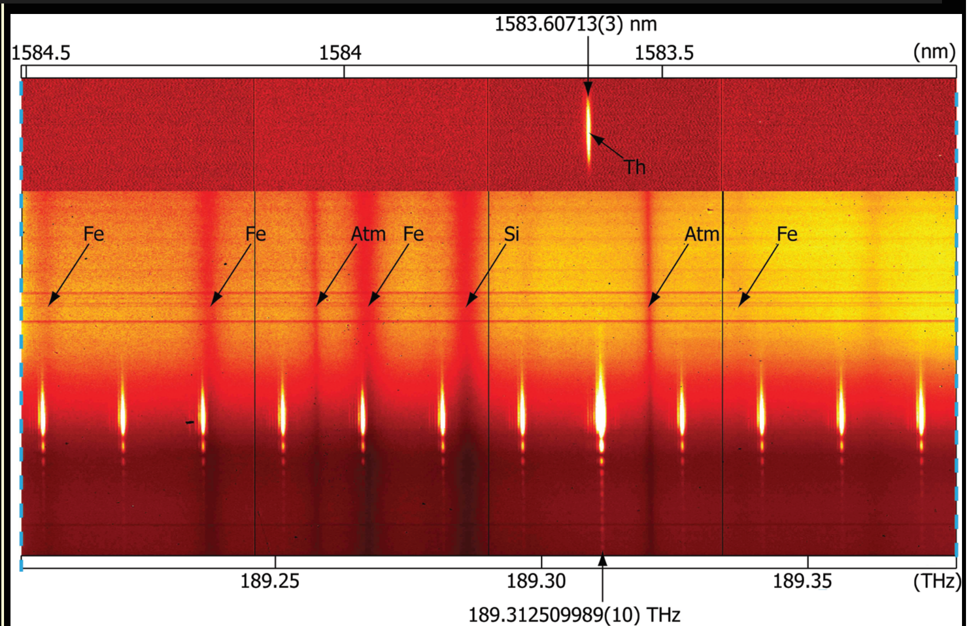
Theodor W. Hänsch and John L. Hall
2005 Nobel Prize in Physics

Regularly spaced train of short (fs) pulses corresponds to a spectrum consisting of discrete, evenly spaced narrow lines, each having an absolute frequency measurable within the accuracy of an atomic clock.



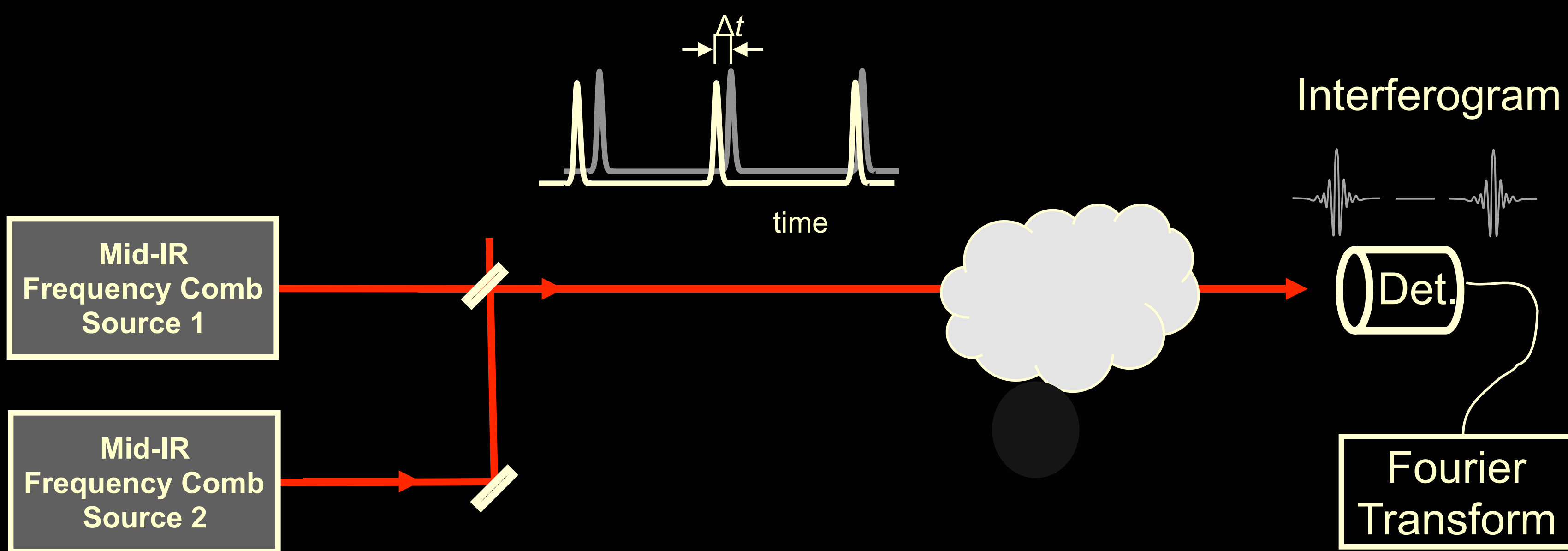

Spectra of the solar photosphere near 1.5 μm overlaid by a Laser Frequency Comb with 15-GHz mode spacing →

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

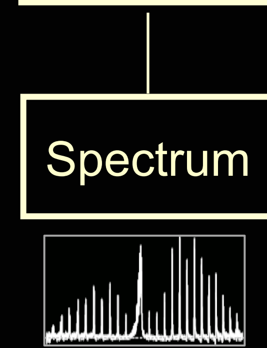


# Dual-comb Fourier-transform spectroscopy

**Keilmann, Gohle, Holzwarth, Opt. Lett. 29, 1542 (2004)**
**Schliesser, Brehm, Keilmann, Opt. Express 13, 9029 (2005)**

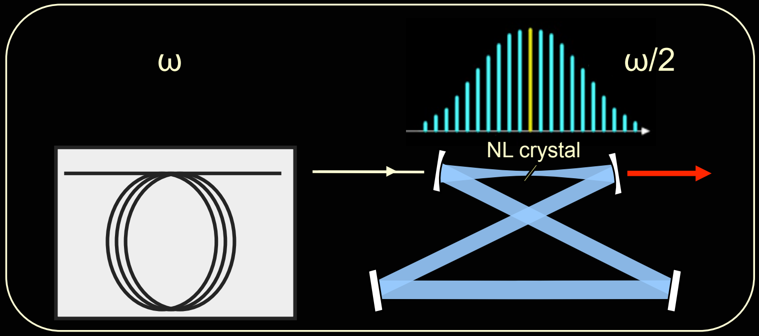


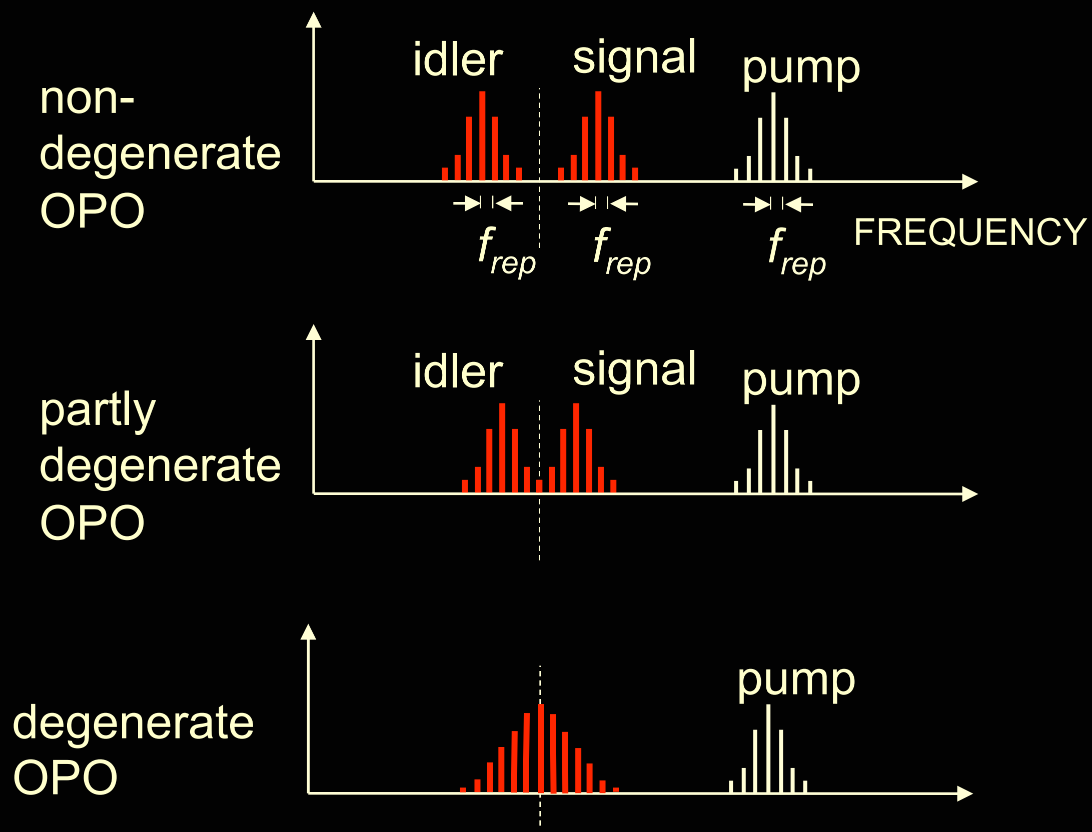

Repetition rates of Comb 1 and Comb 2 have small offset $\delta f_{rep}$ ~ 100 Hz




Up to 1 000 000 spectral points in 10 ms with resolution ~ 100 MHz (0.003 $cm^{-1}$)

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



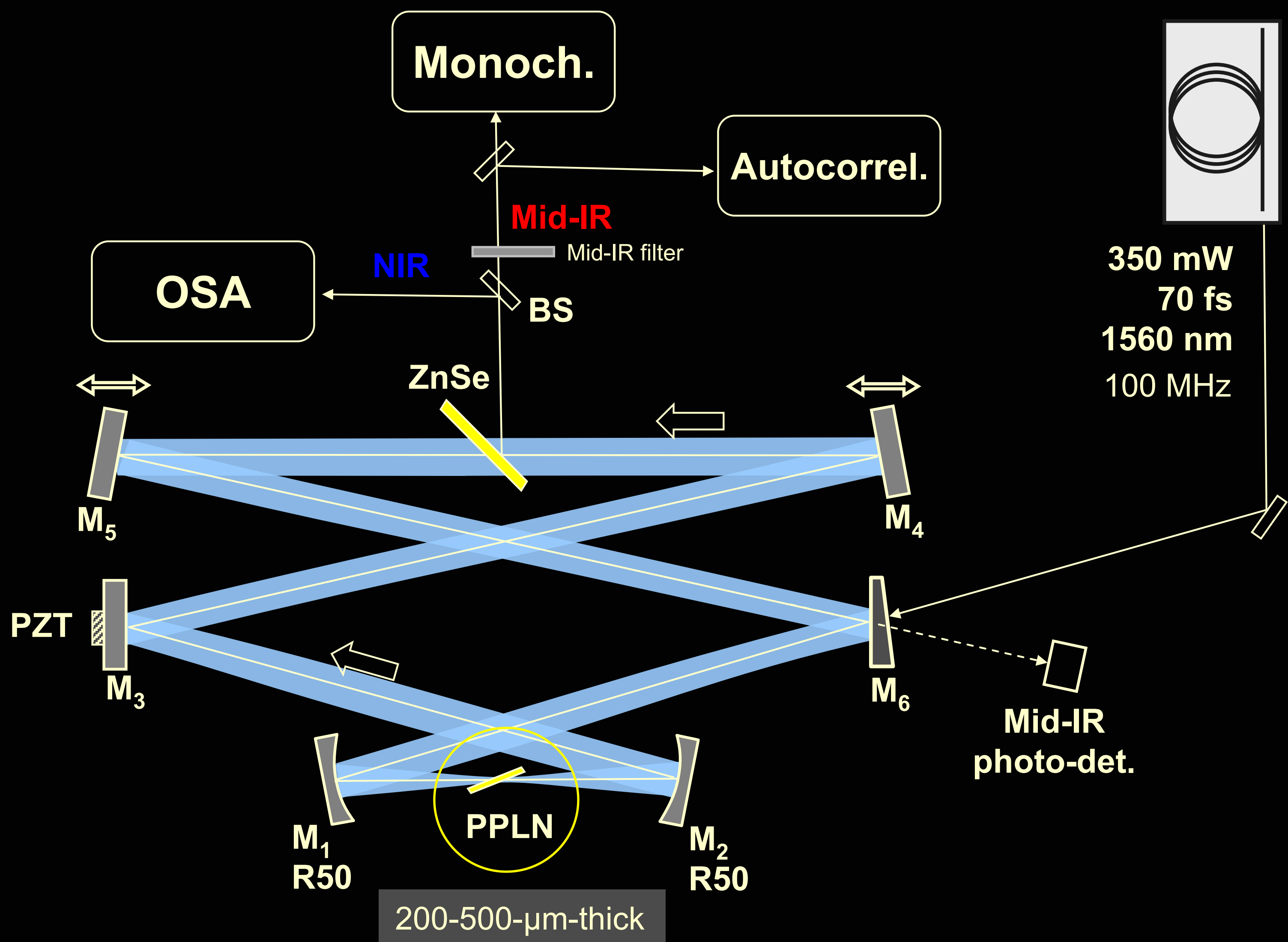




**By pumping a subharmonic OPO with an ultrafast laser one can achieve:**

- **octave –wide spectrum which is coherent to the pump**
- **low ~ 10 mW threshold**

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

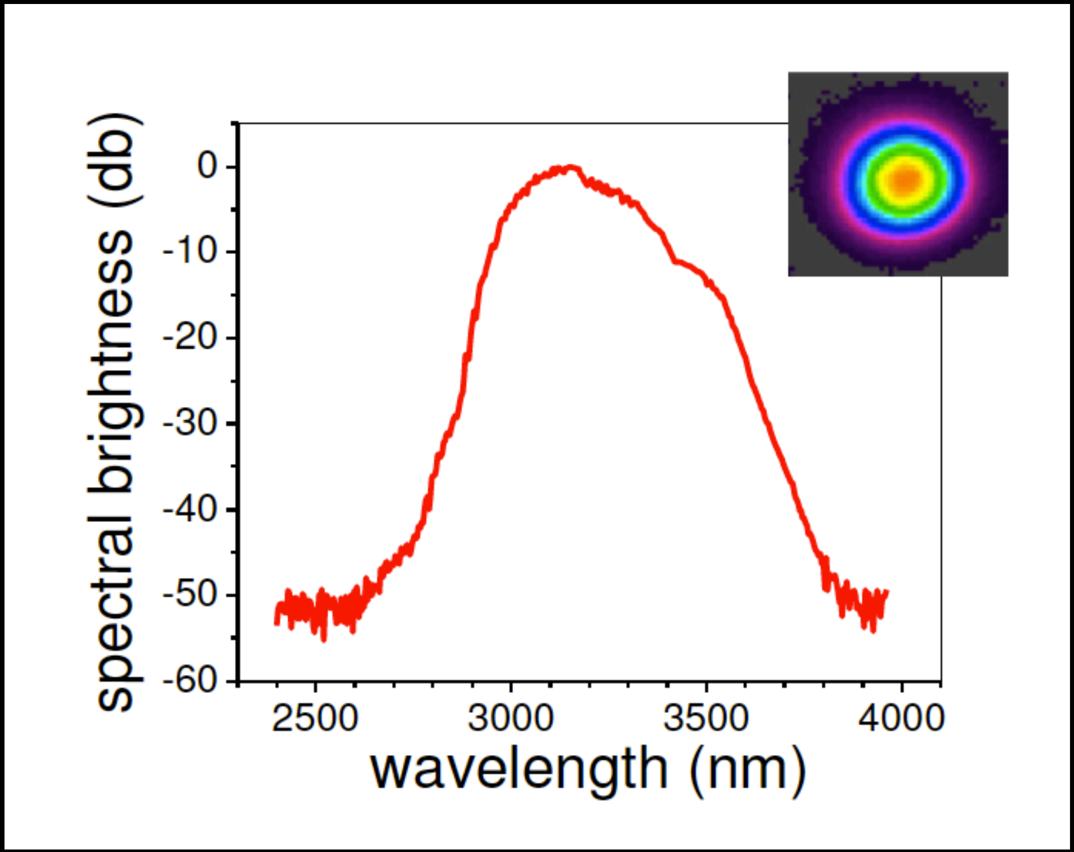
# Mid-IR subharmonic OPO (Er-fiber pumped)



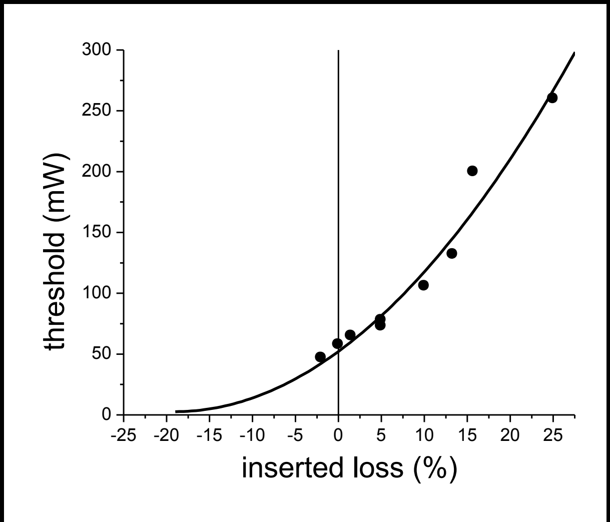

Leindecker, Marandi, Byer, Vodopyanov, Opt. Exp. 19, 6296 (2011)

# Subharmonic OPO near 3-μm: main features

**Spectrum: FTIR**




**Threshold ~ *(loss)*$^2$**




**Pump threshold 9 mW**

**Pump depletion 80-83%**

**Outcoupled power 60 mW**

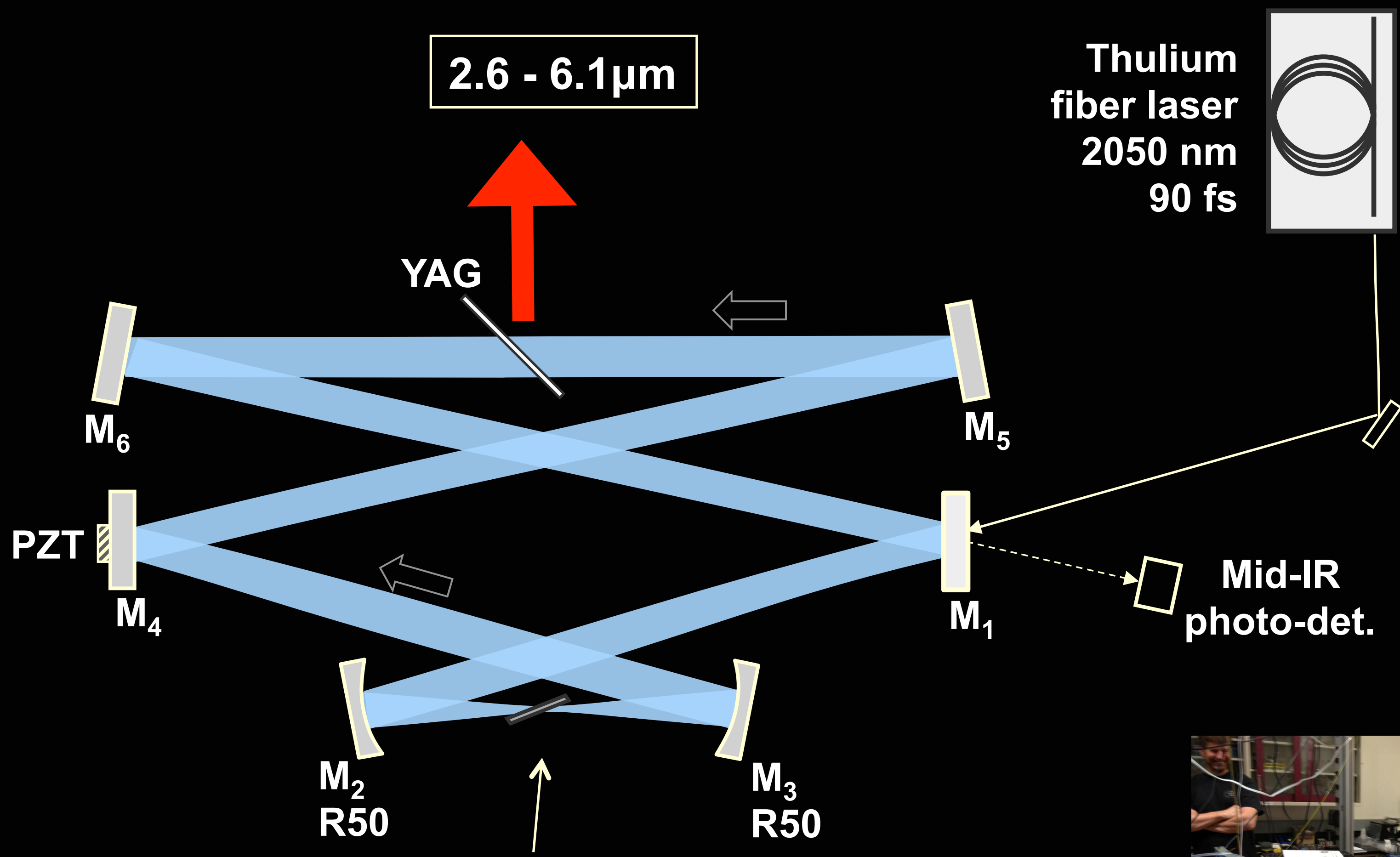
**Bandwidth 2500-3900 nm (2/3 octaves)**

**Can support 3-cycle pulses at ~ 3 μm**

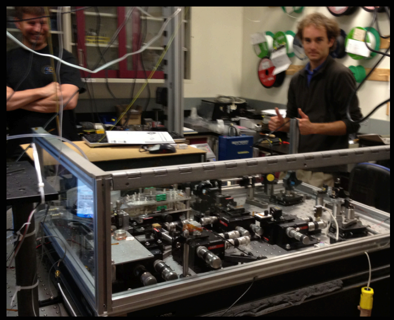
**Intracavity power > 1 W**

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

# Subharmonic OPO based on orientation-patterned GaAs, sync-pumped with an ultrafast 2050-nm fiber laser

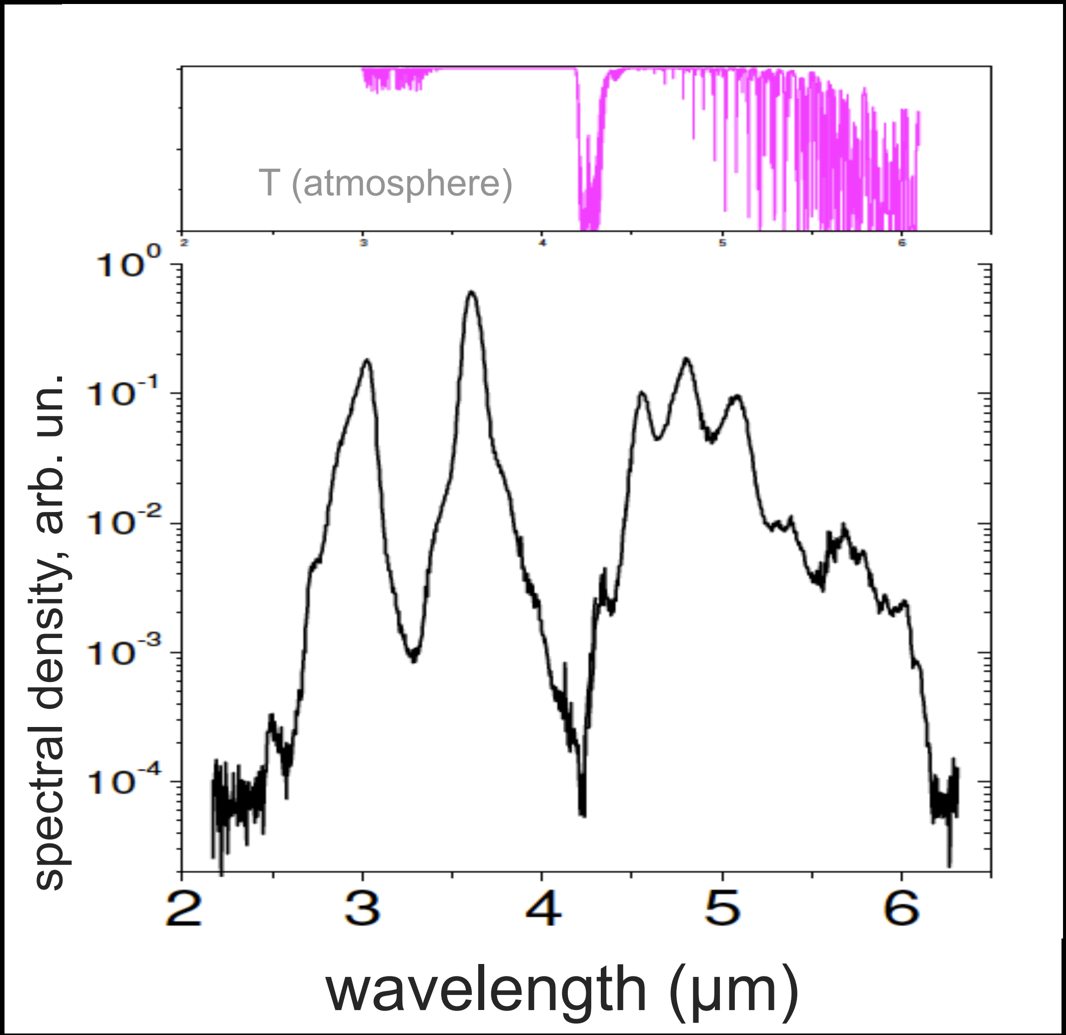



Orientation-patterned GaAs (OP-GaAs):
- nonlinear figure of merit 10 times larger than in lithium niobate
- infrared cutoff of GaAs > 17 μm



Leindecker, Marandi, Byer, Vodopyanov, Jiang, Hartl, Fermann, Schunemann, Opt. Express 20, 7046 (2012)

# Octave wide mid-IR spectrum

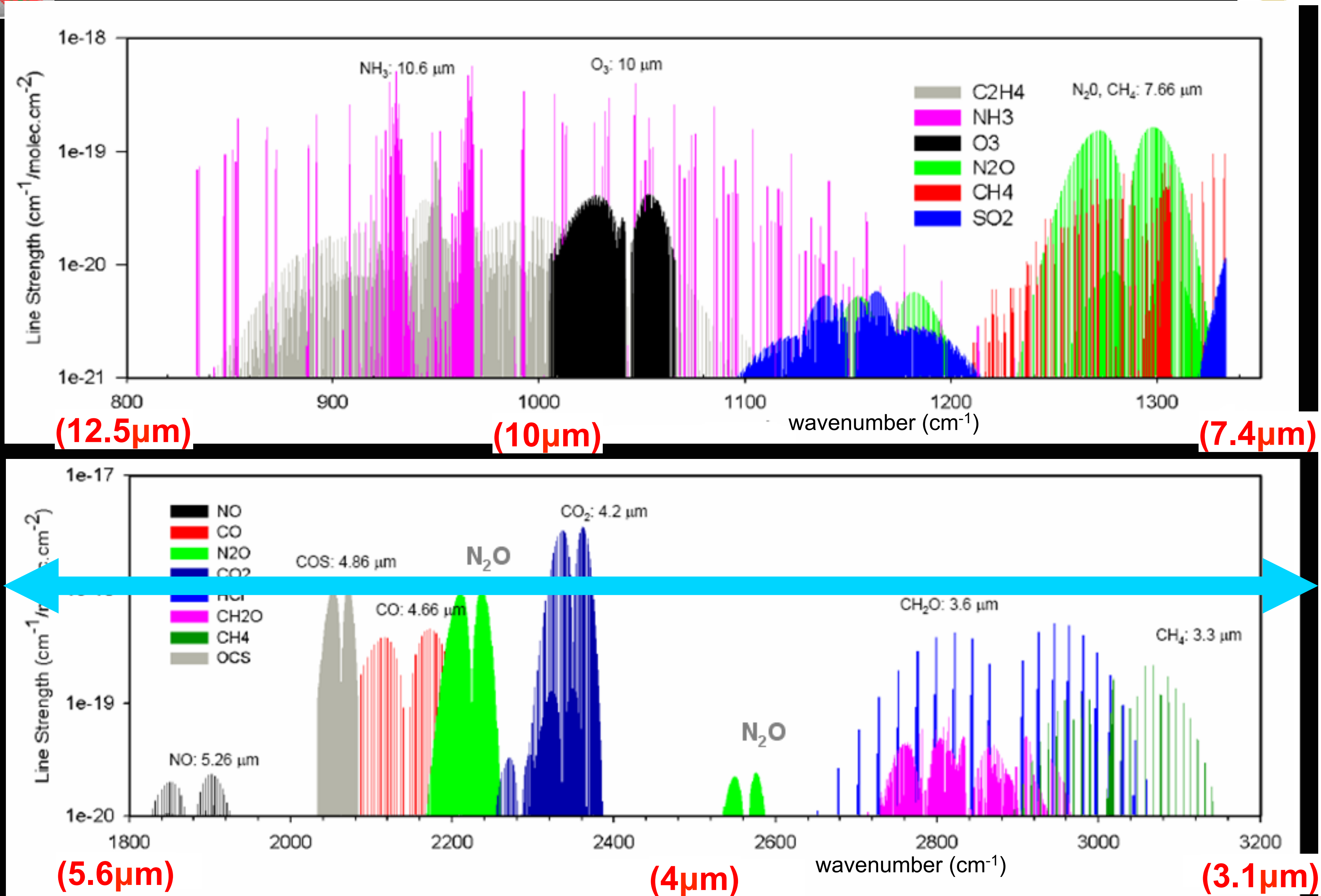



Nick Leindecker

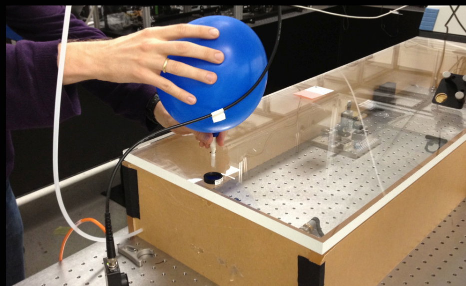
The broadest spectrum achieved with the resonator purged. The dips in the spectra around 4.25 **μ**m are all due to absorption of atmospheric carbon dioxide; transmission through 2 m of atmosphere is shown on top.

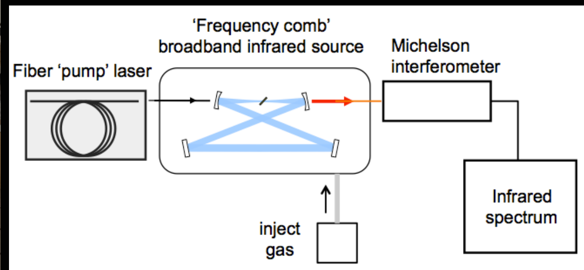
Leindecker, Marandi, Byer, Vodopyanov, Jiang, Hartl, Fermann, Schunemann, Opt. Express **20**, 7046 (2012)

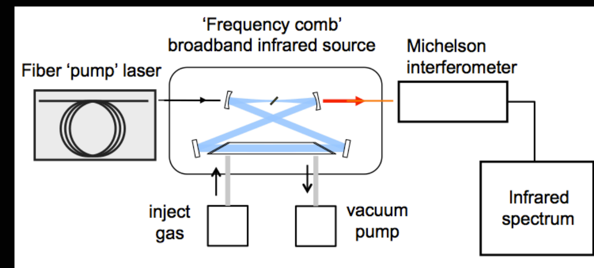
# Spectral coverage of our frequency comb



# Intracavity optical sensing: methane

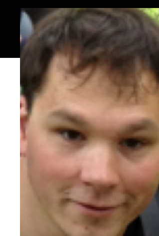


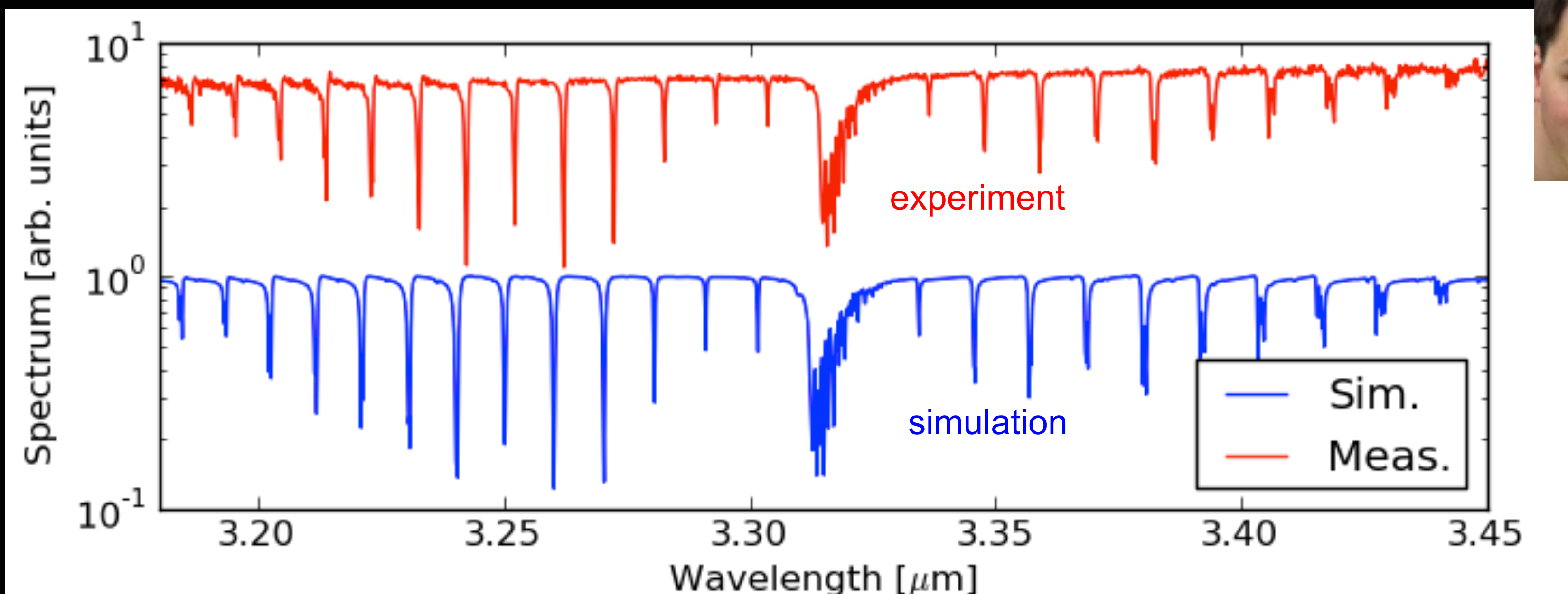



Magnus
Haakestad

Tobias
Lamour

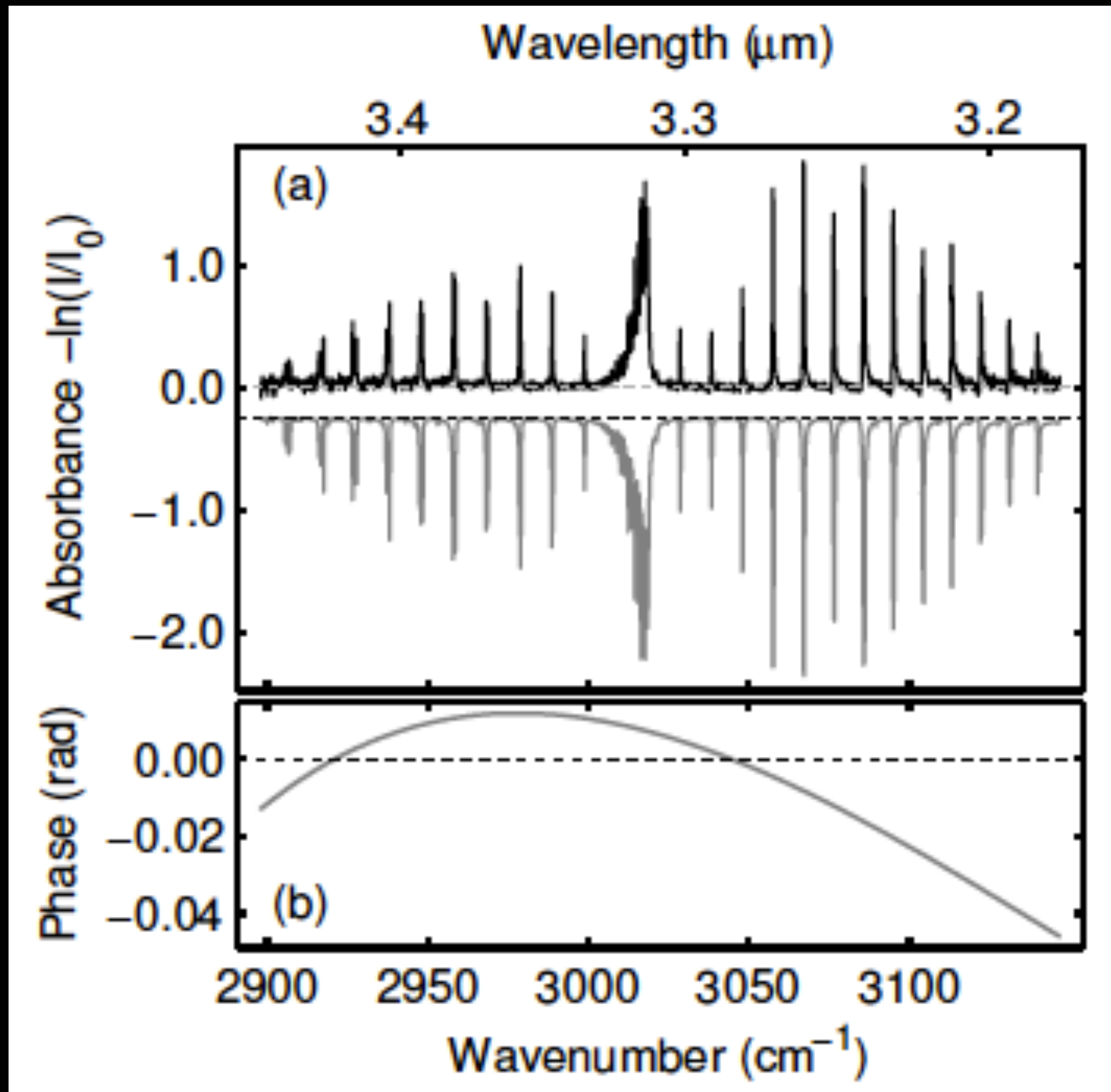




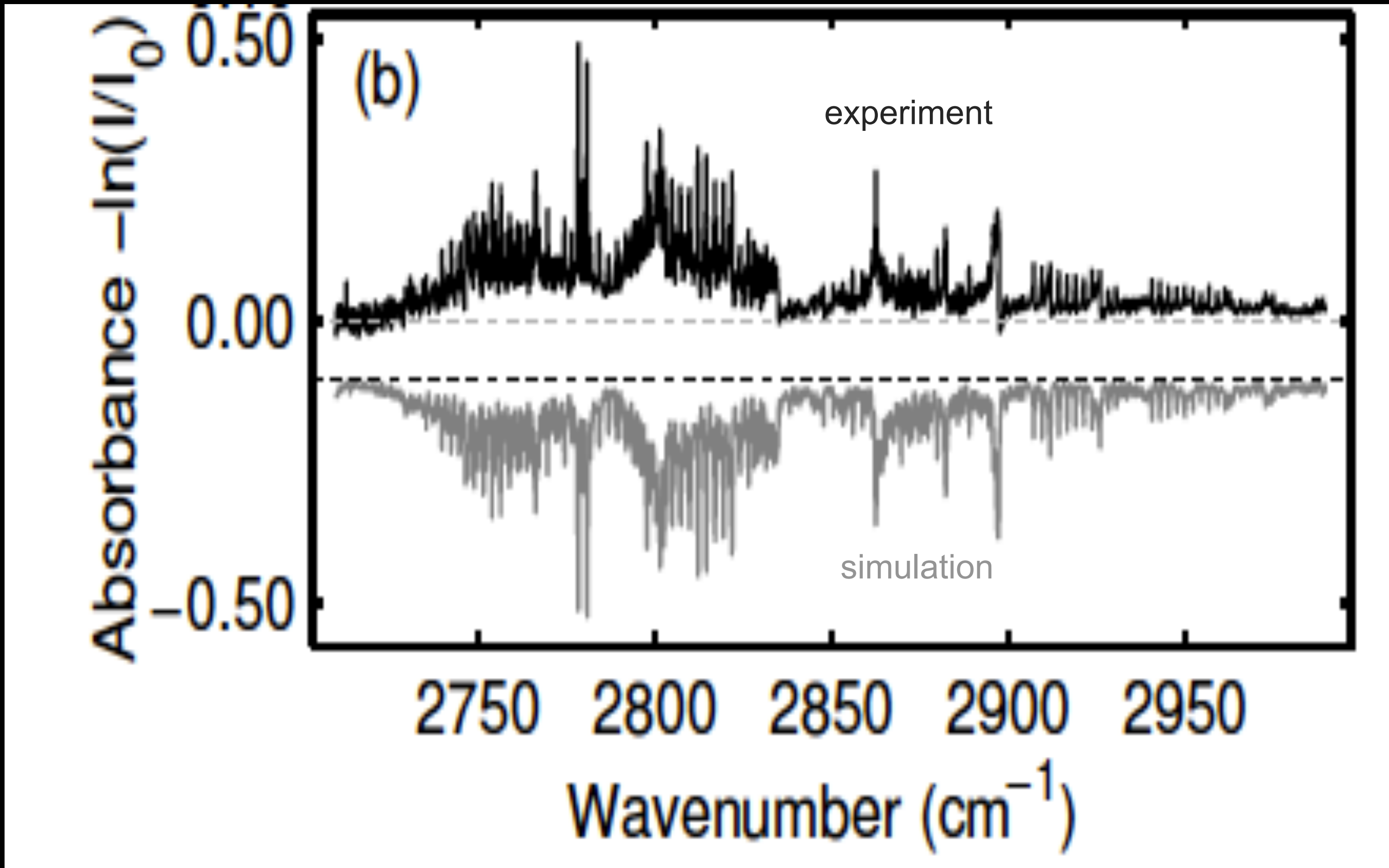

Modulation of the OPO spectrum near λ = 3.3 μm associated with intracavity methane absorption.

Haakestad, Lamour, Leindecker, Marandi, Vodopyanov, JOSA B 30, 631 (2013)

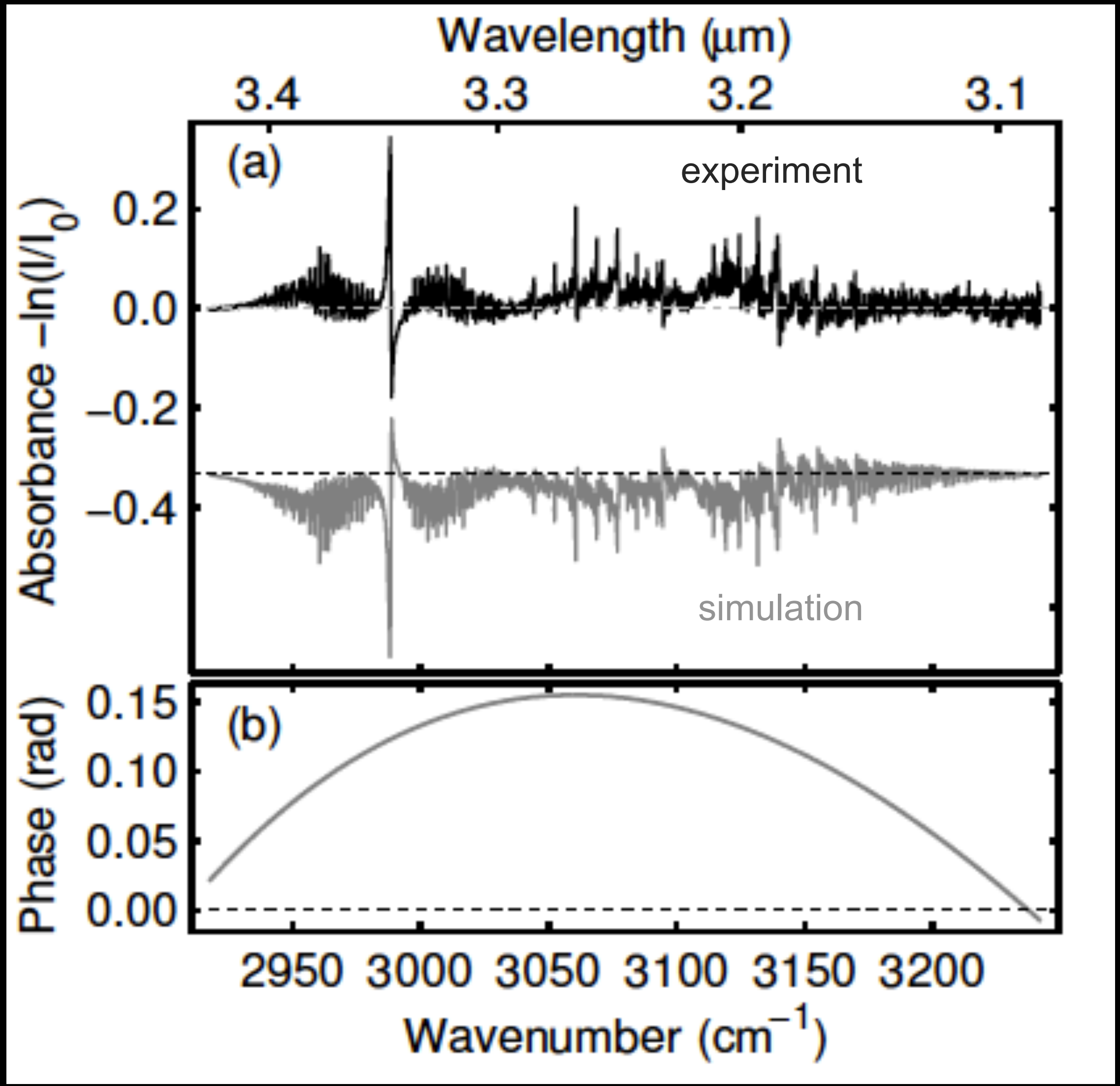
# Detection of methane ($CH_4$)



# Detection of formaldehyde ($CH_2O$)

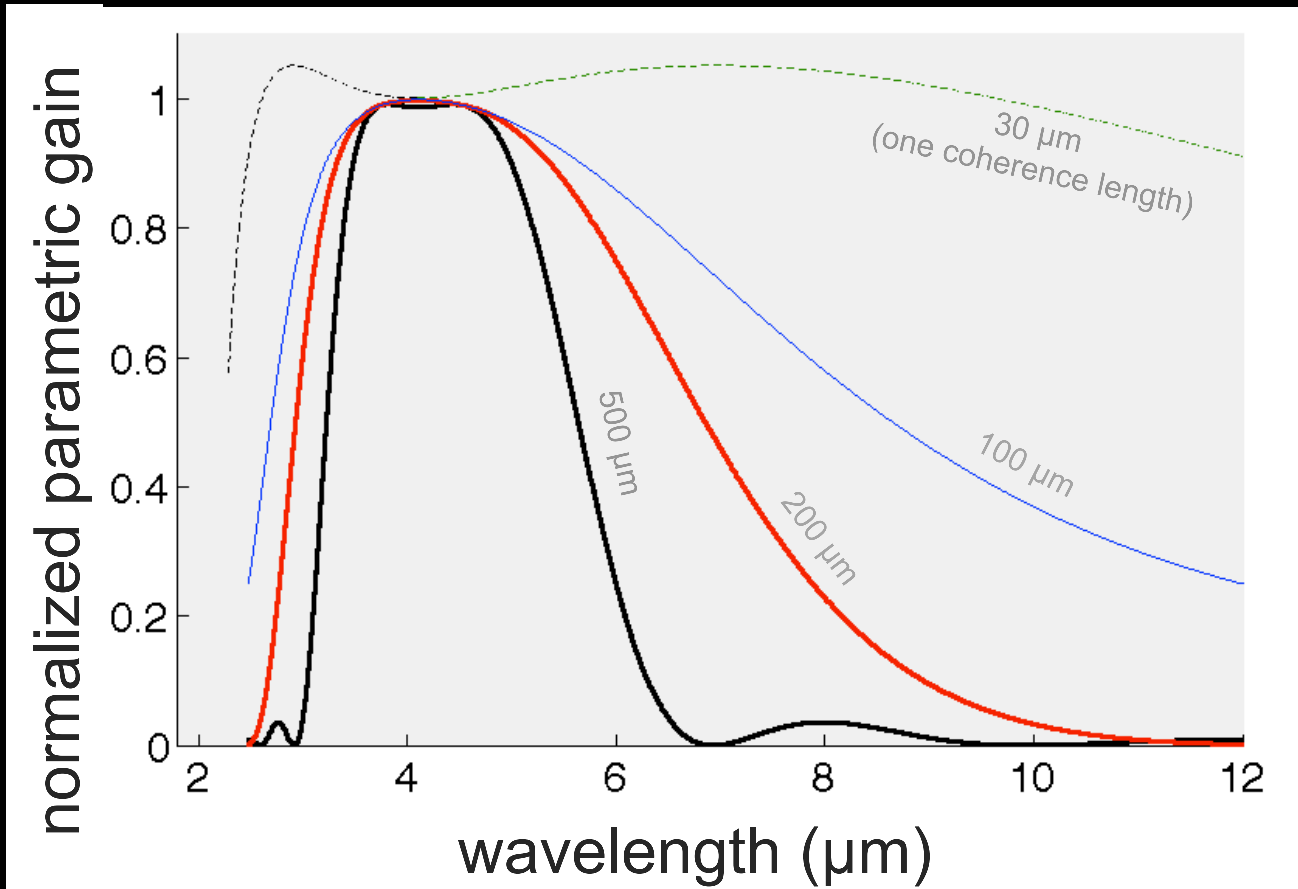


# Detection of ethylene ($C_2H_4$)



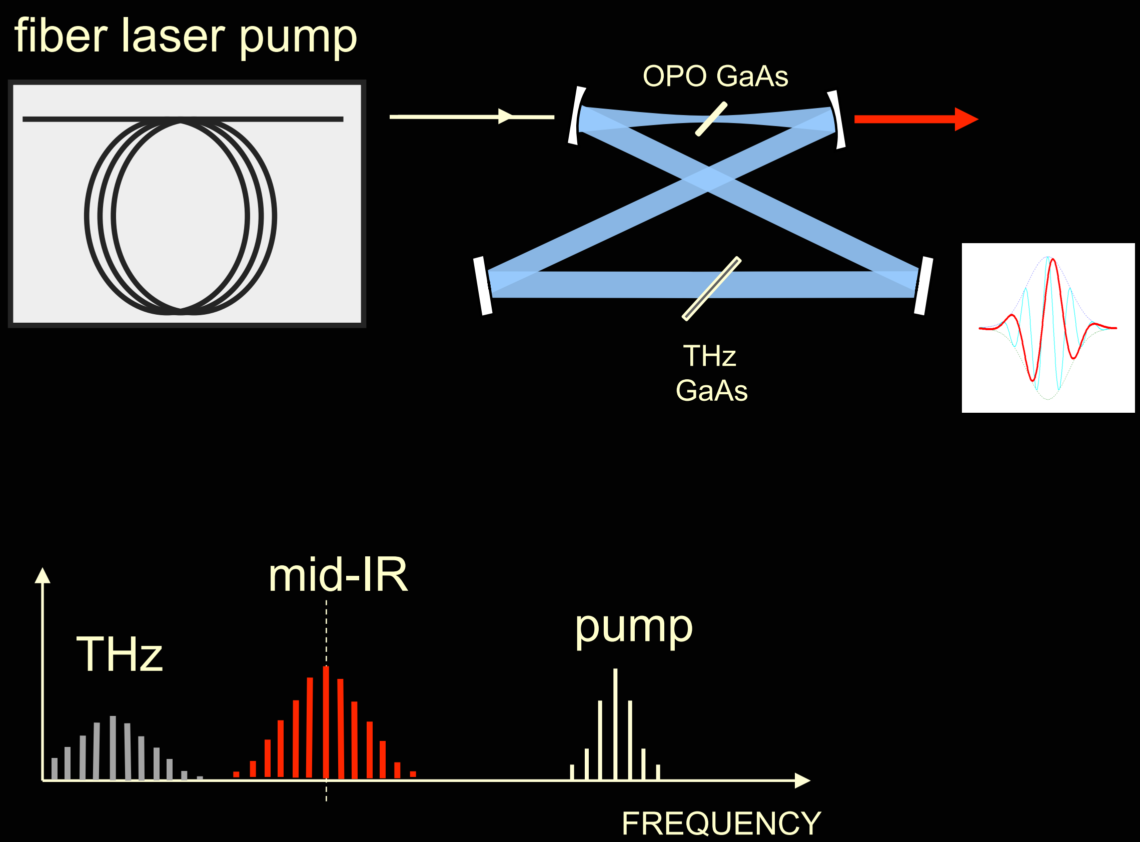
# What limits the spectral width ?

Relative QPM parametric gain vs. GaAs length @ 2050-nm pump




With thin enough GaAs crystal (and enough pump) can extend frequency comb to THz

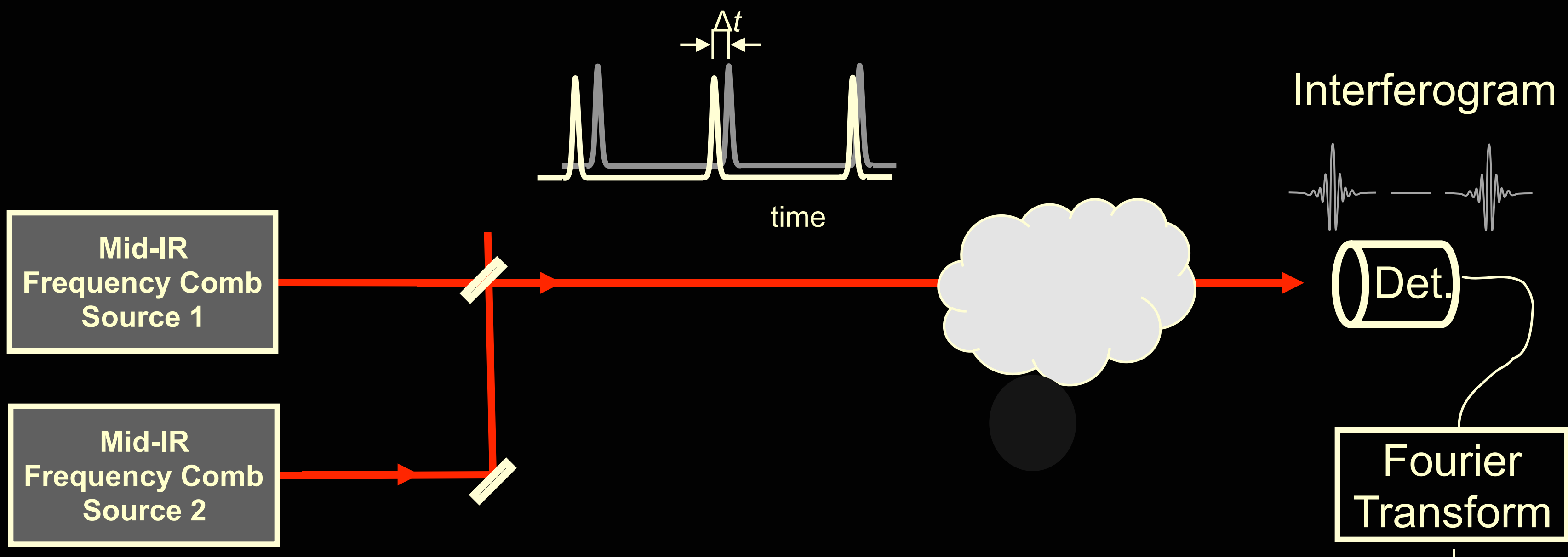
# Mid-IR / THz frequency comb

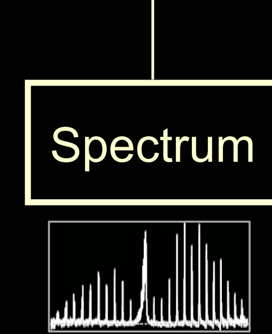



Intense few-optical-cycle mid-iR pulse resonates inside the OPO cavity. Placing second GaAs crystal produces THz frequency comb through optical rectification.

# Dual-comb Fourier-transform spectroscopy

**Keilmann, Gohle, Holzwarth, Opt. Lett. 29, 1542 (2004)**
**Schliesser, Brehm, Keilmann, Opt. Express 13, 9029 (2005)**




Repetition rates of Comb 1 and Comb 2 have small offset $\delta f_{rep}$ ~ 100 Hz

Up to 1 000 000 spectral points in 10 ms with resolution ~ 100 MHz (0.003 $cm^{-1}$)

# Compact systems

## High repetition rate (500 MHz) Tm-fiber pumped subharmonic OPO

CLEO 2012
post-deadline paper

**500 MHz, 58fs highly coherent Tm fiber soliton laser**

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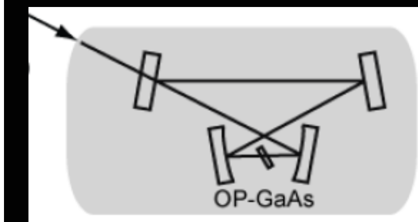


## High repetition rate (500 MHz) system based on a "fractional" OPO

CLEO 2013
submitted

**500-MHz Mid-IR Frequency Comb Source Based on a Compact Subharmonic OPO**

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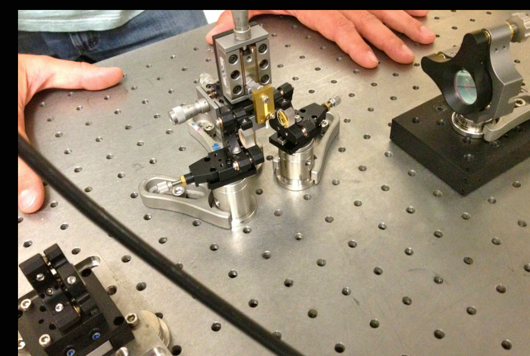

Compact fs laser
from IMRA at 1560 nm

# Conclusion

- About 1 mW of narrowband output tunable between 0.5 and 5 THz was produced in periodically-inverted GaAs
- GaAs was placed inside a high-finesse cavity of a near-degenerate type II (e-eo) or ring-cavity type-0 (e-ee) PPLN OPO
- Manley Row limit can be exceeded by a factor of 10
- Frequency combs approach allows to do high resolution spectroscopy in the whole mid-IR – THz range, potentially 0-100 THz, with resolution of 100 MHz

DARPA

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