



The Abdus Salam
International Centre
for Theoretical Physics



2443-10

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

4 - 15 February 2013

Nonlinear optics - Parametric generation and amplification and extras

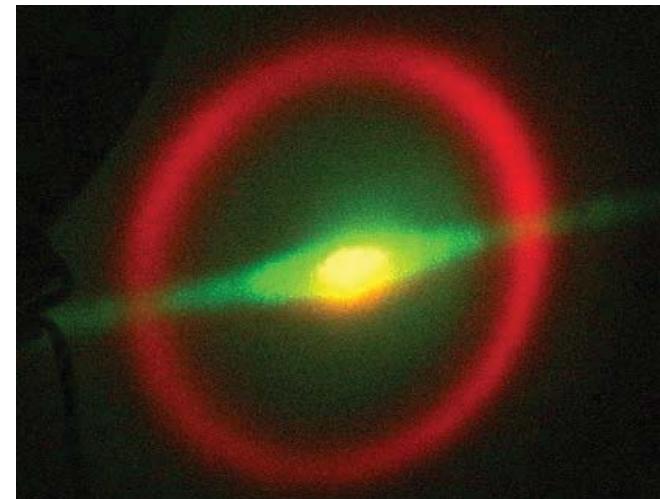
F. Laurell
KTH
Sweden



Nonlinear optics

Parametric generation and amplification and extras

Fredrik Laurell



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AlbaNova, Roslagstullsbacken 21,
KTH – Royal Institute of Technology, 106 91 Stockholm, Sweden



Outline

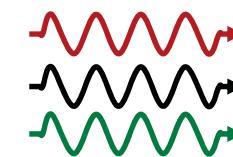
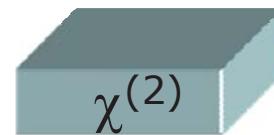
- Parametric generation and amplification
- Theoretical considerations
- Nanodomain engineered ferroelectrics
- Backward OPO
- applications
- Summary
- Damage



Nonlinear processes – optical parametric devices

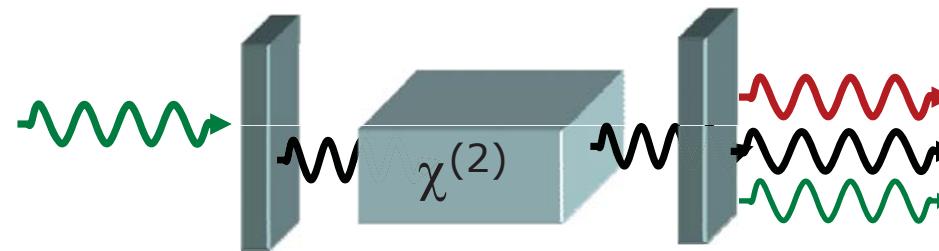
Generator
(OPG)

Pump



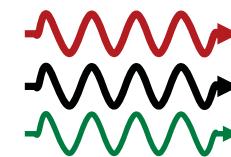
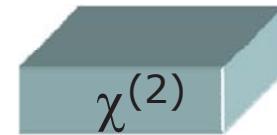
Idler
Signal

Oscillator
(OPO)



Amplifier
(OPA)

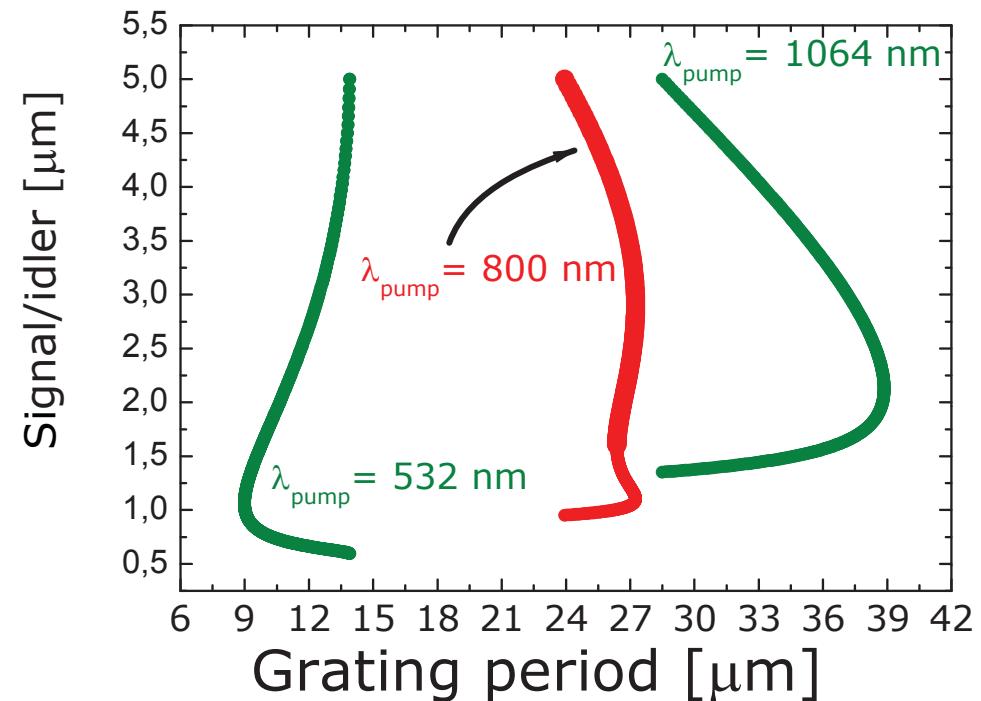
Seed





Quasi-phase-matching

- + Noncritical interaction
- + Longer interaction length
- + Engineerable spectral output
- + Accessing the highest $\chi^{(2)}$ over the entire transparency region
- Additional processing step (= cost)
- $d_{\text{eff}} = 2/\pi \times d_{33}$

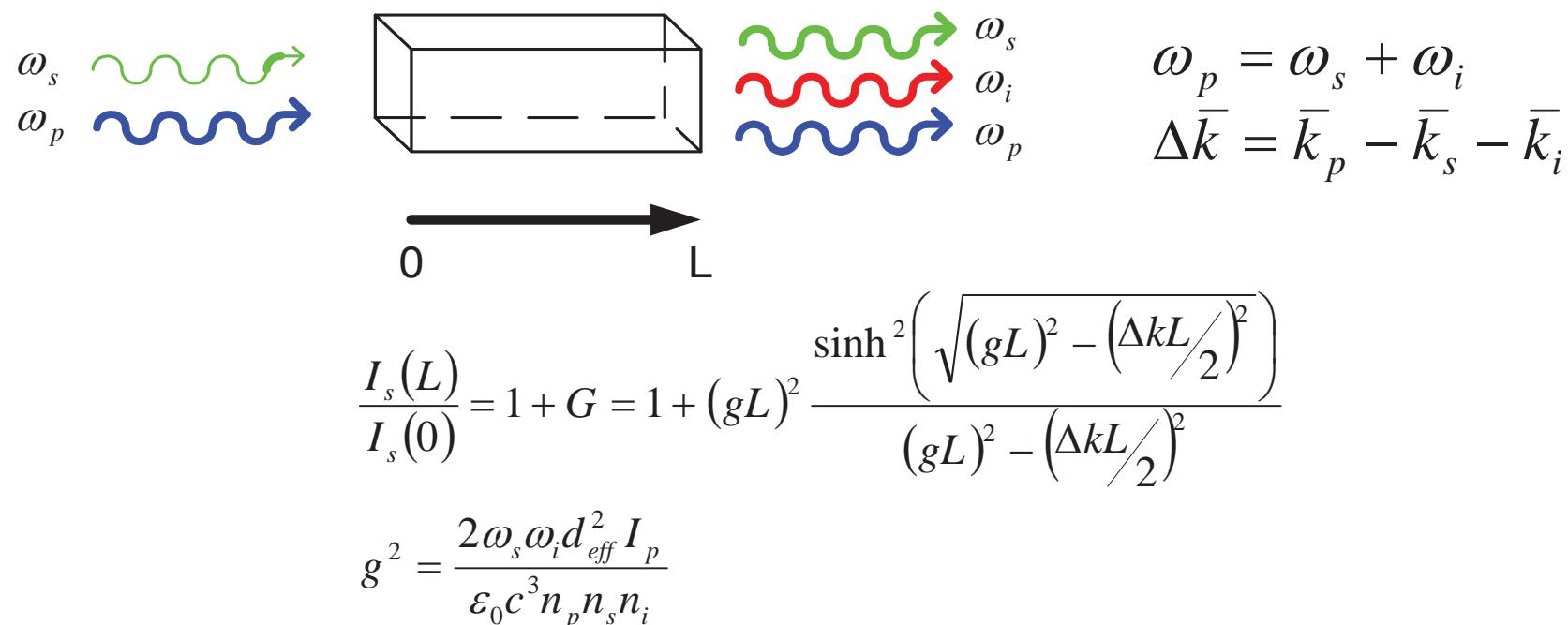




Optical parametric amplification

Assume:

1. No depletion of the pump
2. No losses

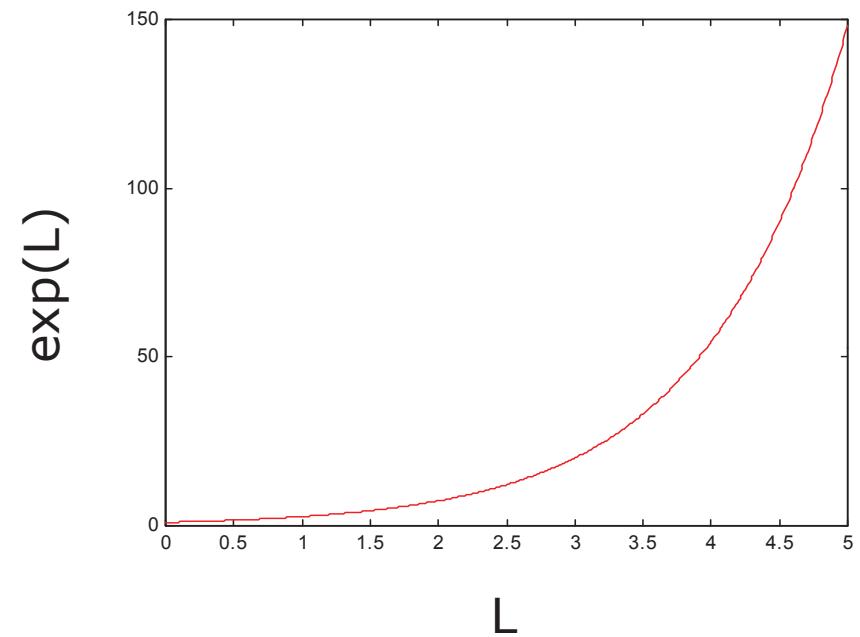
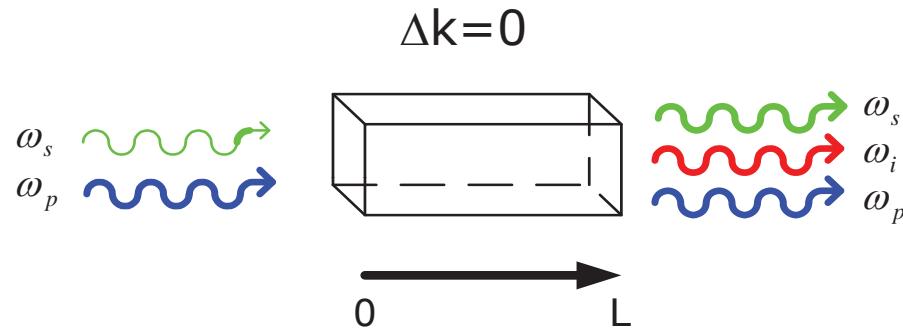




Optical parametric amplification

Assume: high signal gain ($g \gg \Delta k/2$)

$$\frac{I_s(L)}{I_s(0)} = 1 + G = 1 + \sinh^2(gL) \approx 1 + \frac{1}{4} \exp(2gL)$$



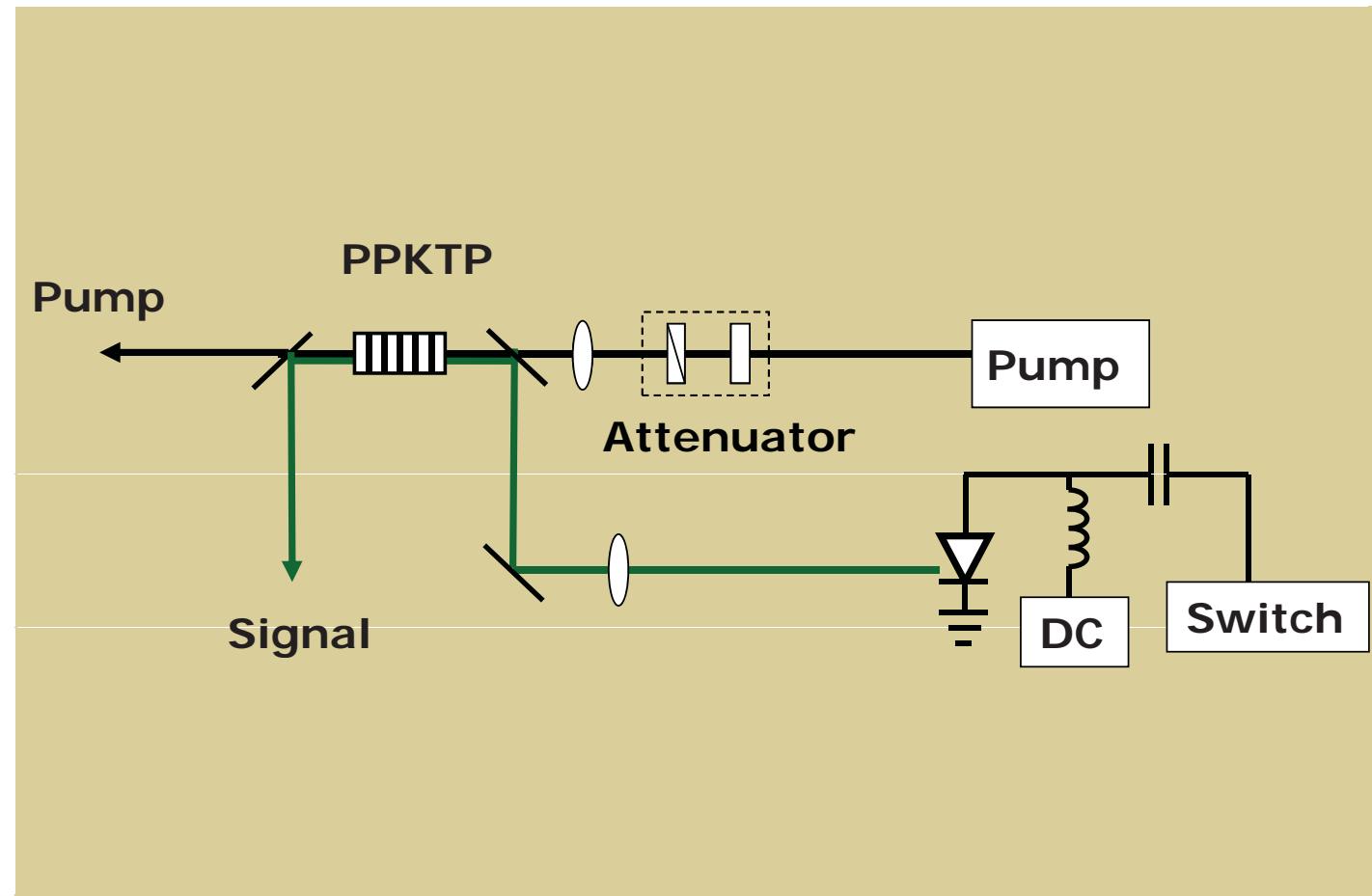


Advantages of OPA

- Large gain
- Flexible
- Low thermal effects
- Phase of seed is maintained

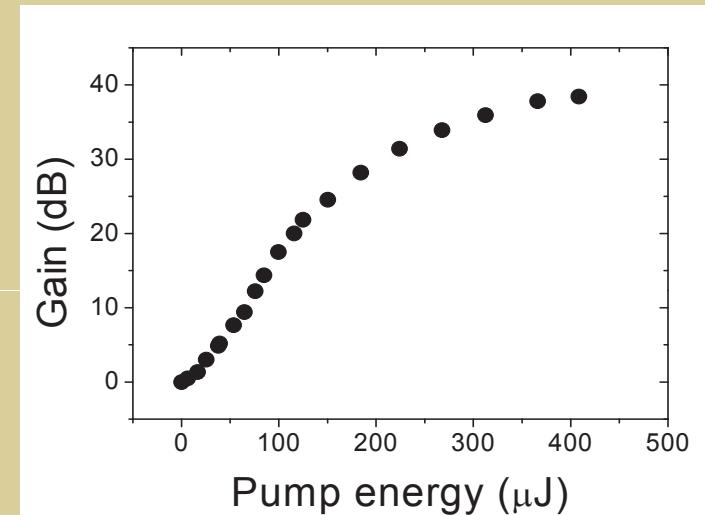
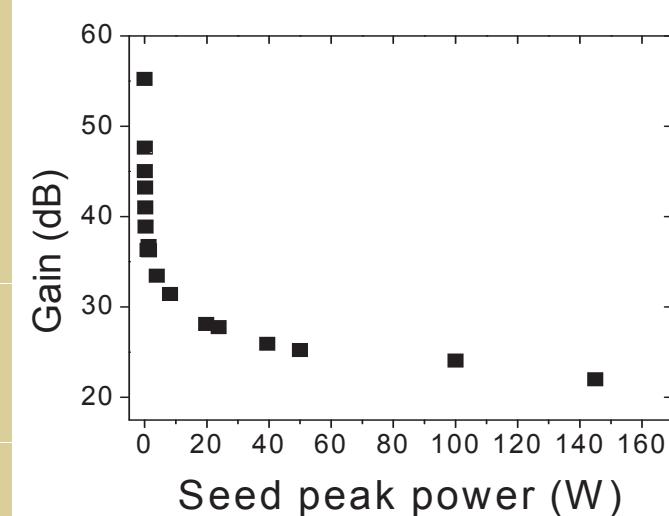


OPA seeded by a Gain-Switched Laser Diode





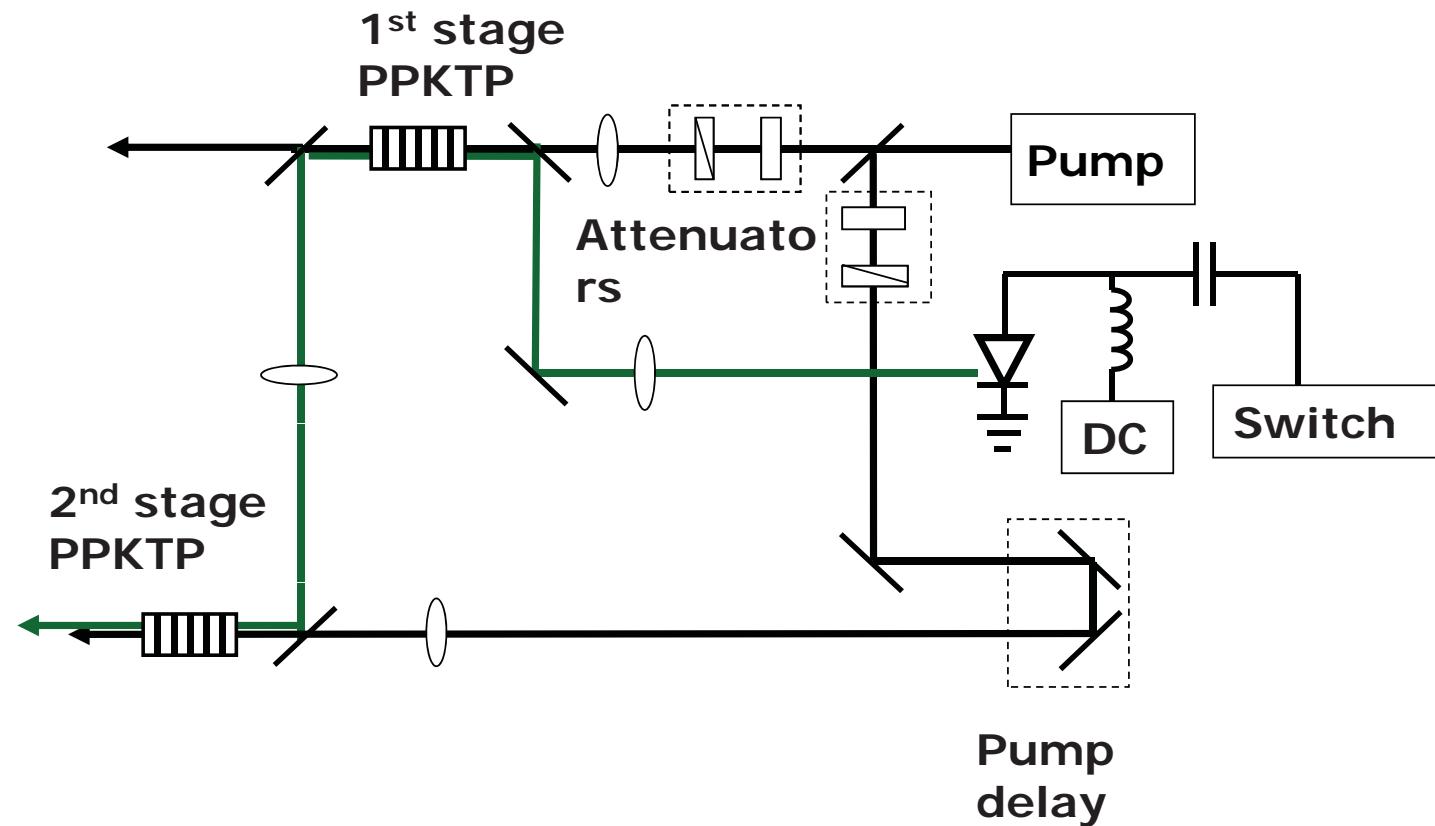
Single Stage OPA



- Operating at high gain
- Small signal gain of 40 - 50 dB

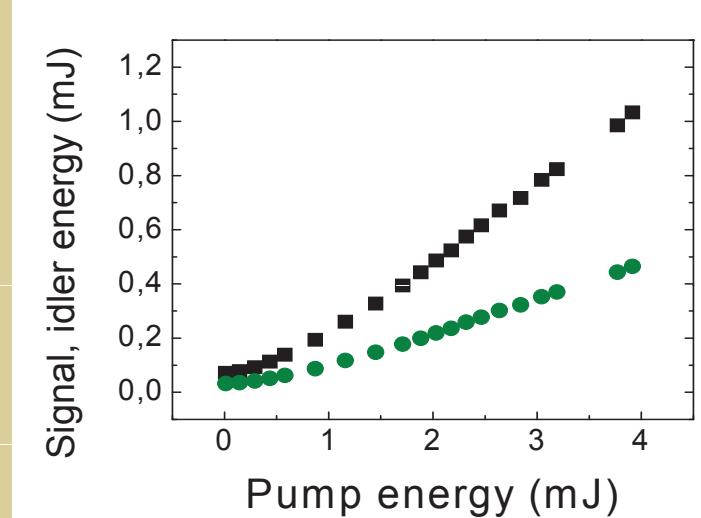
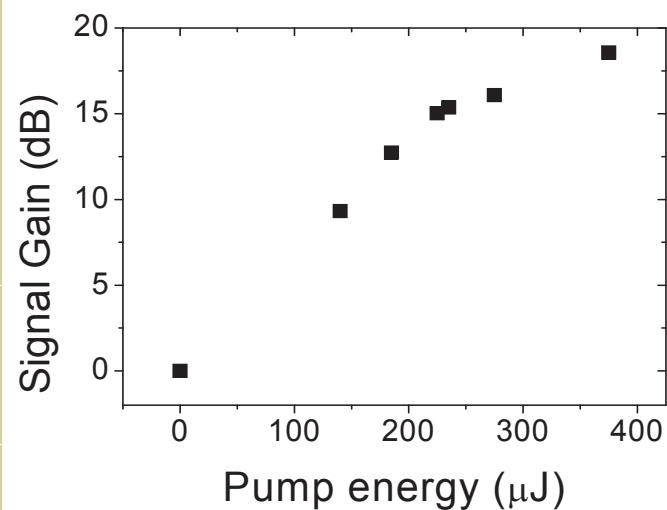


Double stage OPA





2nd Stage OPA



- Operating at low gain: 10 - 20 dB
- Large conversion > 35%



Parametric amplifier at 1.5 μm

Combining two minilasers and a PPKTP

Er:Yb-glass

$$\tau_{\text{seed}} = 36 \text{ ns}$$

$$E_{\text{seed}} = 6 \mu\text{J}$$

$$M_{\text{seed}}^2 = 1.1$$

Nd:YAG

$$\tau_{\text{pump}} = 5 \text{ ns}$$

$$E_{\text{pump}} = 30 \text{ mJ}$$

$$M_{\text{pump}}^2 = 7$$

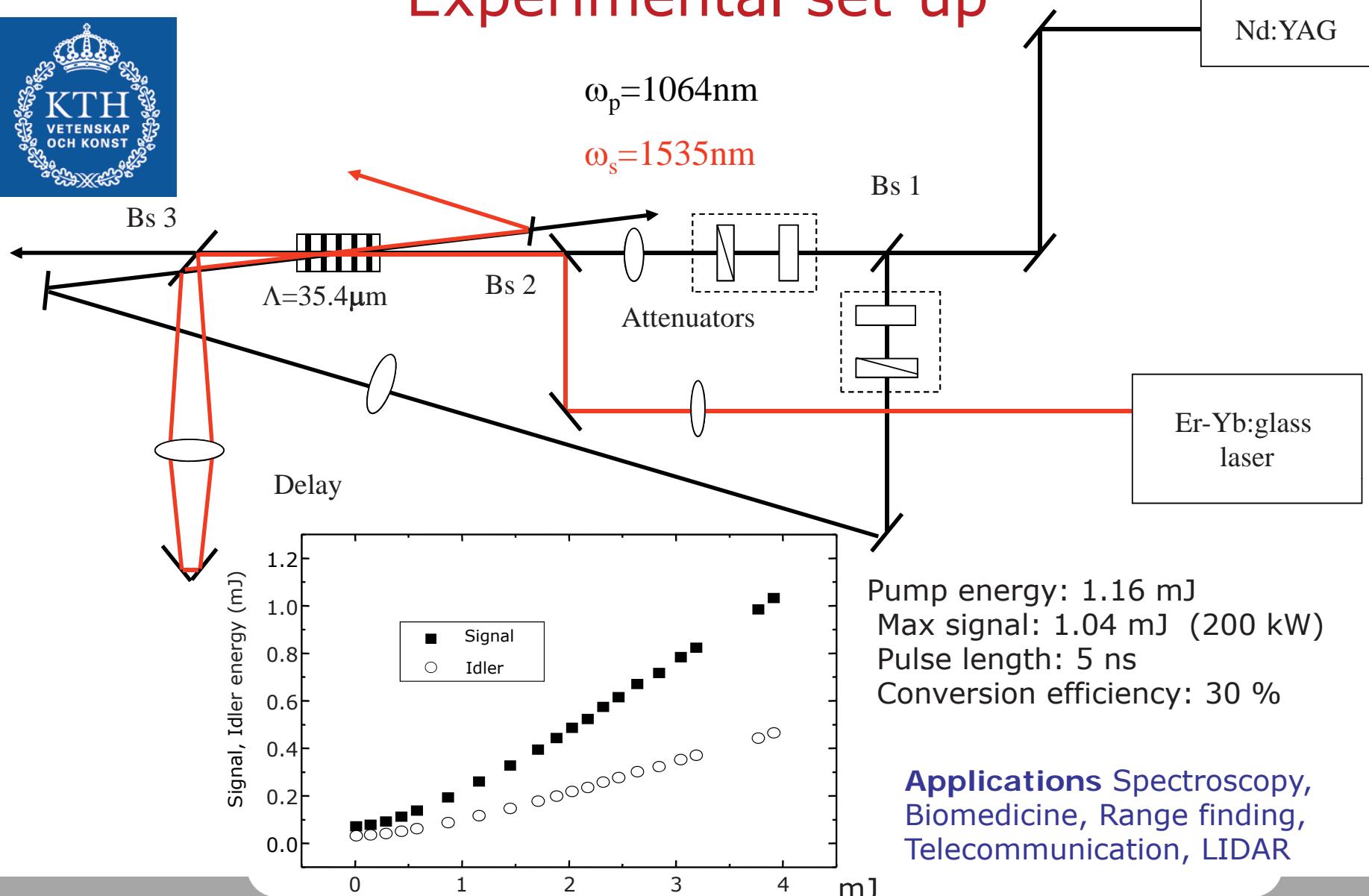
OPA signal

$$\tau_{\text{signal}} = 5 \text{ ns}$$

$$E_{\text{signal}} = 1 \text{ mJ}$$

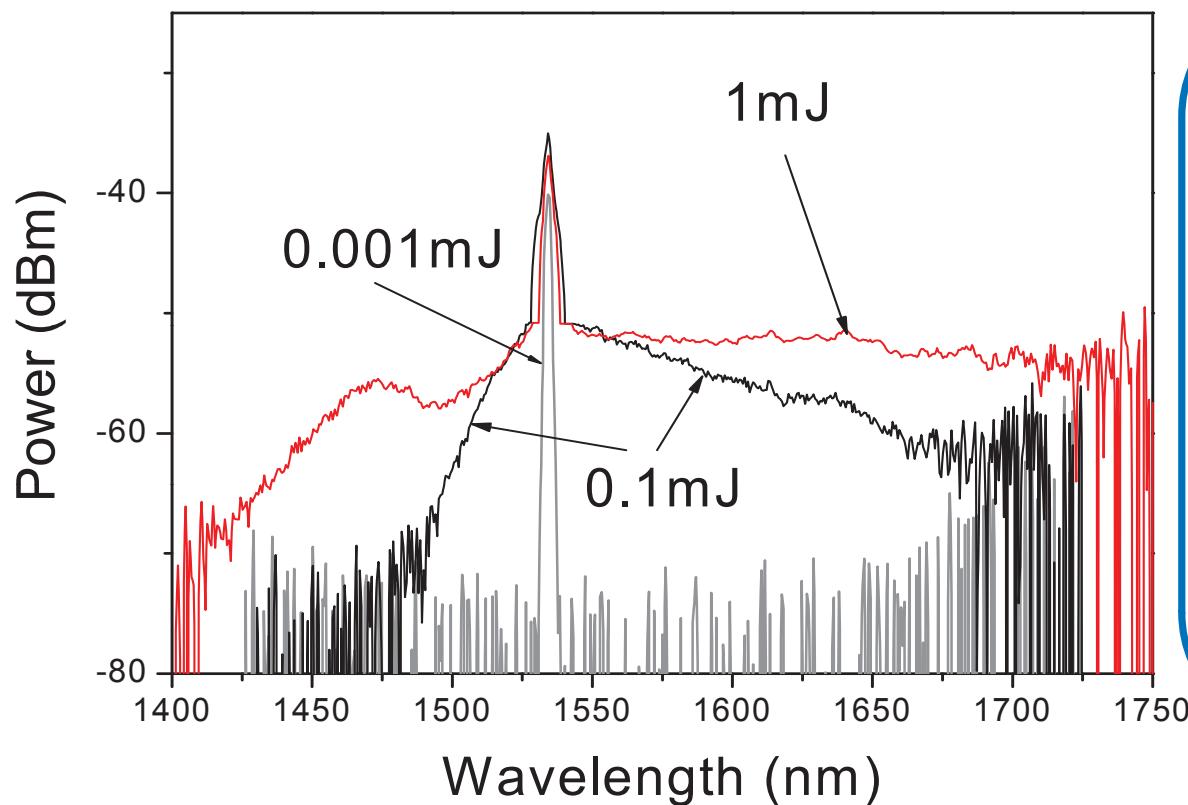
$$M_{\text{signal}}^2 = 1.1$$

Experimental set-up





Spectrum after a single mode fiber

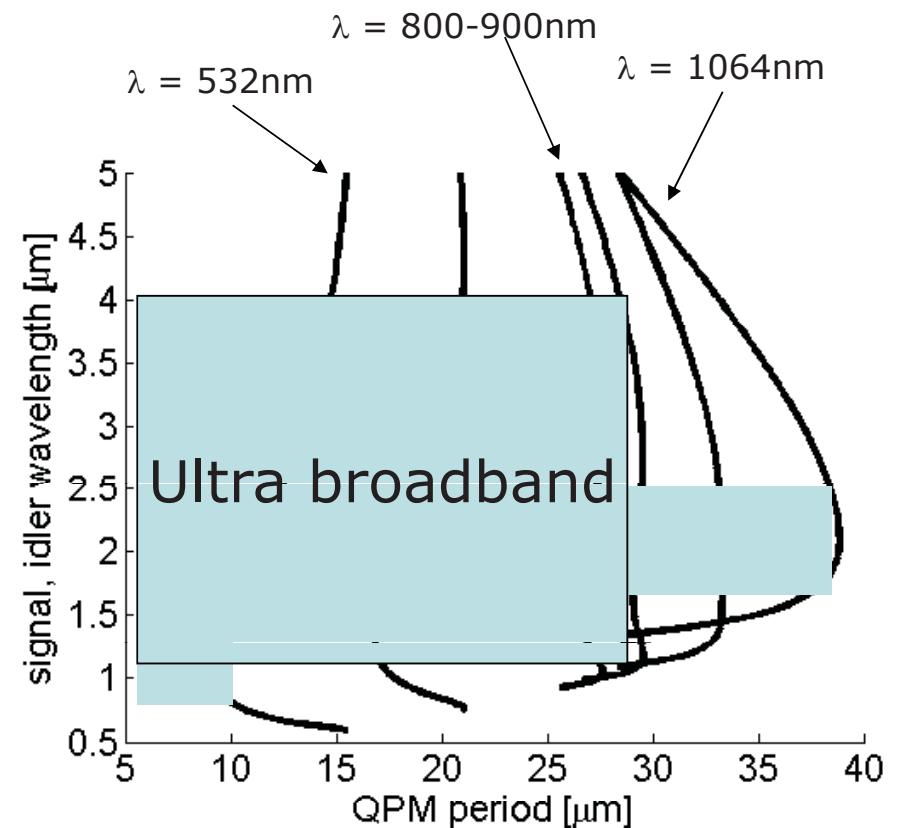


- 5 m SMF
- 250 nm wide spectrum
- Responsible processes:
 - Stimulated Raman Scattering
 - Self Phase Modulation
 - Four Wave Mixing



Strategies for spectral management in QPM OPG

- Broadband generation
- ↓
- Operate at near-degeneracy
- ↓
- Point of zero-group velocity dispersion (GVD)



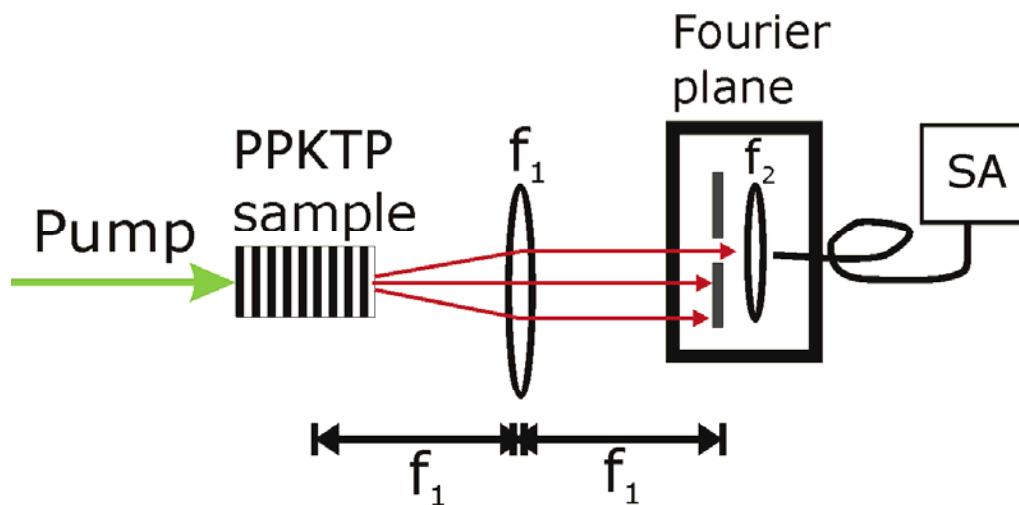


Ultra broadband generation in OPG

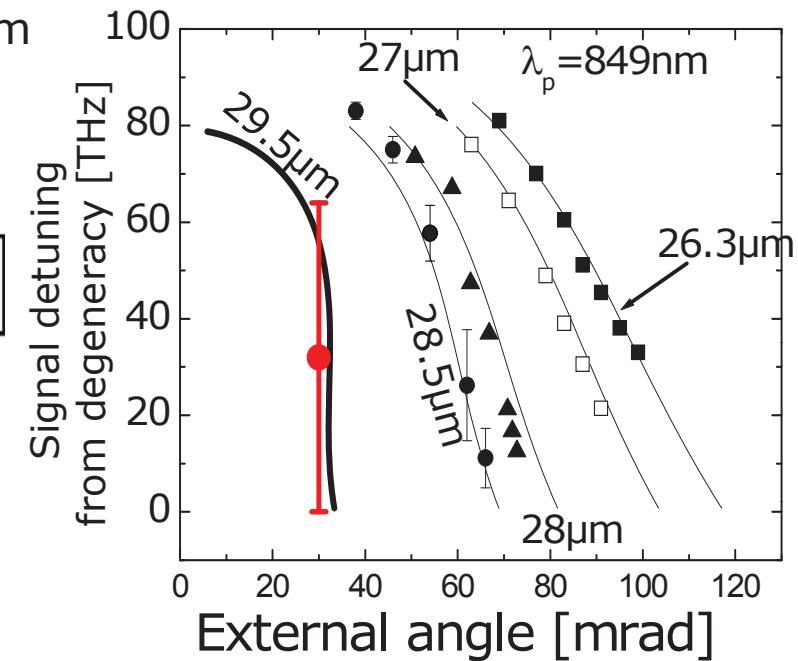
Experimental setup

5 periods: $26.3 - 29.5 \mu\text{m}$

Ti:Sapphire: 1 ps, 788 - 849nm



Noncollinear



$$\Delta\nu_s = 65 \text{ THz}$$

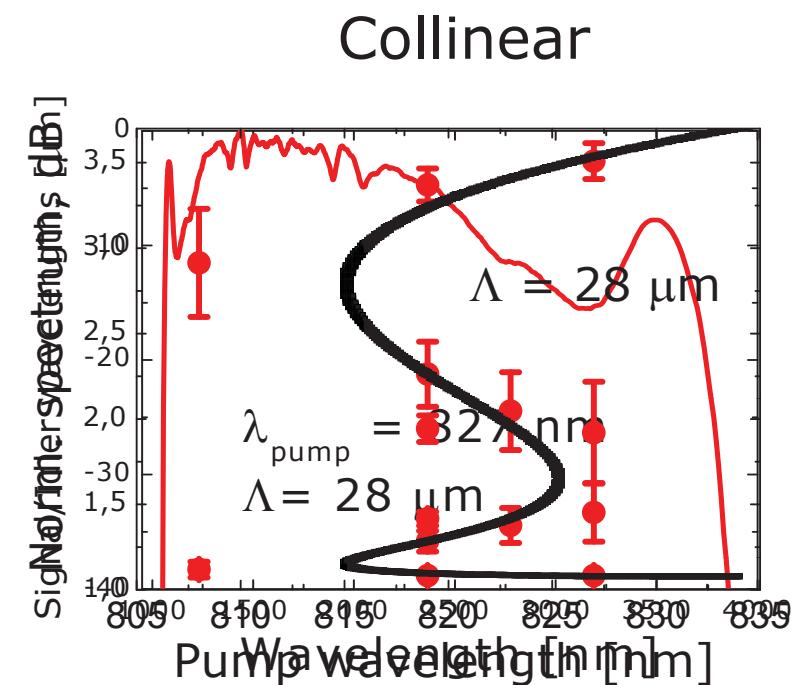
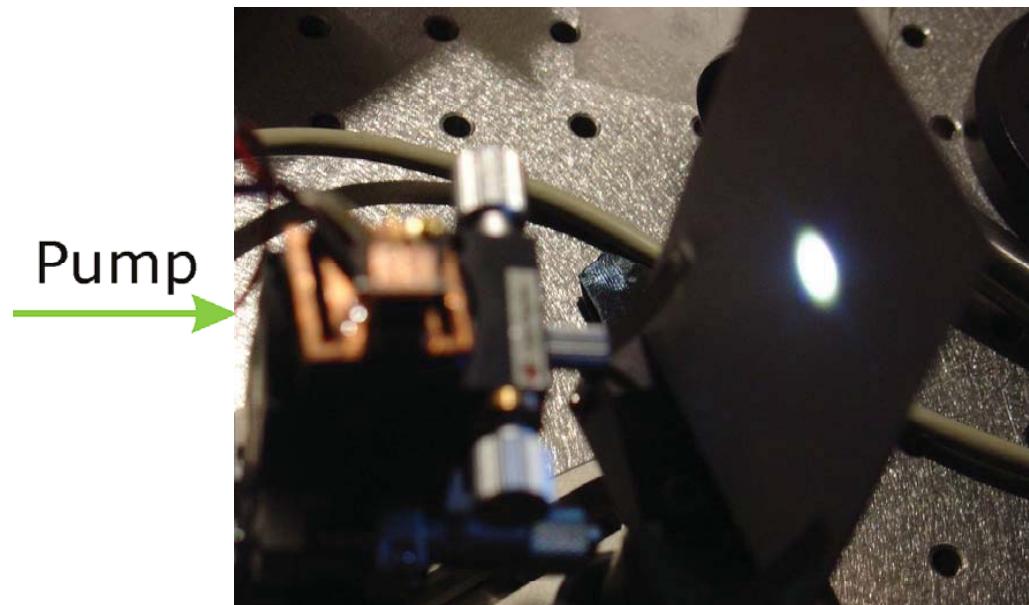


Ultra broadband generation in OPG

Experimental setup

5 periods: 26.3 – 29.5 μm

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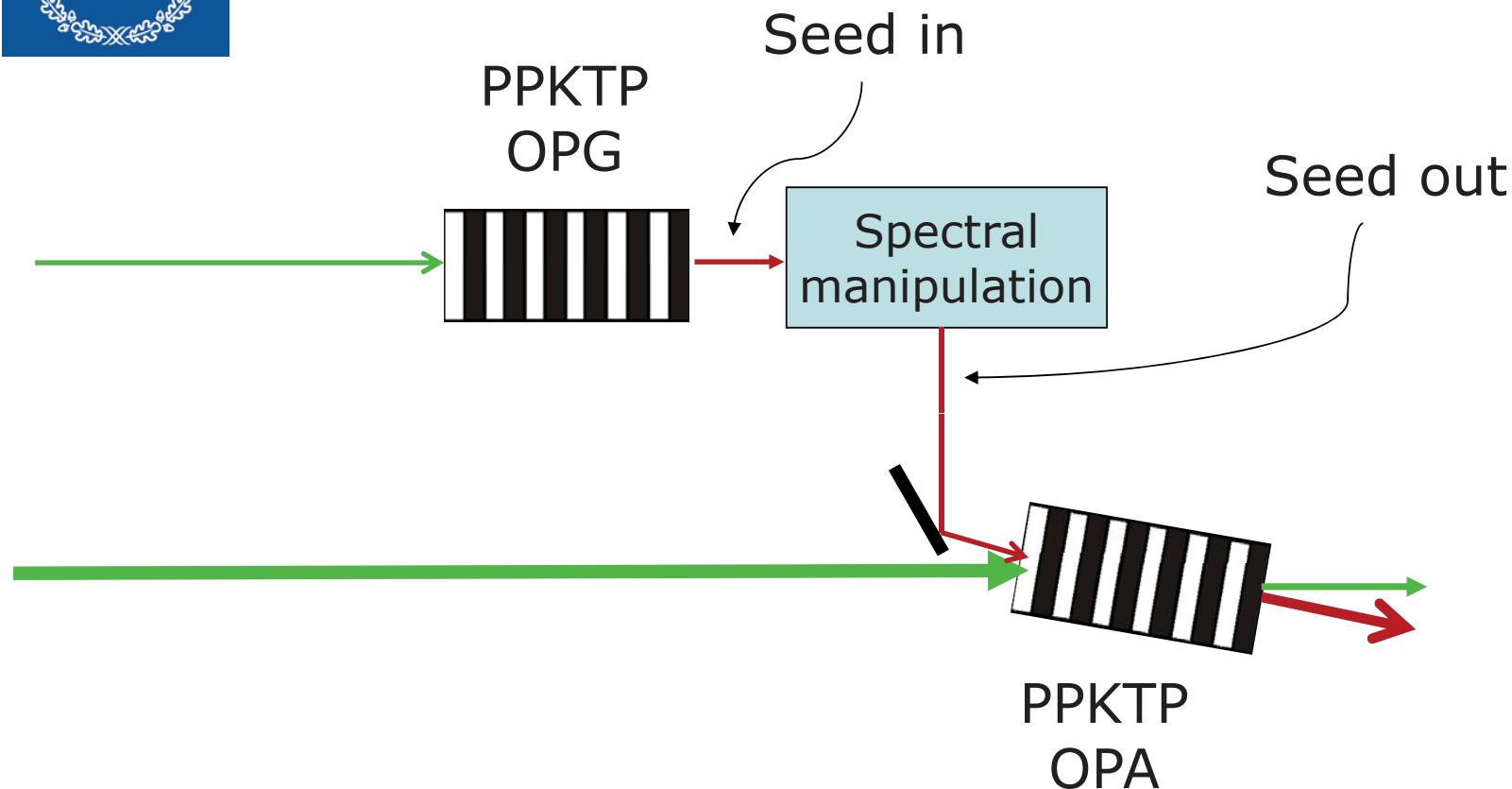
$$\nu = 181 \pm 57 \text{ THz}$$

1 octave

$\Delta\nu \Rightarrow$ seed source \Rightarrow widely tunable OPA

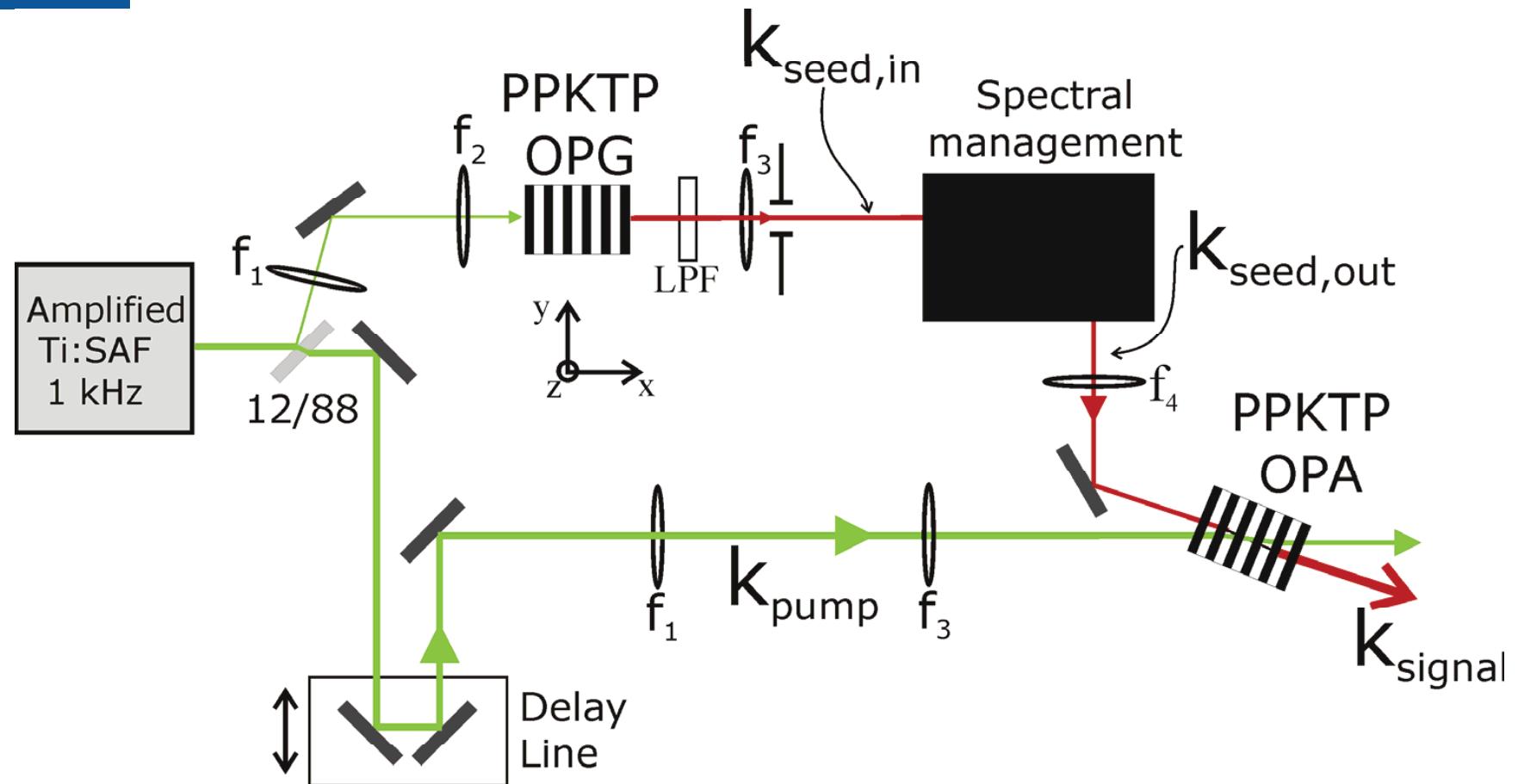


Widely tunable OPA - setup



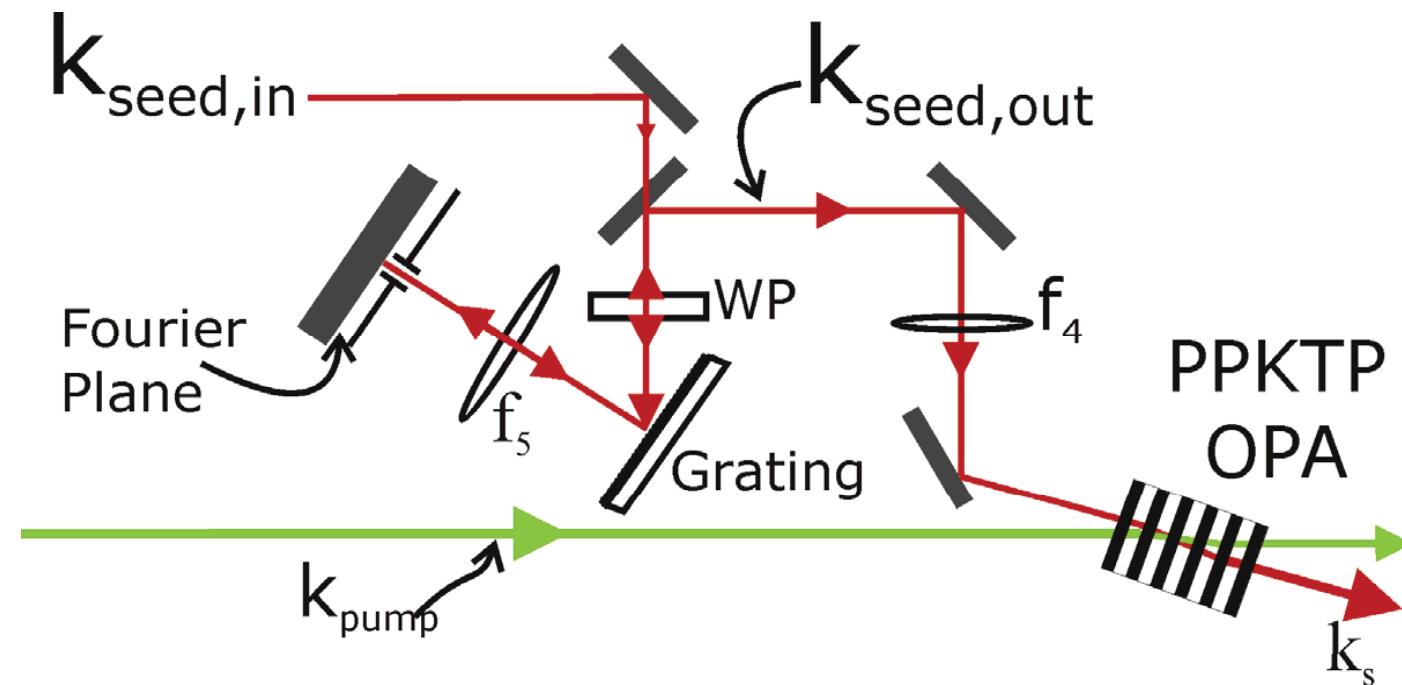


Widely tunable OPA - setup





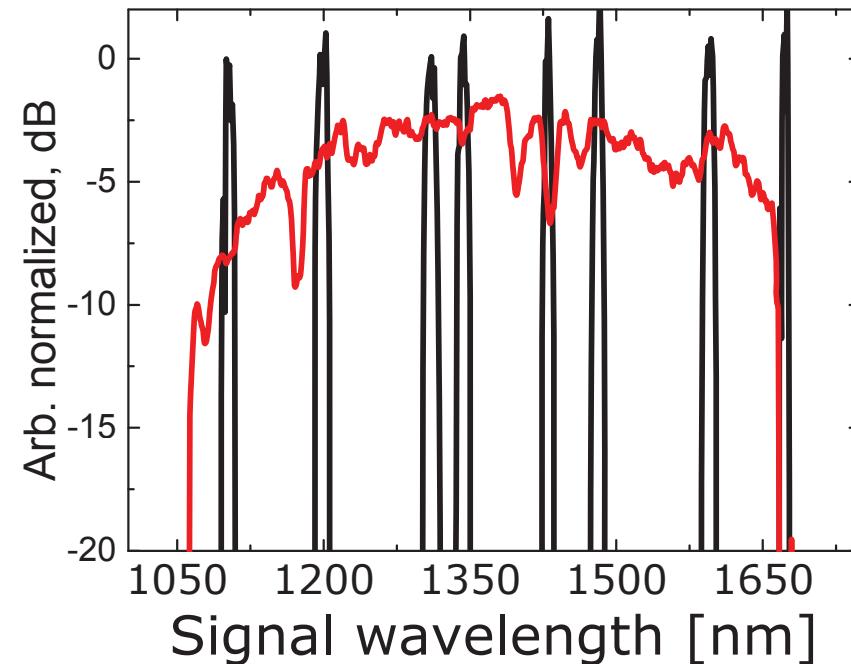
Spectral manipulation of the seed





Results – tunable OPA

Parametric gain spectrum: OPA



Single-pass gain
67 dB
 $\eta = 10\%$

Double-pass gain
70.5 dB
 $E_s = 6.5 \mu J$
 $\eta = 20\%$

Total pump energy budget: <100 μJ



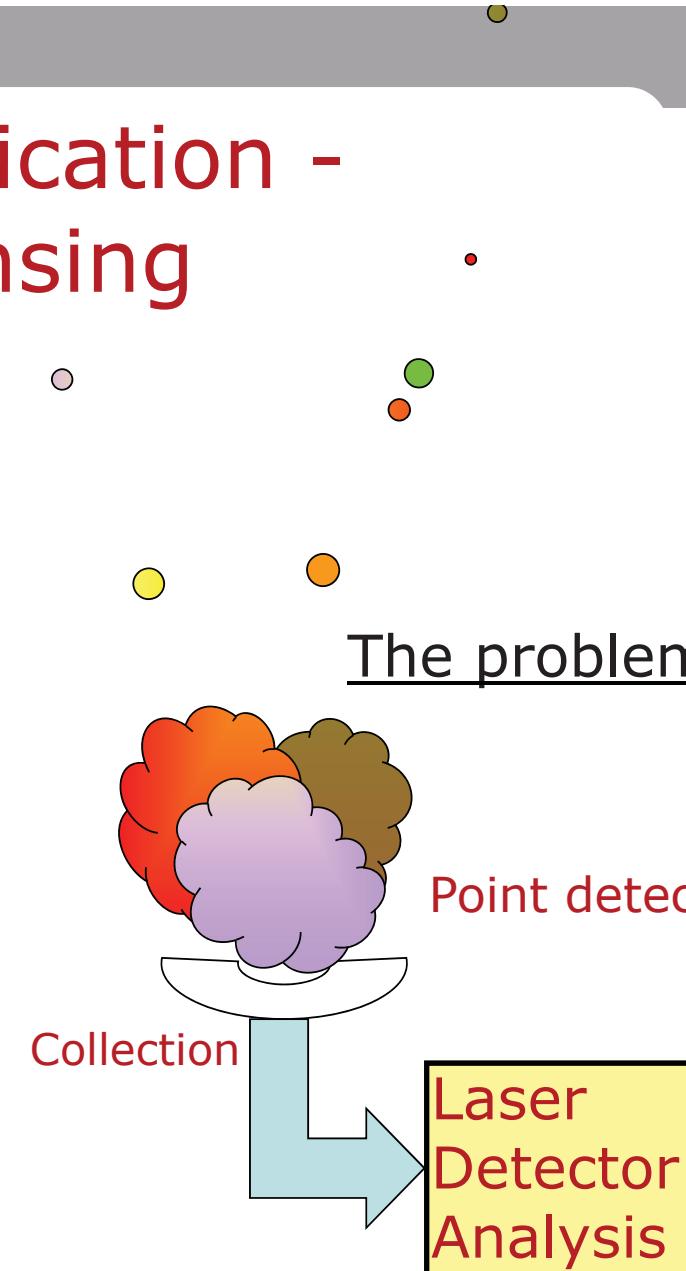
Real life application - biological sensing

The overall task:

Develop and evaluate a multiple-wavelength ultraviolet laser source for detection of biological substances

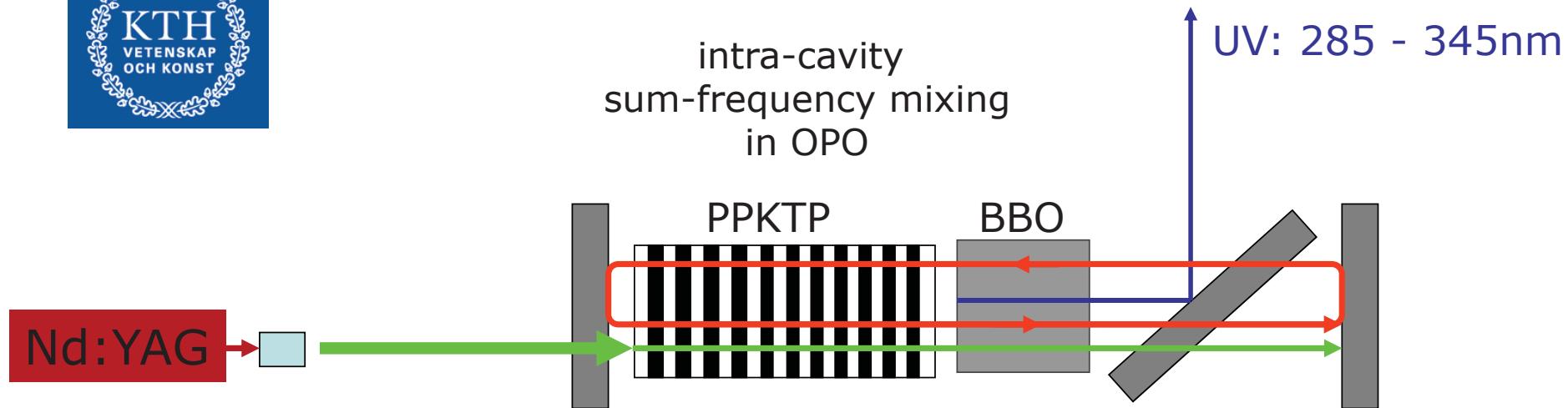
Why UV?

Bioparticles fluoresce when excited in the 280 – 340 nm range

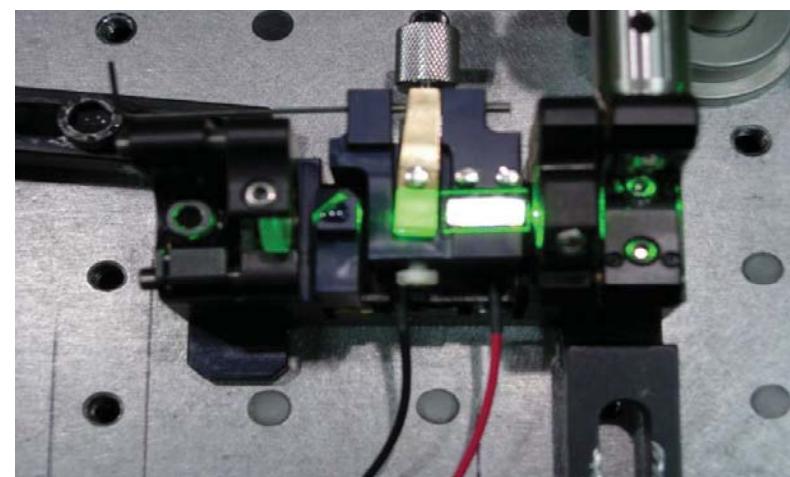
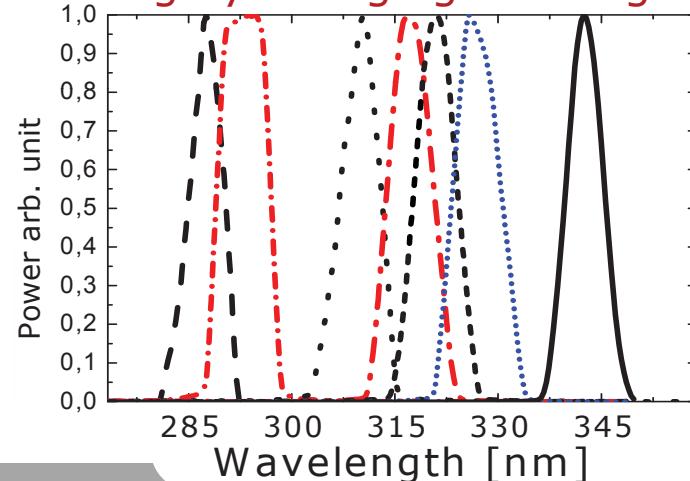




The UV-source – UV generation

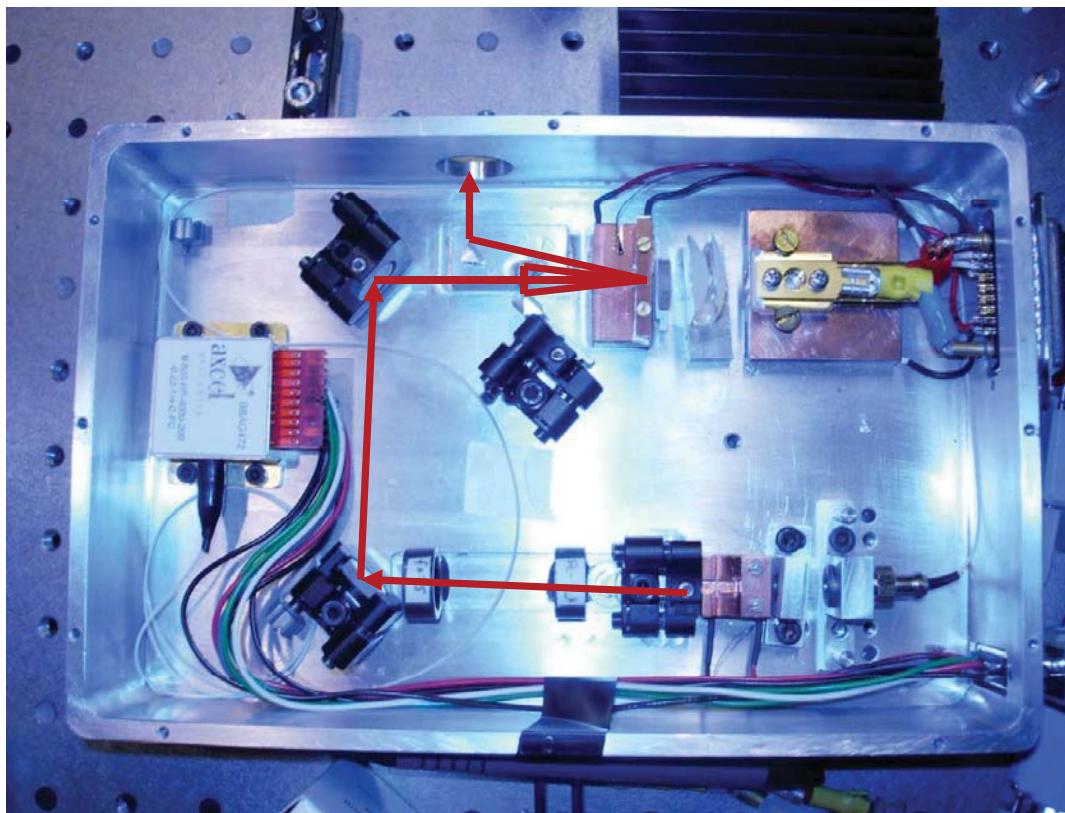


Tuning by changing PPKTP grating





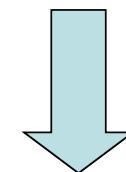
The UV-source – pump laser



At 1064 nm

$E = 400 \mu J$

$\tau = 3.5 \text{ ns}$



At 532 nm

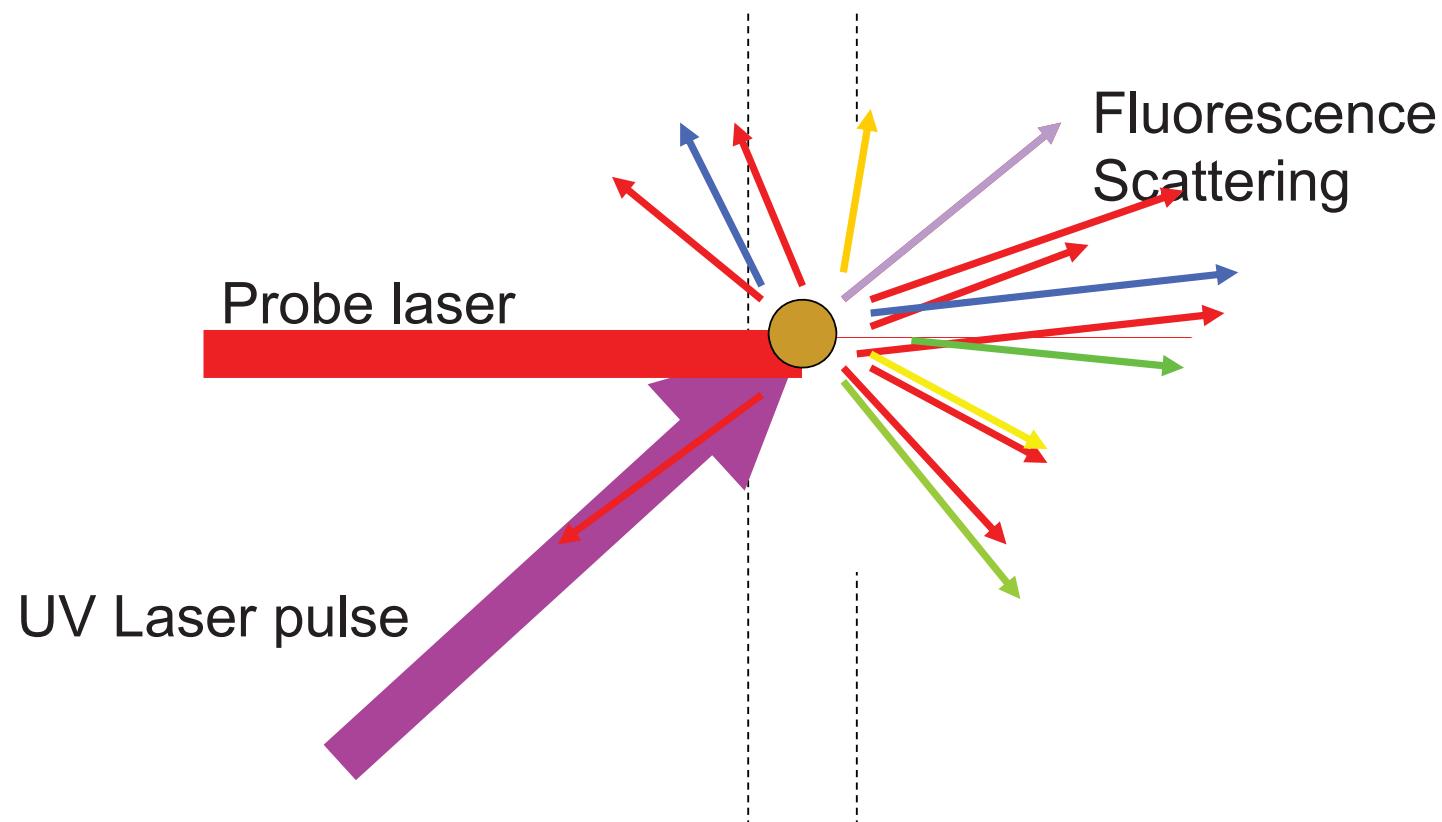
$E = 200 \mu J$

$\tau = 3.0 \text{ ns}$



Detecting bioparticles

Controlled particle beam



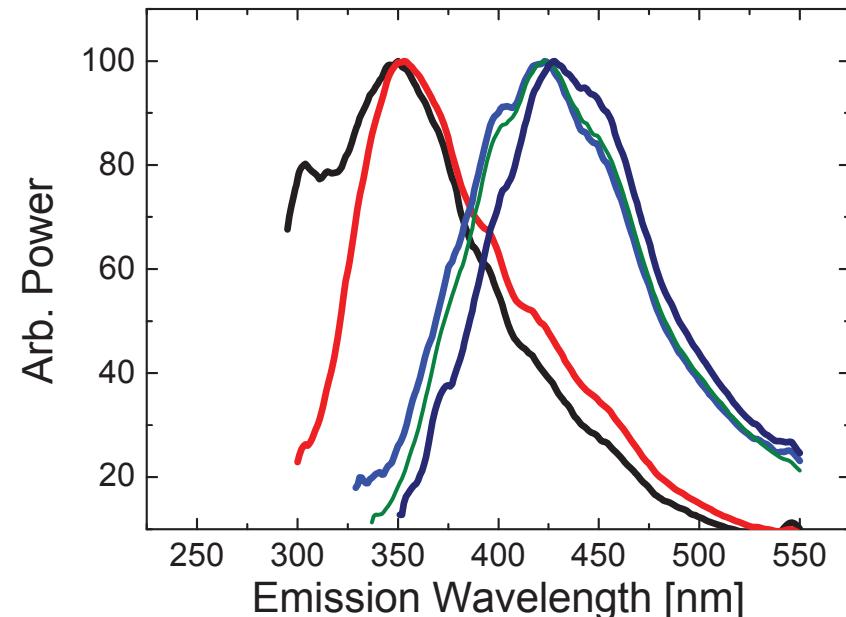
Creator: Dr. P Jonsson (FOI)



The UV source - measurements

- Fluorescence spectra:
Excitation wavelengths
285 nm - 340 nm

Penicillium Chrysogenum

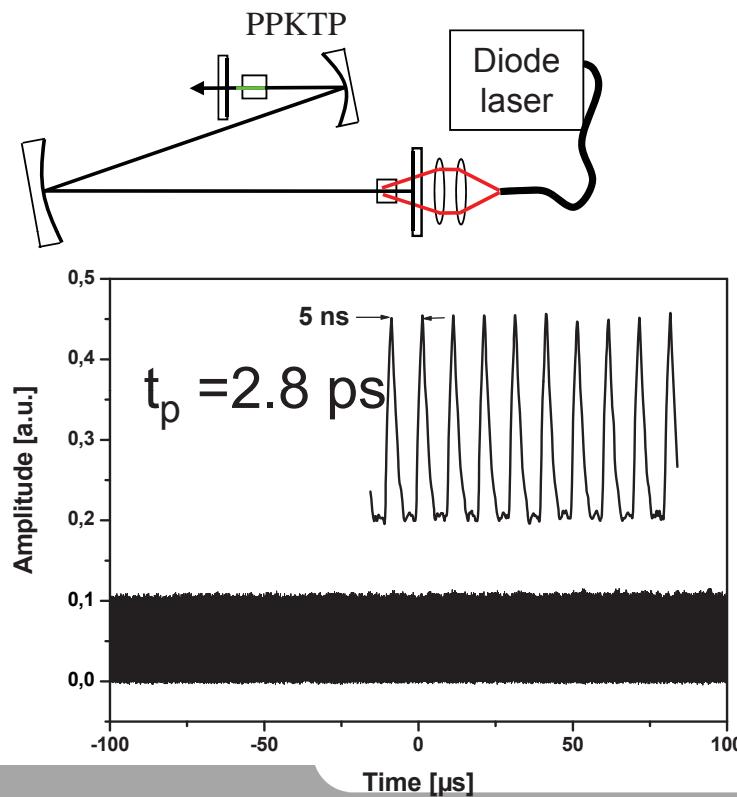


Recorded by Dr. M. Kwasny
MUT, Warsaw, Polen.

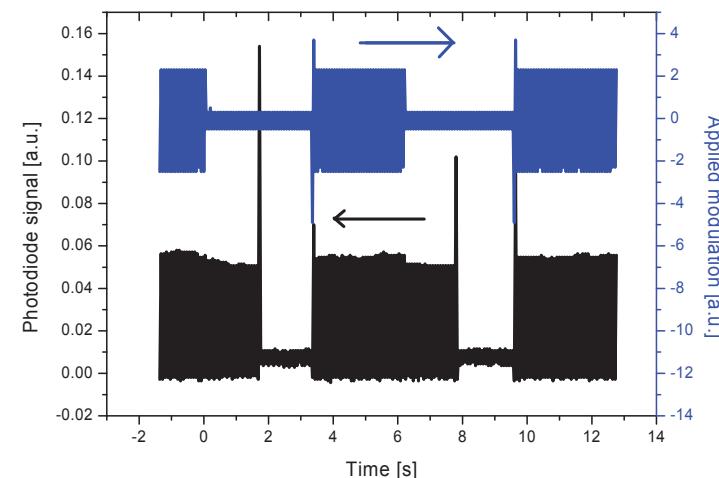
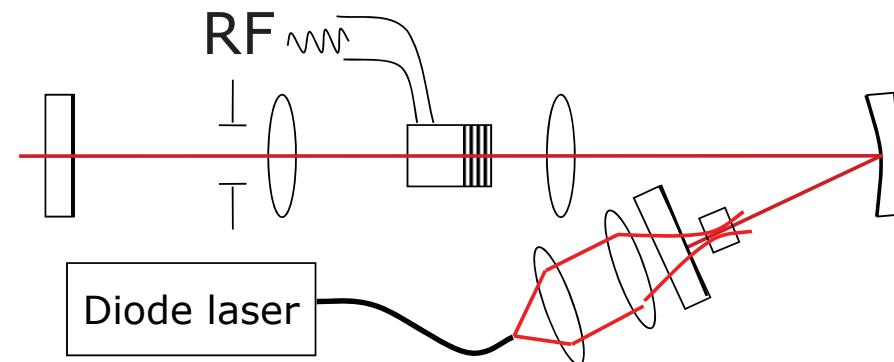


Cascaded Kerr lens mode-locking

Passively mode-locked

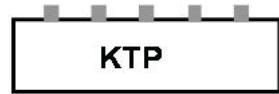


Switchable mode-locked

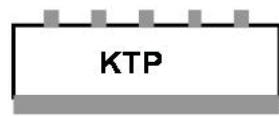




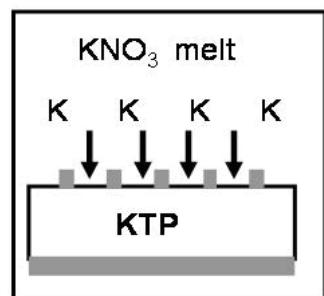
Nanogratings in KTP



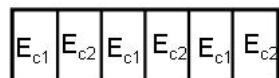
Patterned sample with deep-UV laser lithography



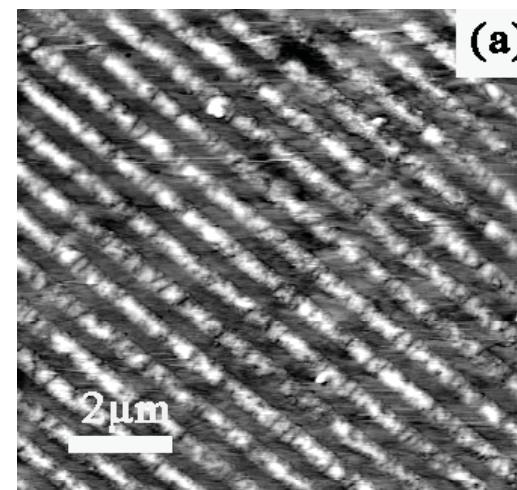
50 nm Al-deposition on the unpatterned face



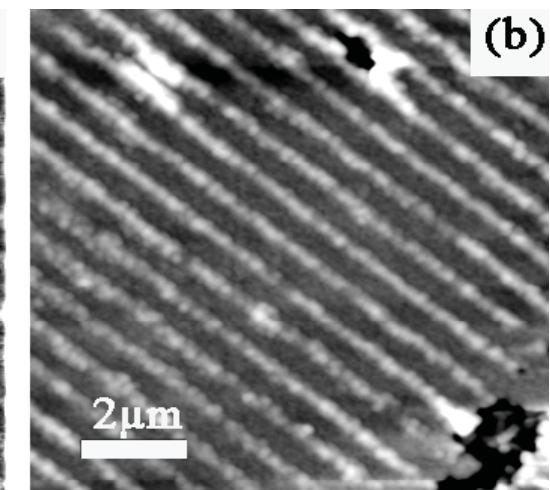
K-enrichment in a KNO₃ melt



Al removal



Former c⁺



Former c⁻

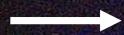
$\Lambda=720$ nm in 1mm thick KTP sample

fs and cw Backward devices



BSHG and backward parametric generation demonstrated in PPKTP with nanogratings

QPM BSHG, 398 nm



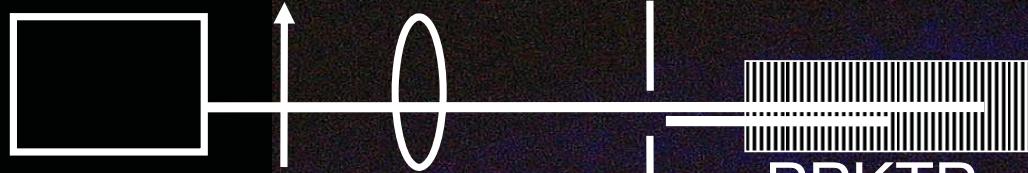
Reflection, forward non-phase-matched SHG

Pump, 795 nm fs



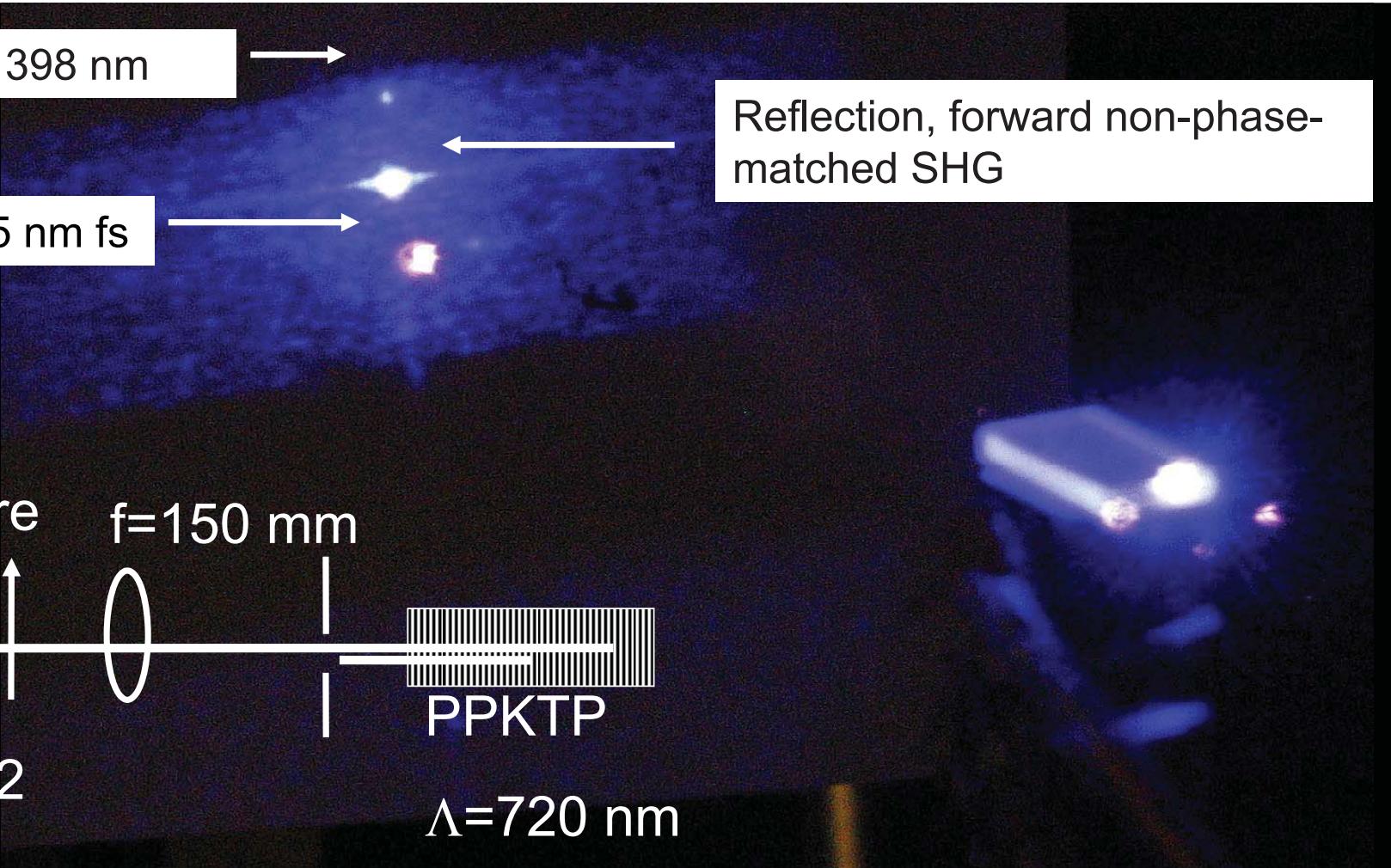
fs Ti:Sapphire

f=150 mm

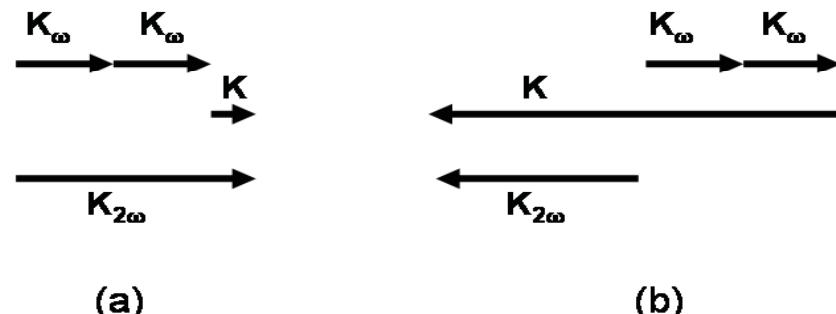


$\lambda/2$

$\Lambda=720$ nm

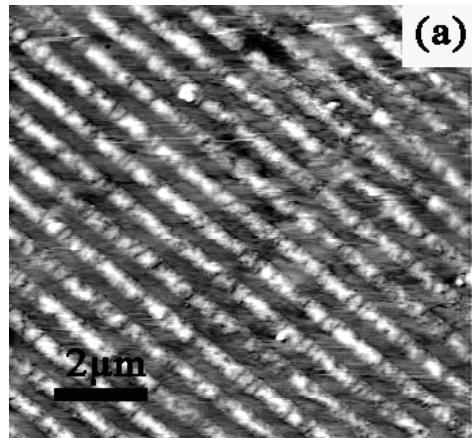


Backward SHG in PPKTP

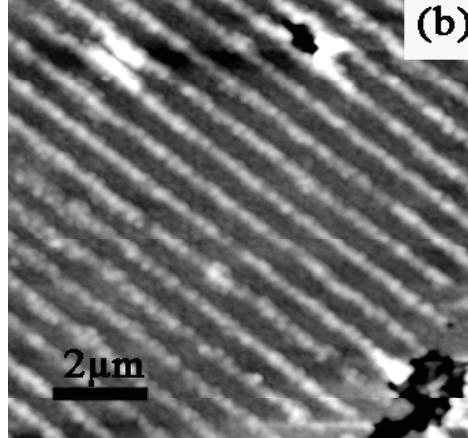


- Optical interferometric $\lambda=244$ nm lithography: $\Lambda=720$ nm
 - Poled structure 7 mm (x-propagation) x 3 mm (y) x 1mm (z -depth)
 - Aspect ratio: Thickness/Domain size = 2778

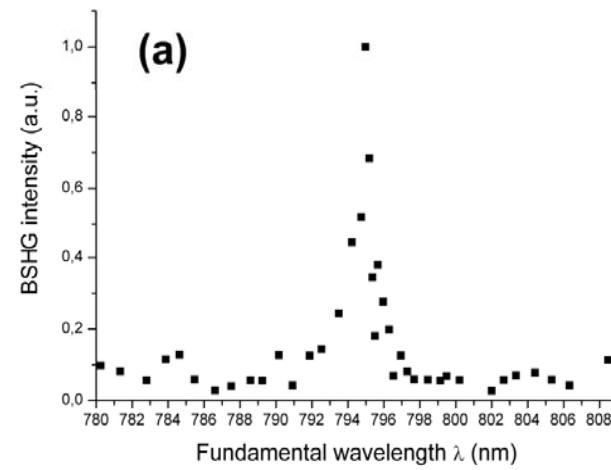
c⁺ surface



C⁻ surface



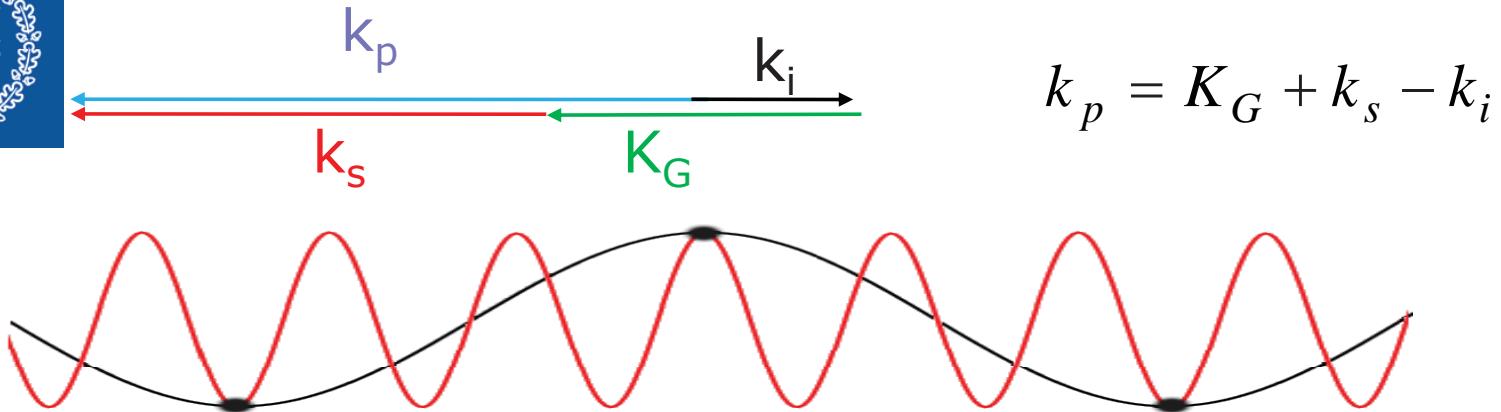
7th-order BSHG





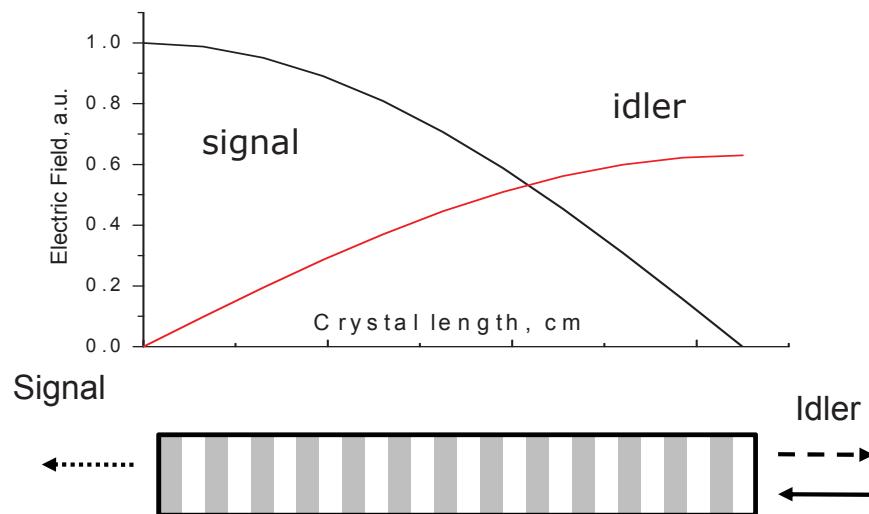
Interactions for QPM periods under μm

Idler counter-propagating TWM:



Automatically established distributed feedback

→ Mirrorless OPO





k_i

k_p

pump @ 822 nm
signal @ 1140 nm
Idler @ 2940 nm

Pump pulse= 47 ps
Idler bandwidth → 3GHz

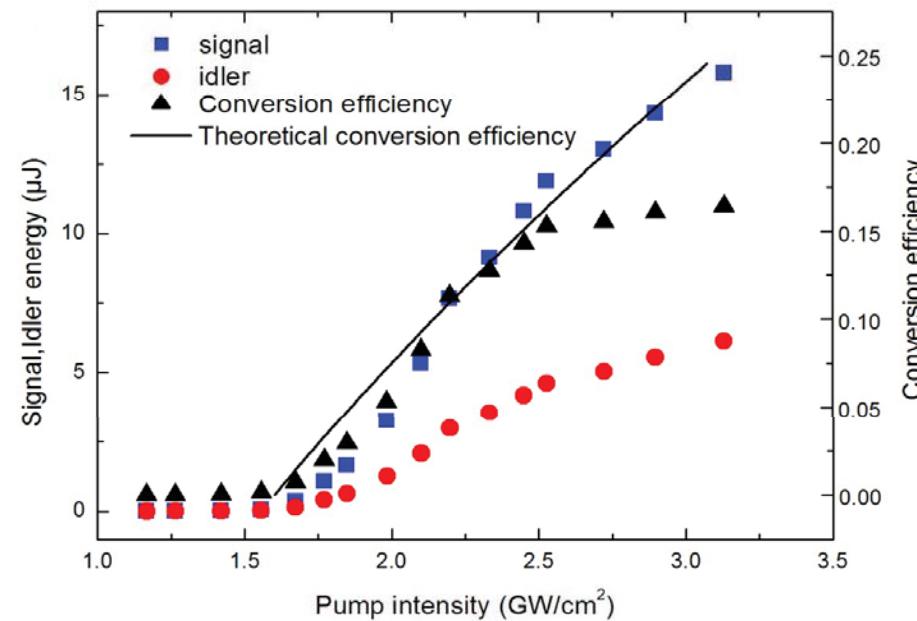
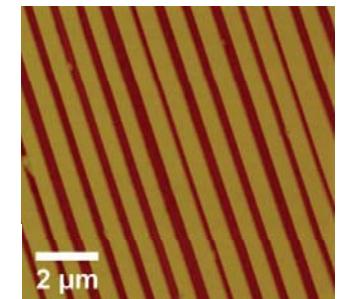
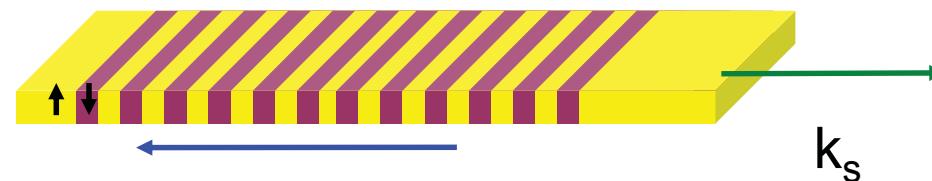
Mirrorless OPO

QPM condition:

$$k_p = K_G + k_s - k_i$$

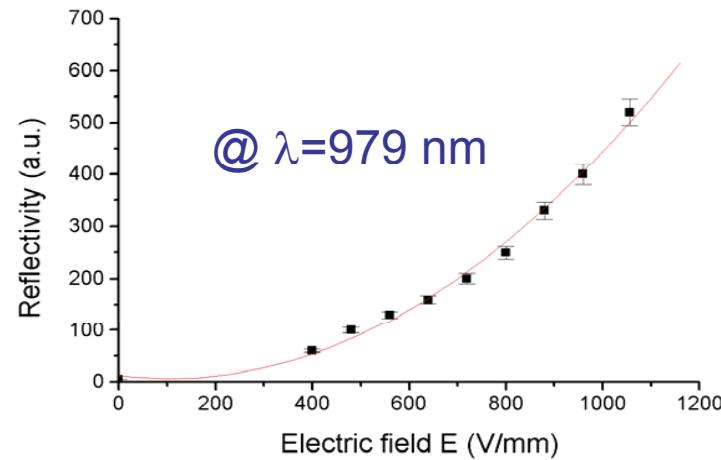
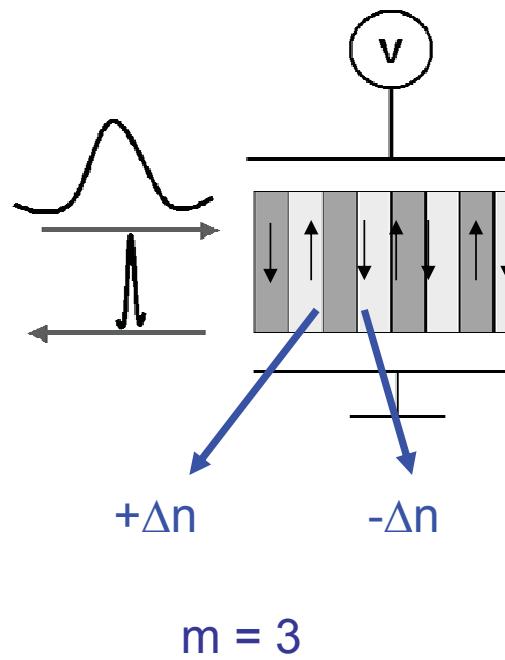
$$K_G = \frac{2\pi m}{\Lambda}$$

$$\begin{aligned}\Lambda &= 800 \text{ nm} \\ L &= 4.5 \text{ mm} \\ d_{\text{eff}} &= 7.5 \text{ pm/V}\end{aligned}$$



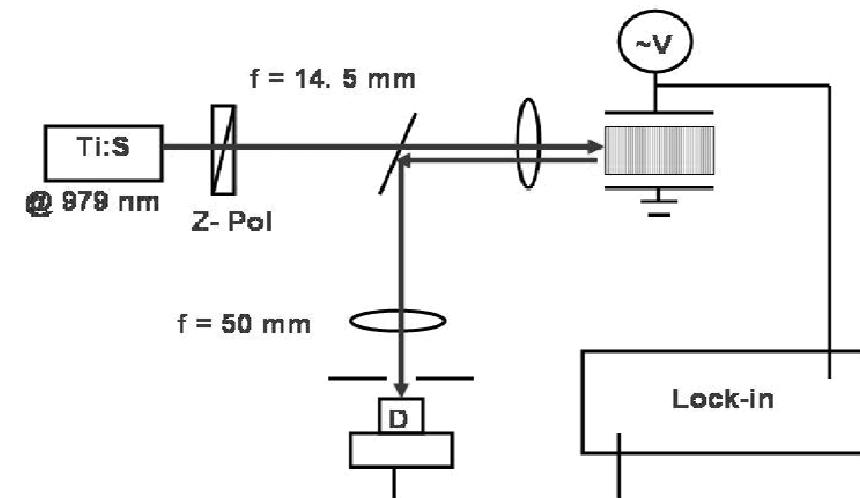


Electrically controlled Bragg reflectors



$$\Delta R = \frac{1}{4} r_{33}^2 E_3^2 n_3^4$$

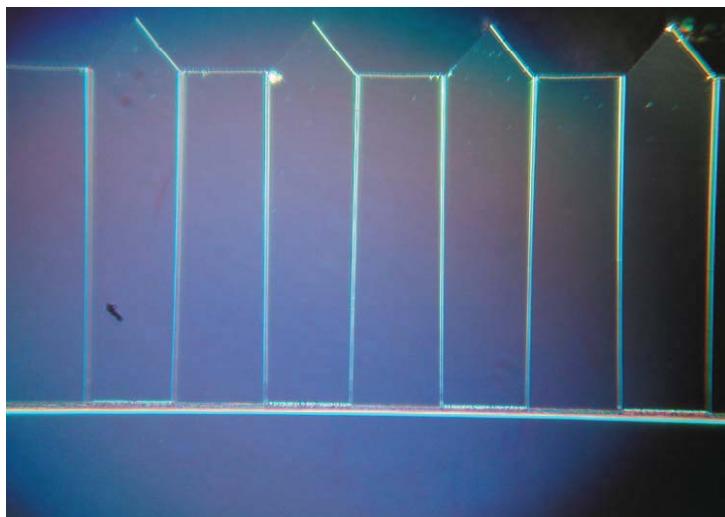
low reflectivity ($\sim 10^{-5}$), only testing 80 μ m long structure





Orientation-patterned GaAs

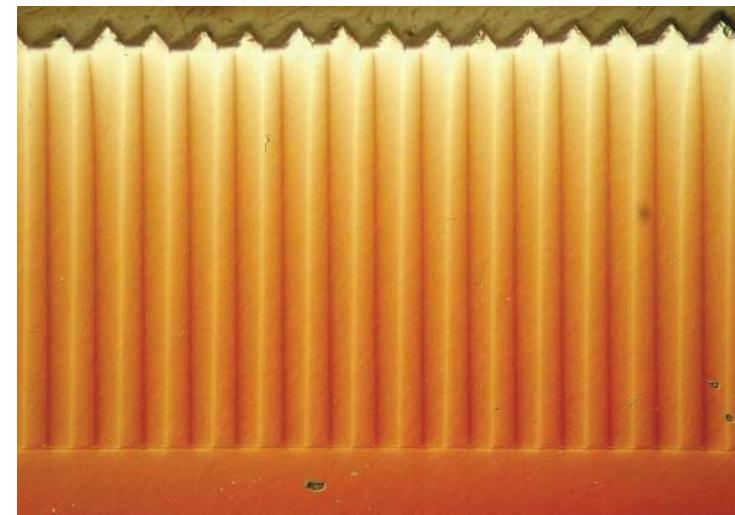
Thicker OP-GaAs samples (up to 750 μm) possible in one growth run with improved domain fidelity of shorter periods



Previous growth:

80 μm period but only 220 μm thick

- Recent thick film growths show lowest losses to date of 0.01 cm^{-1} at 2 μm wavelength
- Access to thick films at short periods with low material loss will enable pumping of OP-GaAs with near-IR lasers at 1.5 μm or 2 μm
- Thick OP-GaAs (>1mm) very nearly achieved, useful for THz generation in GaAs



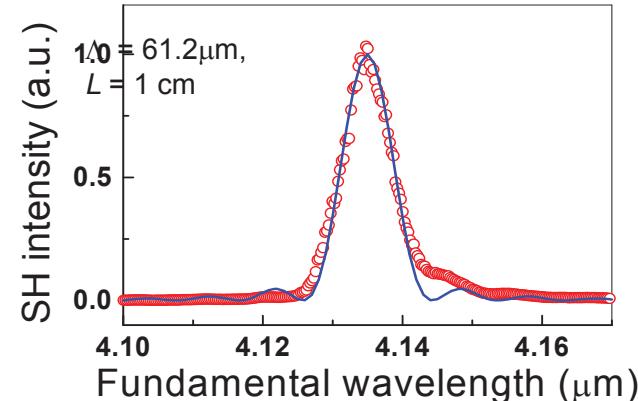
Recent growth:

80 μm period that is 700 μm thick

Devices in OP-GaAs

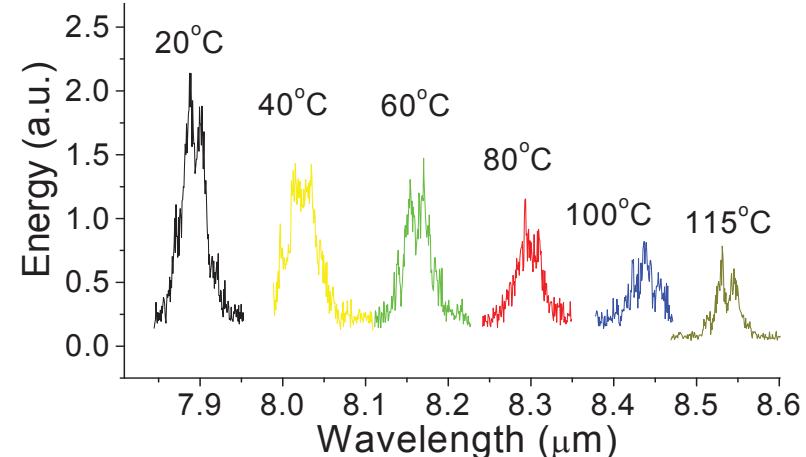


Second Harmonic Generation



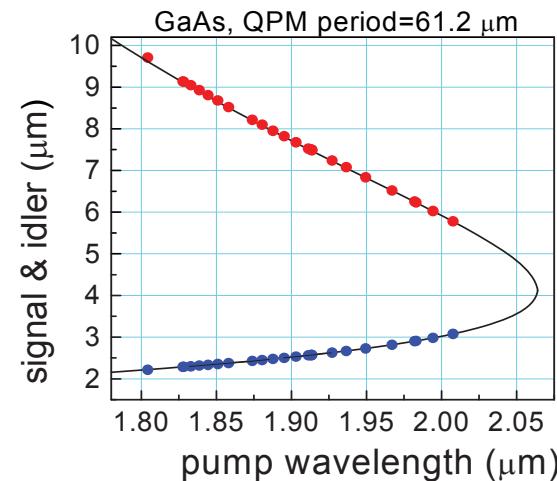
Skauli, et al., Opt. Lett. **27**, 628 (2002).

Mid-IR Different Frequency Generation



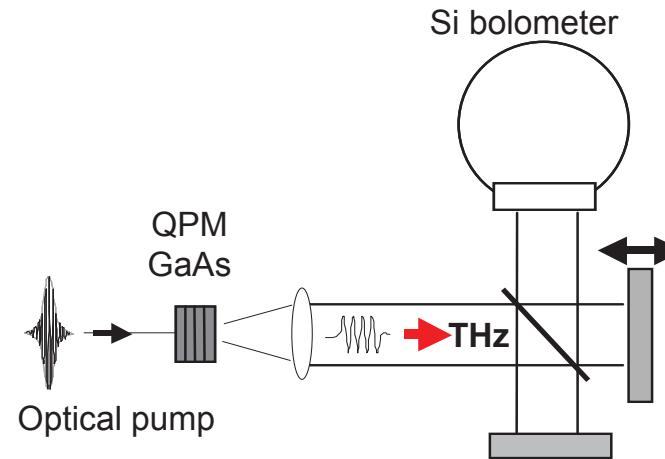
Levi, et al., Opt. Lett. **27**, 2091 (2002).

Optical Parametric Oscillator



Vodopyanov, et al., Opt. Lett. **29**, 628 (2004).

Terahertz Generation

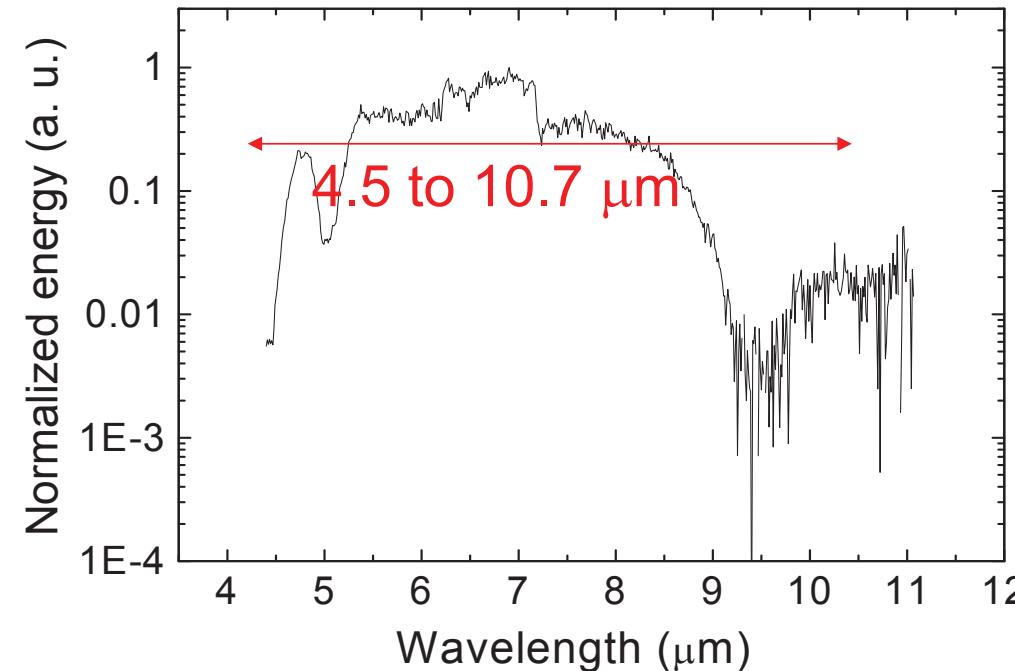


Vodopyanov, et al., Appl. Phys. Lett. **89** 141119 (2006).

OPG in Oriented Patterned GaAs

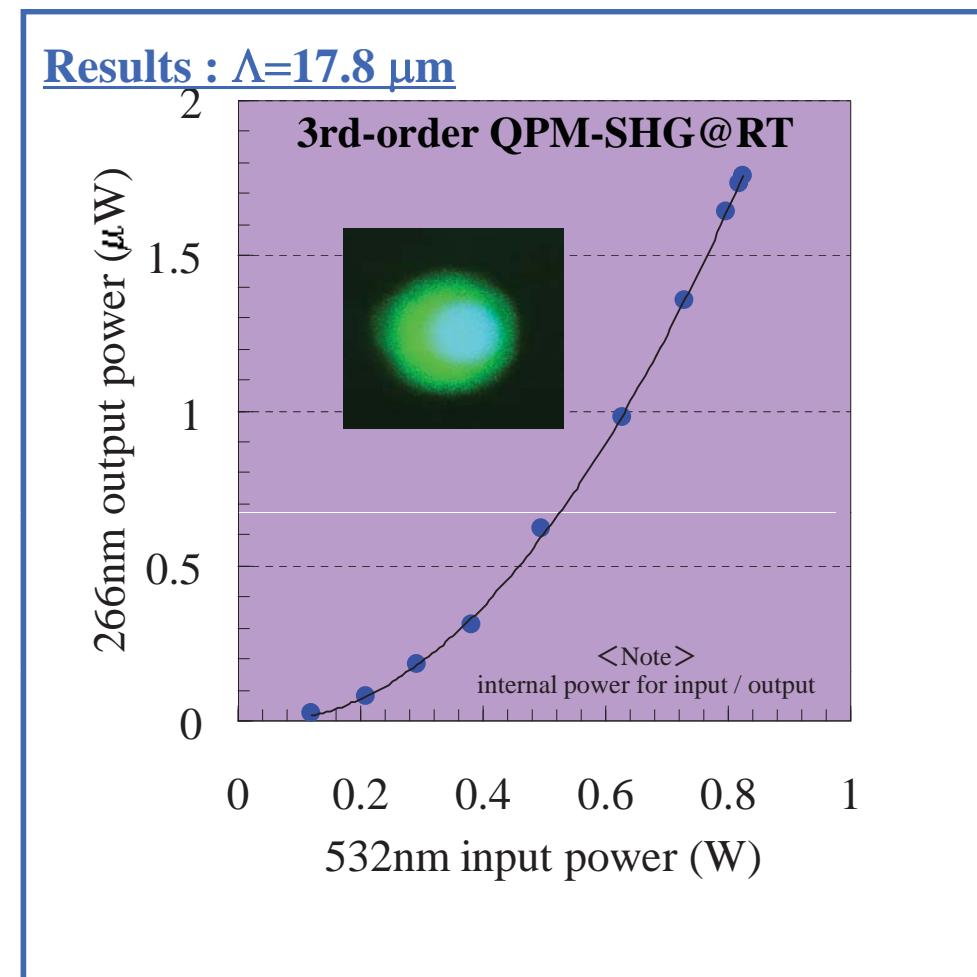
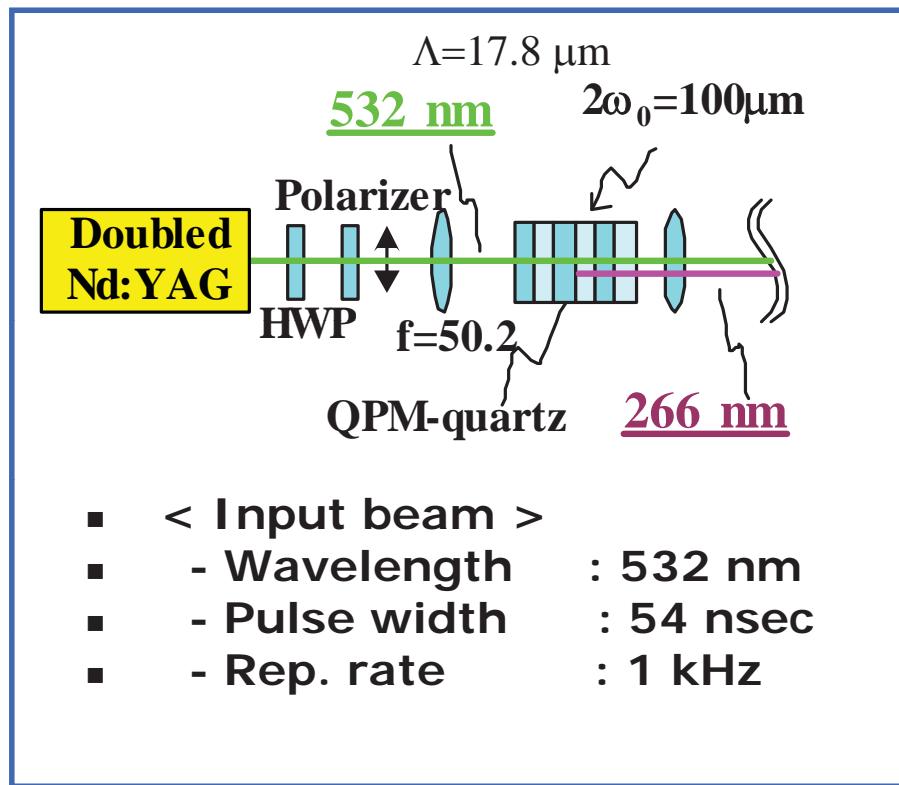


- Pumped with $3.3\mu\text{m}$, 1ps pulses, an extremely broad mid-IR spectrum was generated
- Spanned 4.5 to 10.7 microns with 55 nJ threshold and up to 15% conversion efficiency



Kuo, et al., Opt. Lett. **31**, 71 (2006).

266 nm generation in QPM quartz





Summary

- Different spectral manipulating techniques for parametric devices

In OPOs:

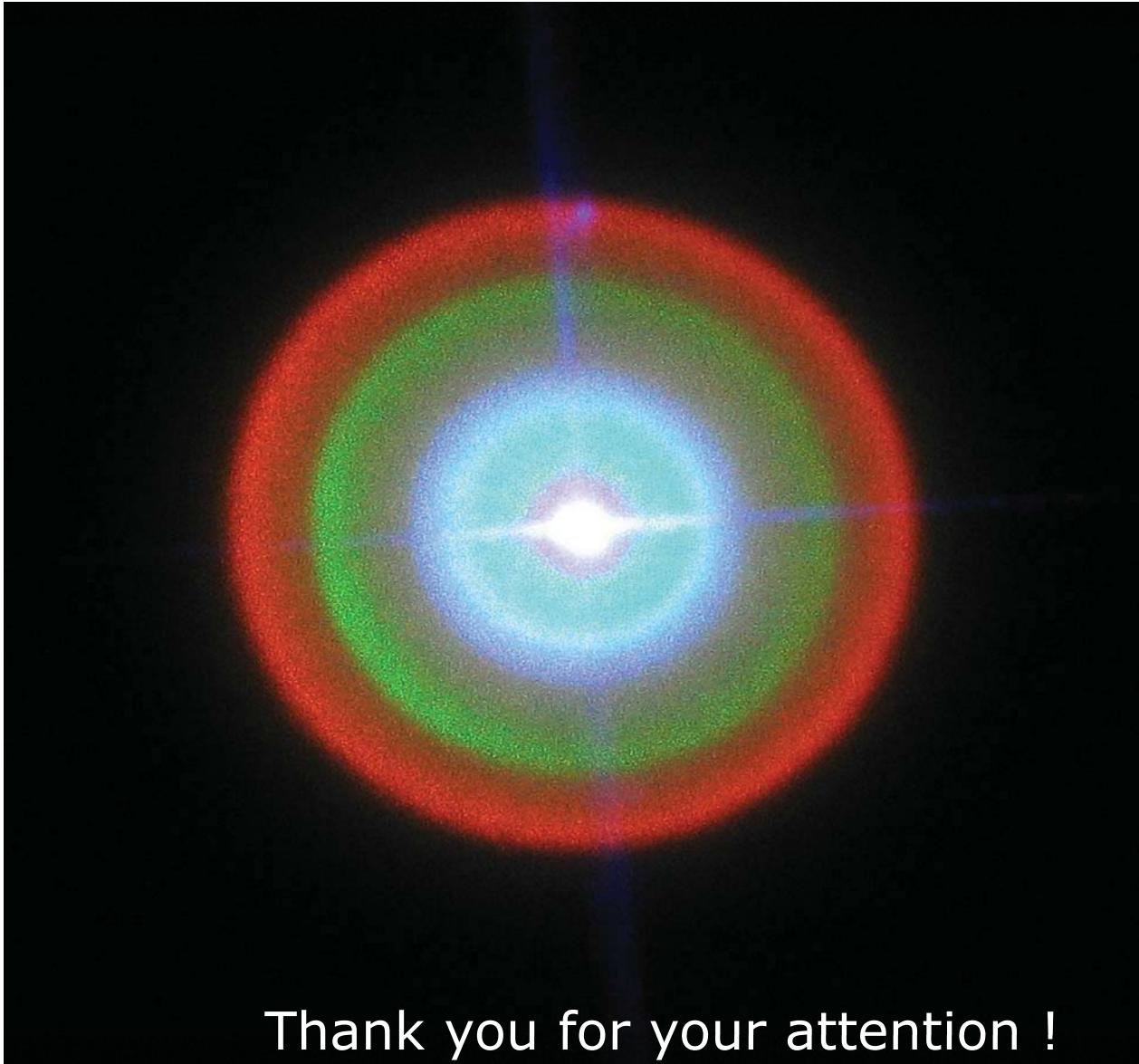
- Using the angular dispersion
- Creating 2D-structure
- Self-seeding
- Line narrowing with volume Bragg grating

In OPG and OPA:

- Point of zero-GVD
- Widely tunable OPA

- Construction of a ultraviolet laser

Used for detection of biological particles



A large, circular diffraction pattern is centered on the slide. It consists of several concentric rings of light, with colors transitioning from red on the outer edges to blue at the very center. The pattern is set against a solid black background.

Thank you for your attention !