The Abdus Salam International Centre for Theoretical Physics

2443-9

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

4 - 15 February 2013

Nonlinear optics continued - optical parametric oscillators and amplifiers

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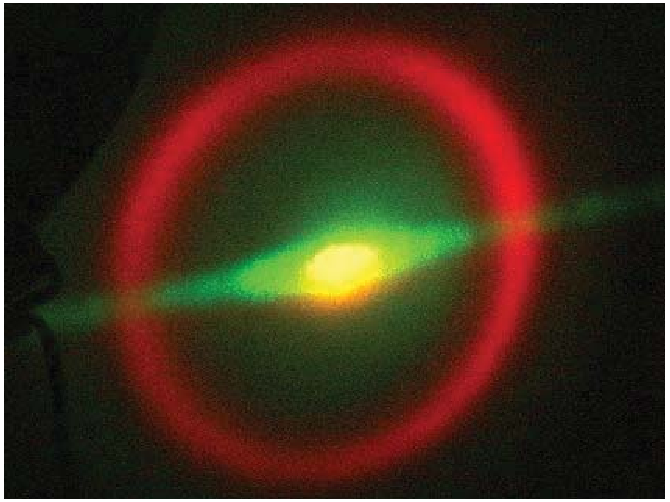
Nonlinear optics continued-

optical parametric oscillators and amplifiers

Fredrik Laurell



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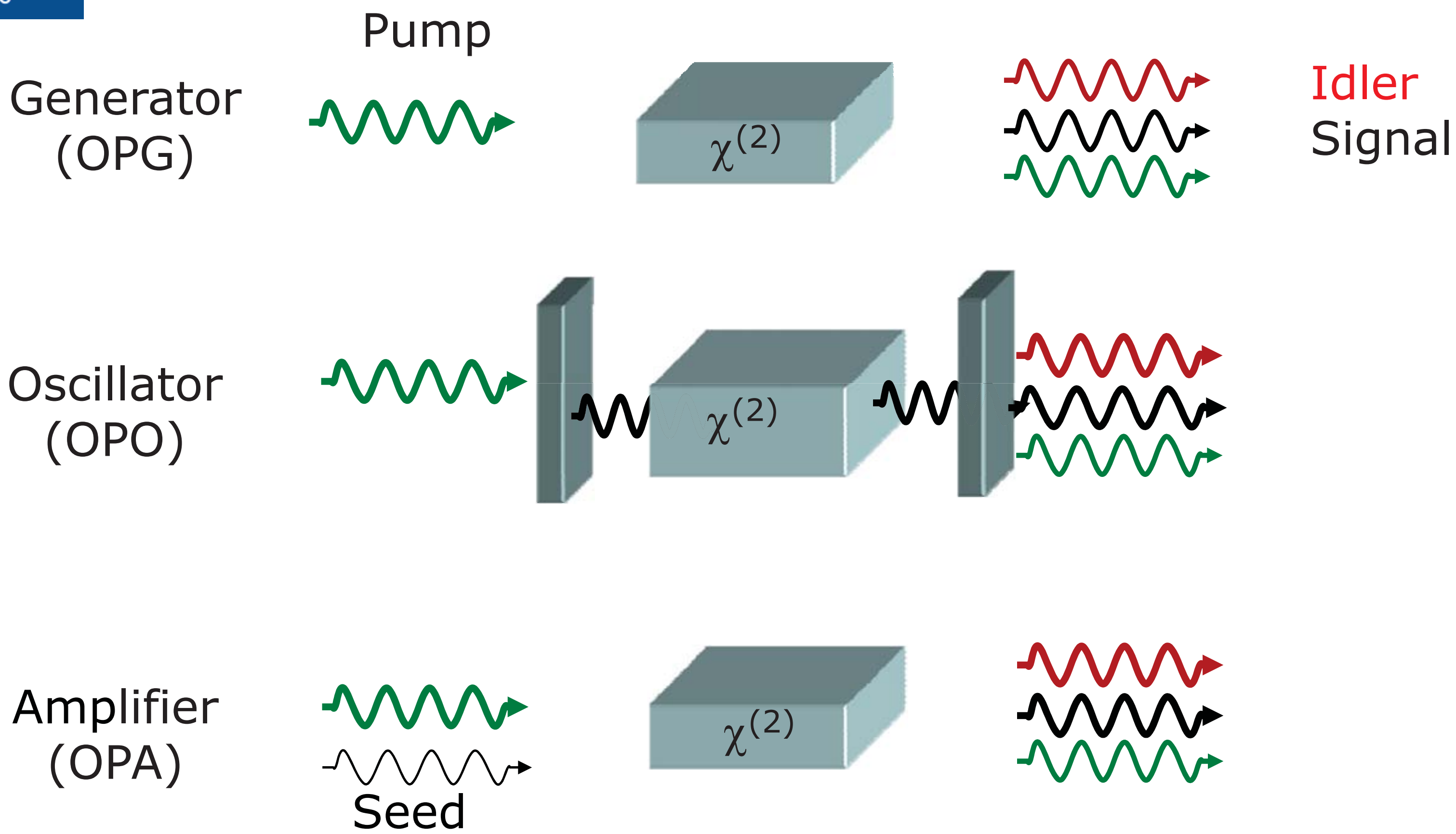
Outline

- Introduction – parametric devices
  motivation and aim
- A bit of theory
- Optical parametric oscillators
  - Singly resonant OPOs vs. doubly resonat OPOs
  - CW, pulsed operation Spectral properties
  - Generator and Amplifier - Ultra broadband generation, amplification
- applications
- Summary

Why optical parametric devices

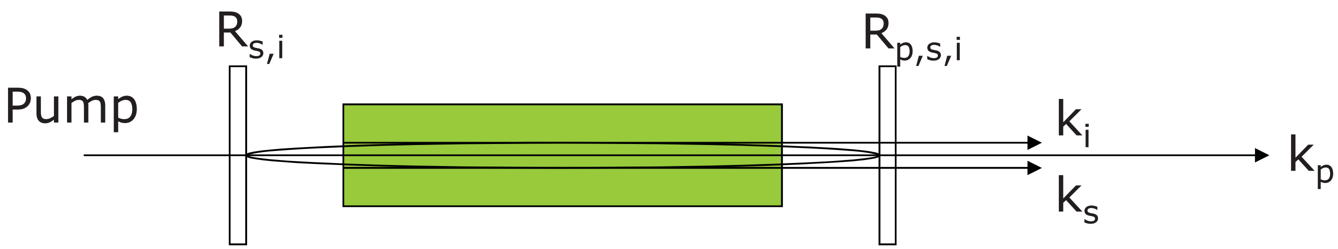
- Very wide continuous tuning from a single device, via tuning the phase-match condition
- High efficiency
- No heat input to the nonlinear medium
- No analogue of spatial-hole-burning as in a laser, hence simplified single-frequency operation
- Very high gain capability
- Very large bandwidth capability

Nonlinear processes – optical parametric devices



The Optical Parametric Oscillator

Add feedback to OPA → OPO

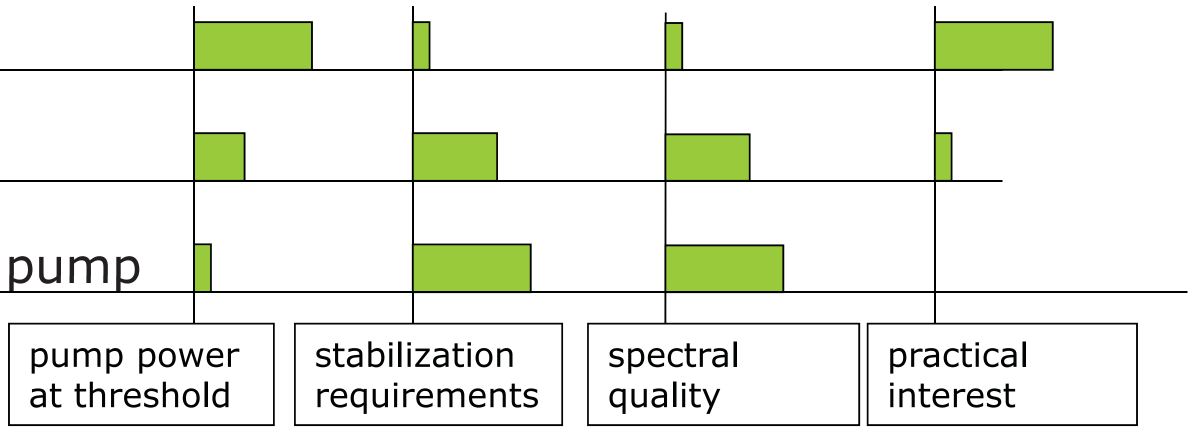


Three basic types of OPO depending on feedback:

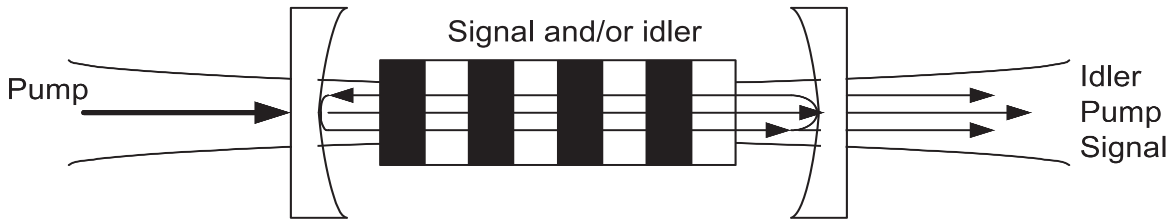
SRO - resonant signal or idler

DRO - resonant signal and idler

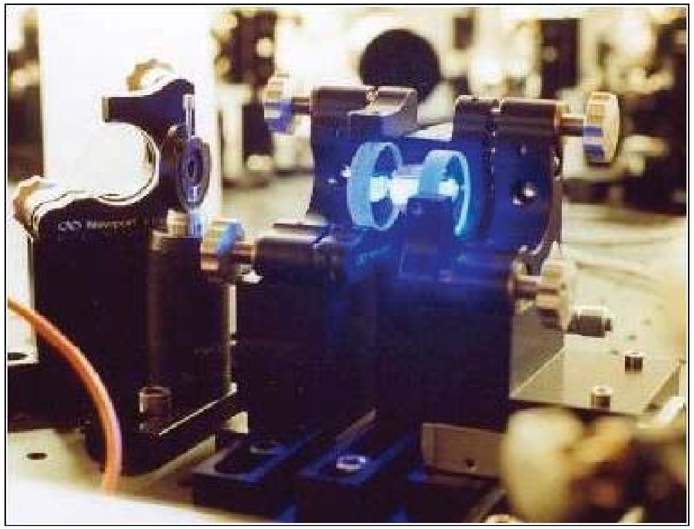
TRO - resonant signal, idler, and pump

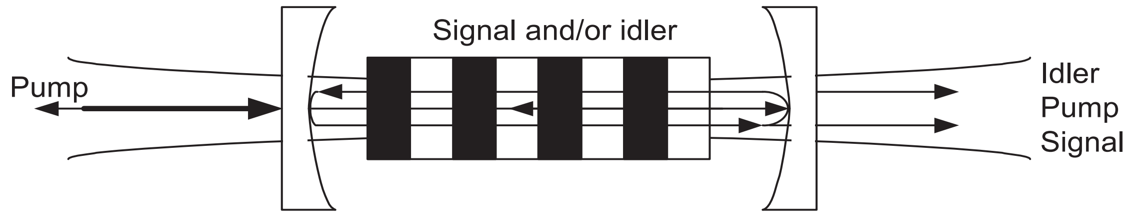


Optical parametric oscillation (OPO)



Singel or double resonant OPO
(SRO or DRO)





Back reflected pump beam,
Singel or double resonant OPO
(DPSRO or DPDRO)

Manley-Rowe relations

Integrals of the coupled equations

$$n_3|E_3(z)|^2/\omega_3 + n_2|E_2(z)|^2/\omega_2 = \text{const}$$

$$n_3|E_3(z)|^2/\omega_3 + n_1|E_1(z)|^2/\omega_1 = \text{const}$$

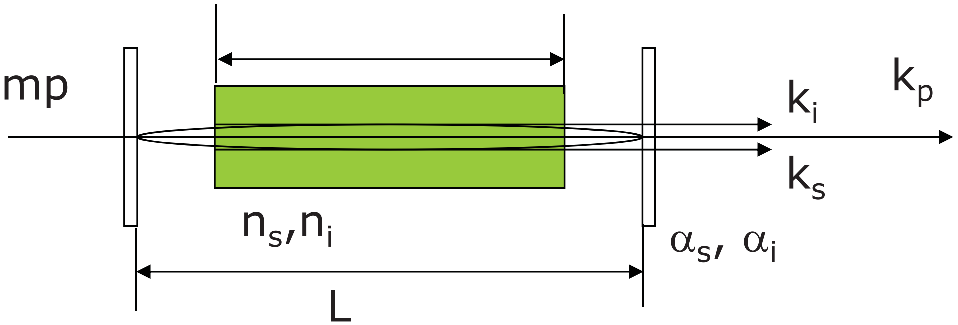
$$n_2|E_2(z)|^2/\omega_2 - n_1|E_1(z)|^2/\omega_1 = \text{const}$$

Imply

$n_3|E_3(z)|^2 + n_2|E_2(z)|^2 + n_1|E_1(z)|^2 = \text{const}$
i.e. conservation of power flow in propagation direction

Number of pump photons annihilated in the NL medium equals
The number of signal photons created,
which also equals the number of idler photons created

The resonance condition

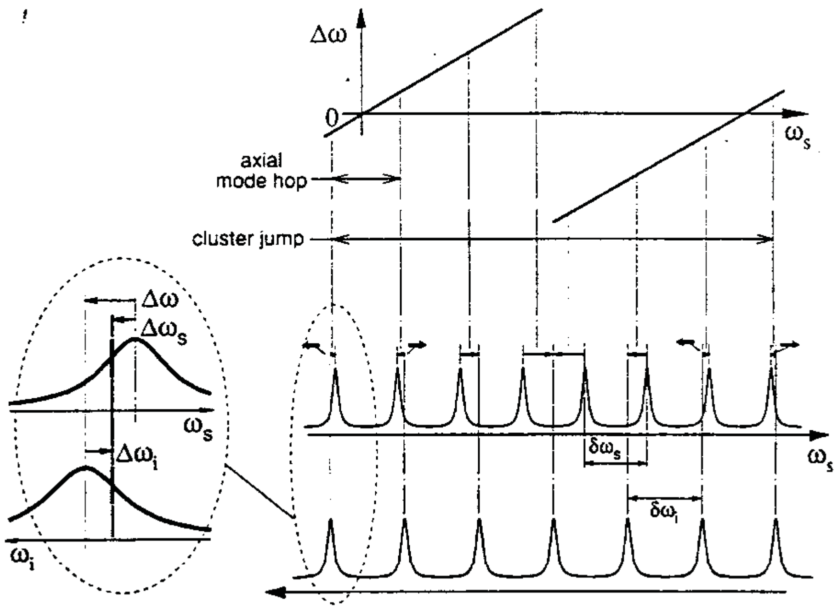


DRO is an over-constrained system, where energy conservation, cavity resonance and phase matching have to be satisfied at the same time.

Total cavity losses: α_s, α_i

Cavity finesses: $F_s \approx \frac{\pi}{\alpha_s}, \; F_i \approx \frac{\pi}{\alpha_i}$

Free-spectral range: $\delta\omega_j = \frac{\pi c}{L_j + (n_j - 1)l}$



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

$$n_p\omega_p = n_s\omega_s + n_i\omega_i$$

Cavity resonance:

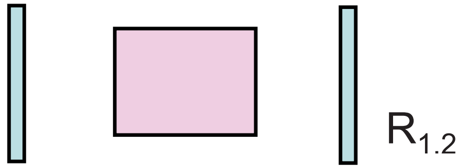
$$\omega_s = \frac{m_s c\pi}{L_s + (n_s - 1)l}, \quad \omega_i = \frac{m_i c\pi}{L_i + (n_i - 1)l}$$

The OPO threshold

Represent round-trip power loss by one cavity mirror having reflectance R_1 (idler), R_2 (signal)

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

$$n_p \omega_p = n_s \omega_s + n_i \omega_i$$



Threshold → round-trip gain = round-trip loss

(for signal only, SRO, for signal and idler, DRO)

If $\Delta k = 0$, threshold condition
(assuming pump, signal & idler phases $\Phi_3 - \Phi_2 - \Phi_1 = -\pi/2$ at input to crystal)

$$\cosh \Gamma L = \frac{1 + (R_1 R_2)^{1/2}}{R_1^{1/2} + R_2^{1/2}}$$

OPO threshold: SRO vs DRO

For SRO, $R_1 = 0$ ⇨ $R_2 \cosh^2 \Gamma L = 1$

If $1 - R_{1,2} << 1$

SRO ⇨ $\Gamma^2 L^2 = 1 - R_2$

DRO ⇨ $\Gamma^2 L^2 = (1 - R_2)(1 - R_1) / 4$

Advantage of DRO is low threshold:

Example:

DRO with $R_1 = 98\%$

$$\frac{SRO_{threshold}}{DRO_{threshold}} = 200 \quad \text{for } 1 - R_1 = 0.02$$

Consequences of phase relation between pump, signal, idler

- If more than one wave is fed back in an OPO is the phase condition over-constrained
- Double- or multiple pass amplifiers can also suffer similar problems
- The fixed value of relative phase φ_3-φ_2-φ_1, can be exploited to achieve self-stabilisation of carrier envelope phase (CEP)
- In a SRO, the relative phase of pump and signal are not determined, hence the signal selects the cavity resonance frequency

Stability:
comparison of SRO and DRO

SRO: No idler input. Gain does not depend on pump/signal relative phase.
Signal frequency free to choose a cavity resonance;
Idler free to take up appropriate frequency and phase. Signal frequency stability depends on cavity stability and pump frequency stability.

DRO: Cavity resonance for both signal & idler generally not achieved;
Overconstrained
Signal/idler pair seeks compromise between cavity resonance and phase-mismatch;
large frequency fluctuations

Plane-wave, phase-matched, parametric gain

If gain is small, ($G_2(L) << 1$) , gain increment is

$$\Gamma^2 L^2 = \frac{2\omega_1\omega_2 |d|^2 I_3}{n_1 n_2 n_3 \varepsilon_0 c^3}$$

Note: incremental gain proportional to pump intensity

~ proportional to ω_3^2

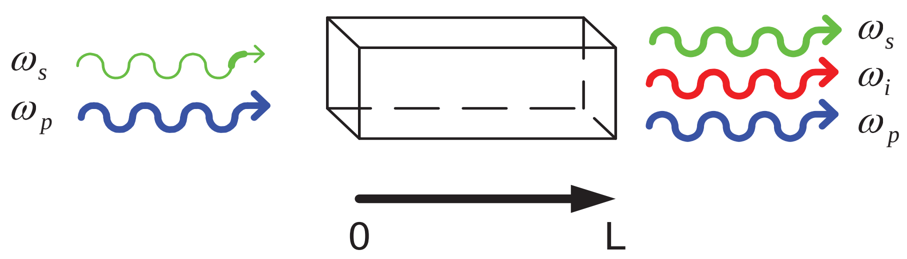
proportional to d^2 / n^3 (NL Figure Of Merit)

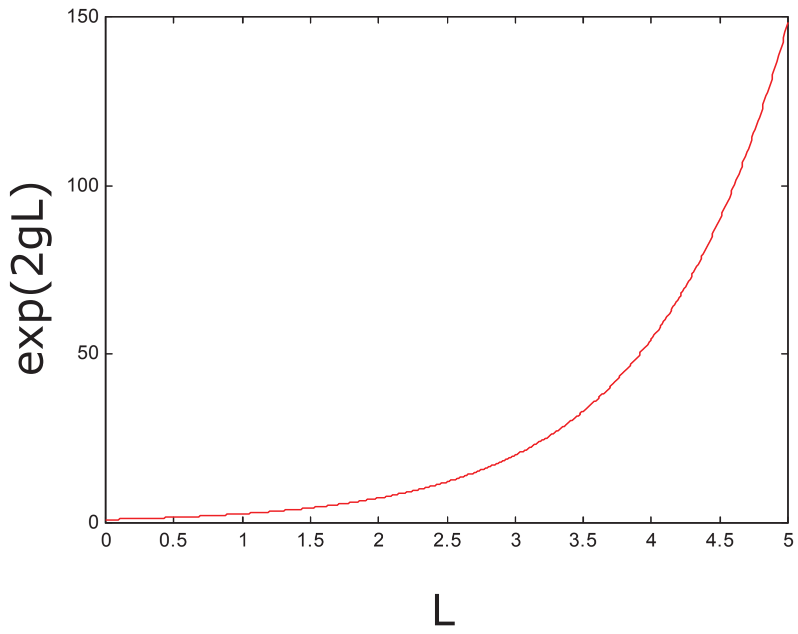
Optical parametric amplification (OPA)

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

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

$\Delta k=0$





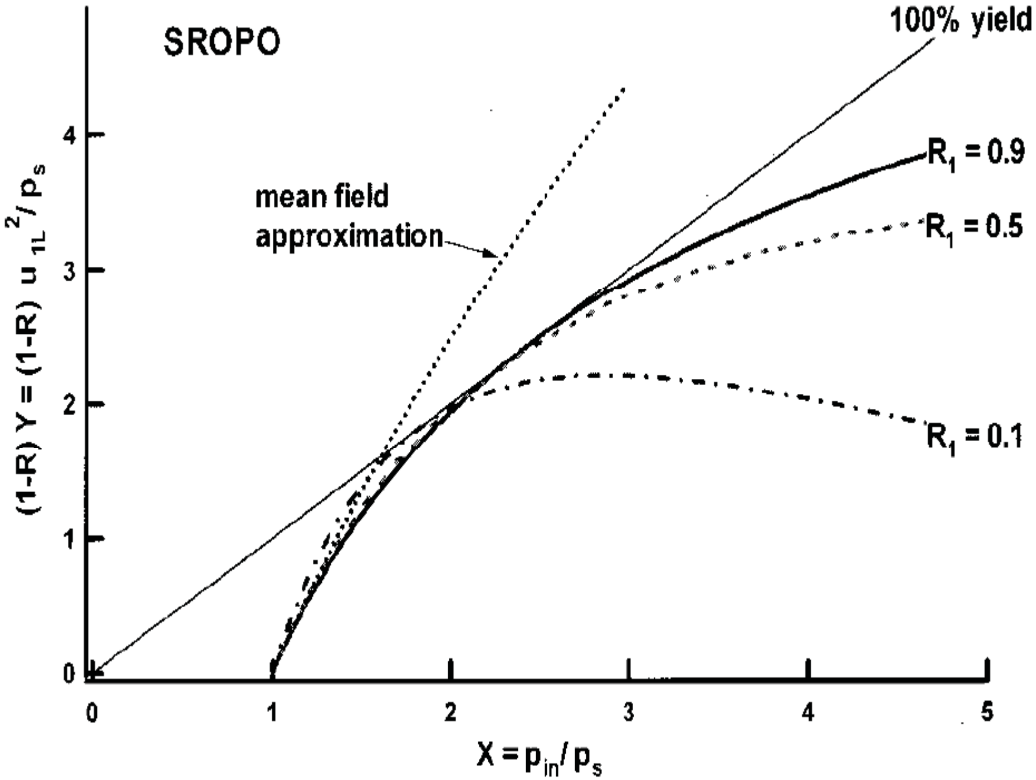
Typical OPO conversion efficiencies

Normally high conversion efficiency (>50%) obtained at 2-3x threshold

Initial slope efficiency >100% typical

Pumping appr. 3-4 x threshold
results in reduced efficiency
back-conversion of signal/idler to pump

Unlike lasers, OPOs do not have competing pathways for loss of pump energy

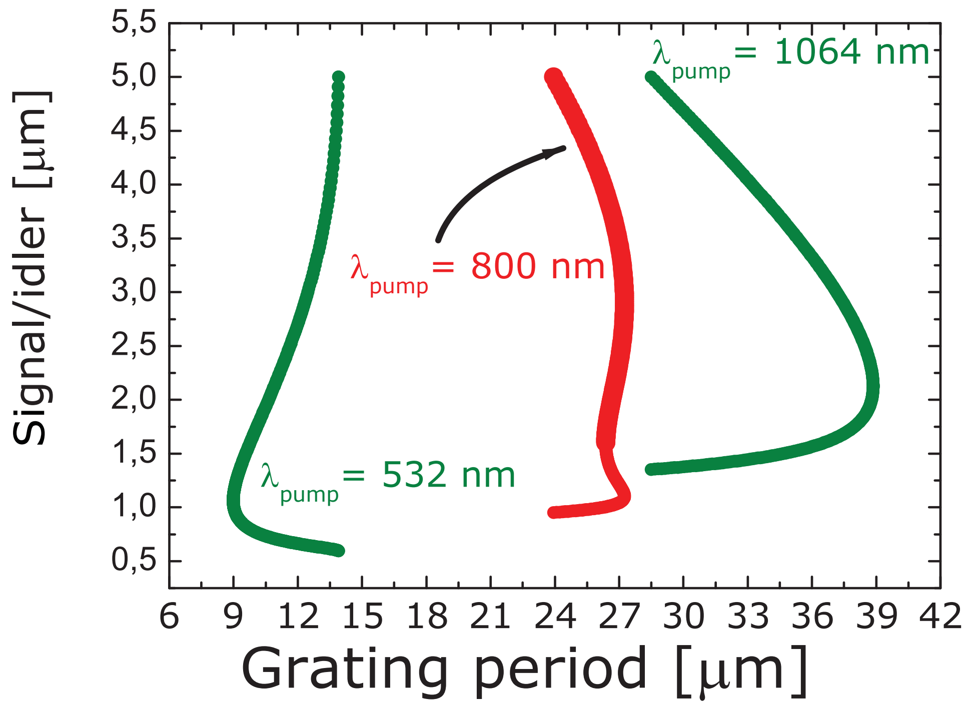


(p_s is normalised pump threshold intensity)

Rosencher & Fabre, JOSA B, 19, 1107, 2002

Quasi-phase matching for OPOs

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



OPO configurations

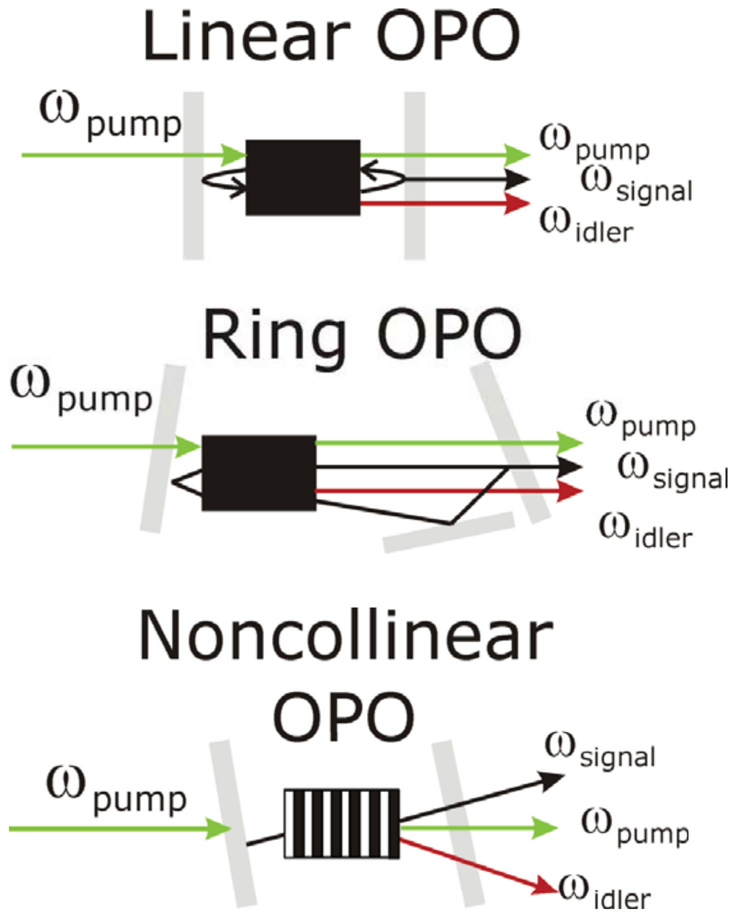
Advantages with nanosecond QPM-OPOs

Low threshold

Increased interaction length

Spatial filtering => better M^2 than the pump.

Easy tunability



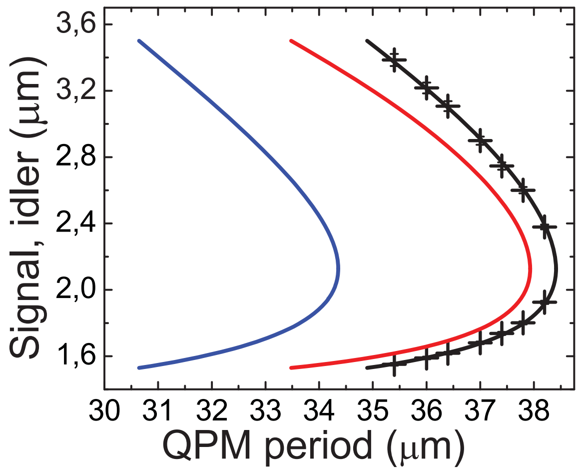
Quasi-Phase-Matching
OPO Tuning Techniques

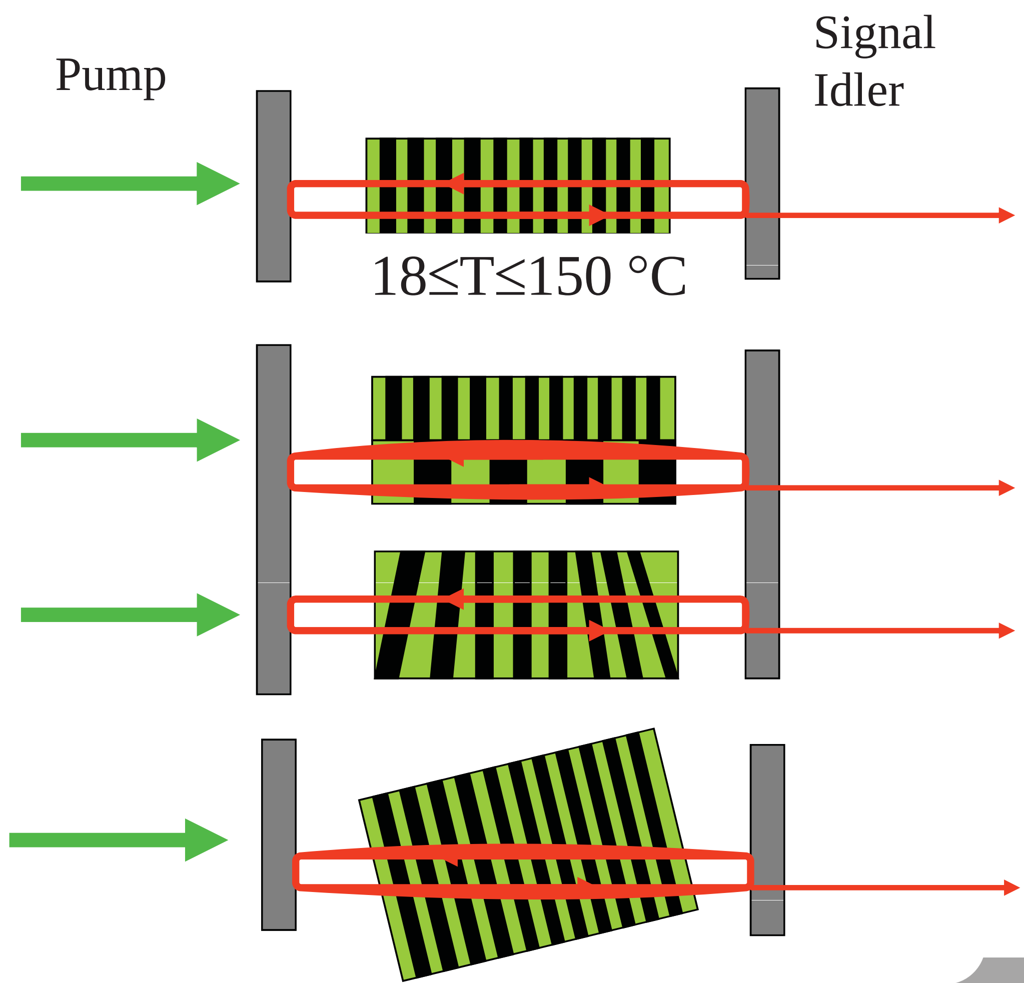
Temperature tuning

Multigrating structures

Fanned grating

Non-collinear configuration

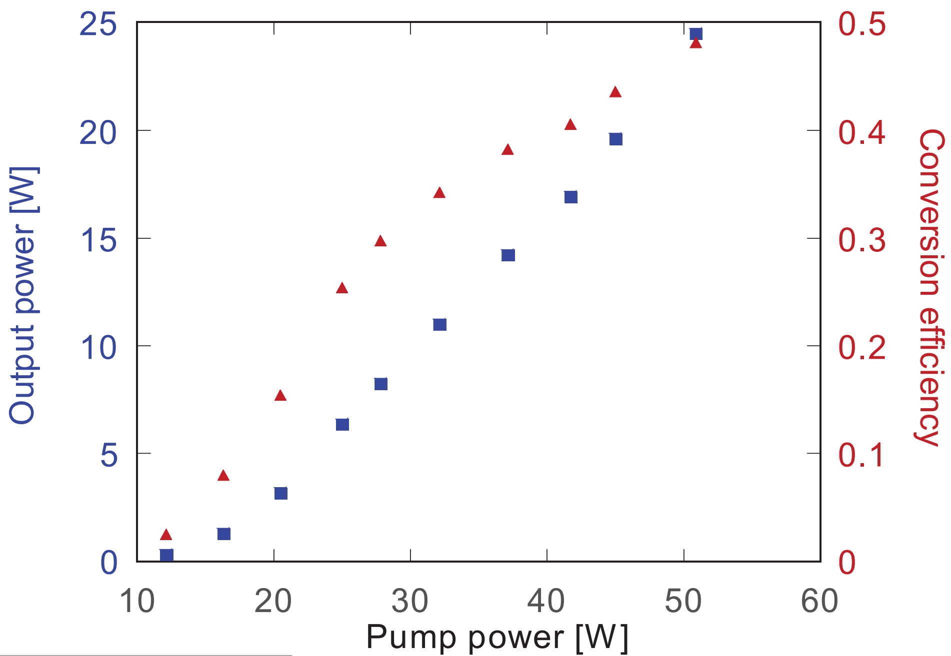


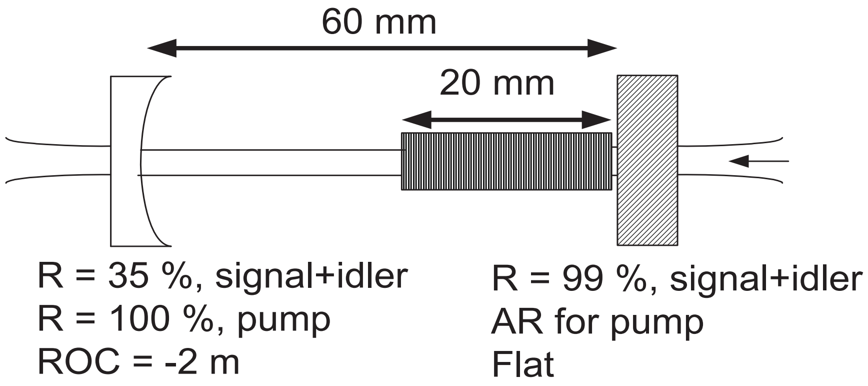


High repetition rate DRO

3 mm thick PPKTP OPO pumped at 1064 nm, signal at 1.5 μm

Pump laser: (Mitsubishi Electric Corporation)
Diode pumped, Q-switched, Nd:YAG laser
$f_{rep.\ rate}$ = 15 kpps, 60 kHz, τ = 40 ns (FWHM), M^2 = 1.1





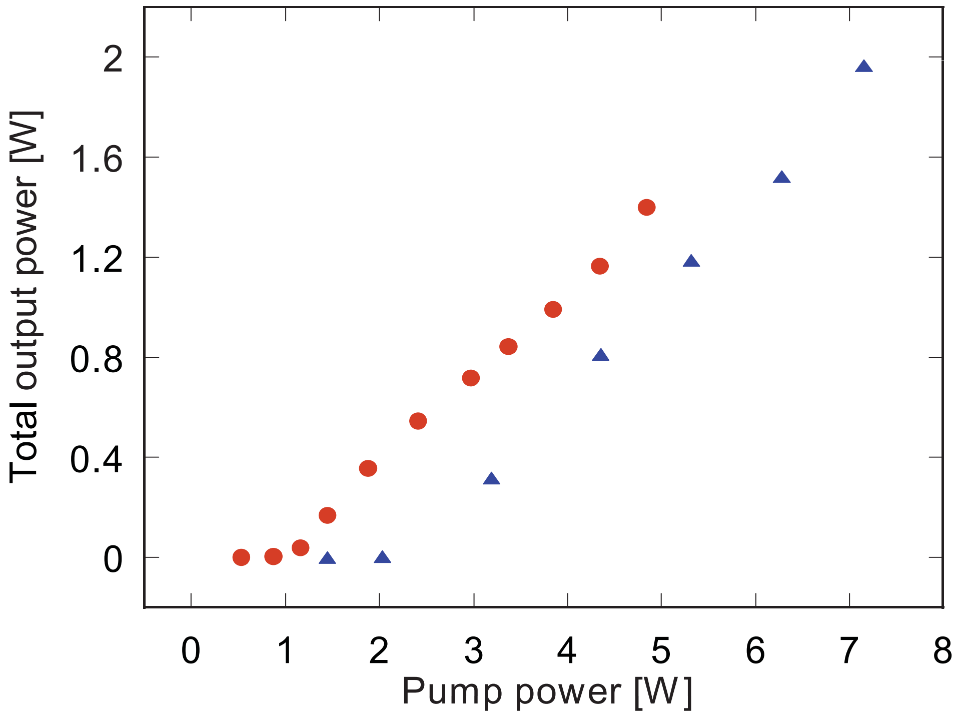
w_0 = 0.25 mm

η = 48 %

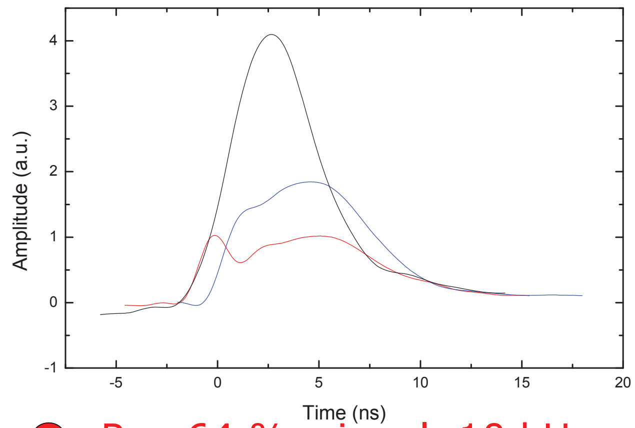
$P_{out,max} \approx$ 24 W

SRO high repetition rate

3 mm PPKTP OPO pumped with ns pulses at 1064 nm, signal at 1.5 μm



Depletion of the pump



● R = 64 %, signal, 10 kHz

▲ R = 64 %, signal, 20 kHz

Conversion efficiency

η_{20kHz} = 28 %

η_{10kHz} = 28 %

$P_{out,max} \approx 2$ W

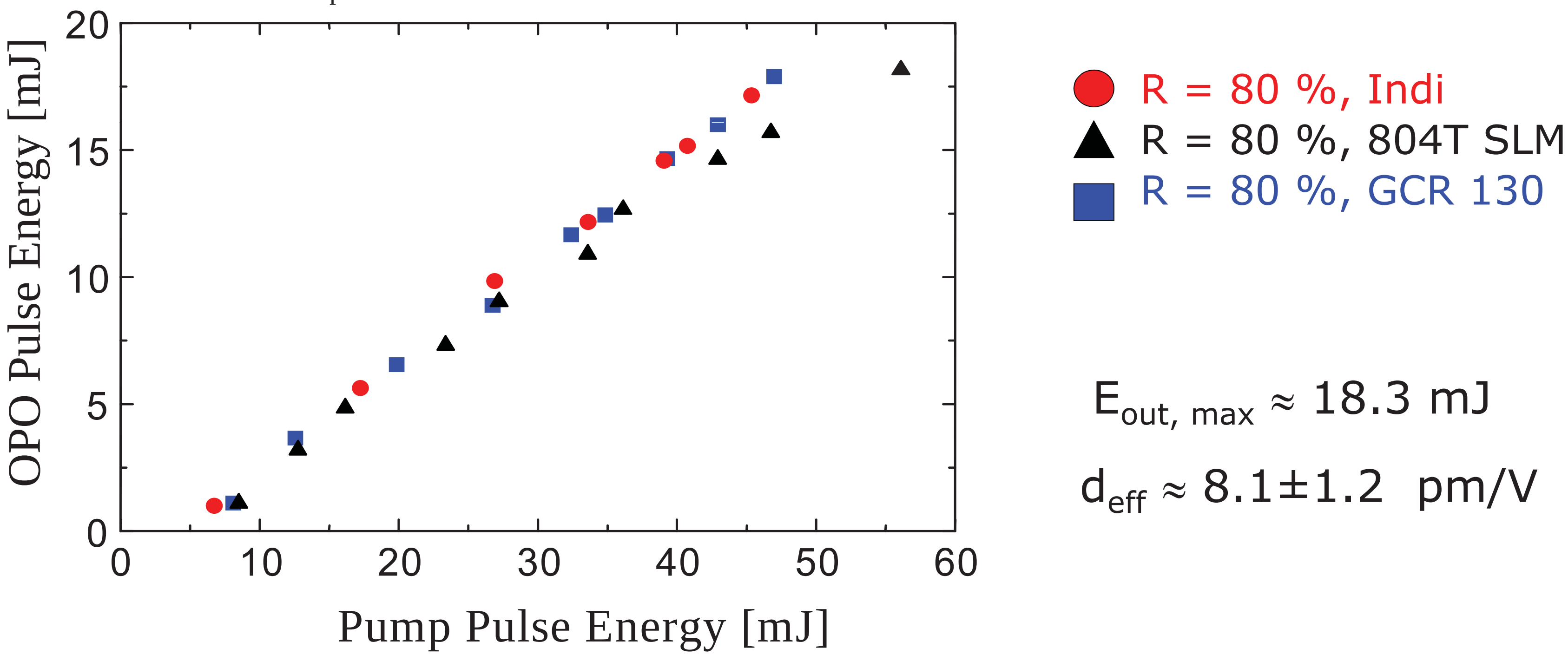
$d_{eff} \approx 8.0$ pm/V

SRO low repetition rate

3 mm thick PPKTP OPO pumped at 1064 nm, signal at 1.5 μm

Flash-lamp pumped, Q-switched, Nd:YAG lasers

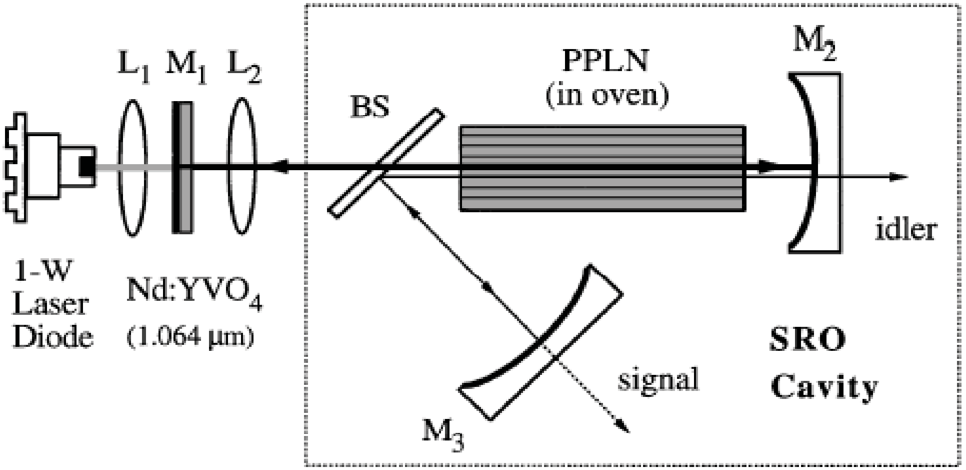
$f_{rep.\ rate}$ = 10 Hz, τ = 5 - 11 ns (FWHM), w_0 = 1.1 - 1.3 mm (radius)

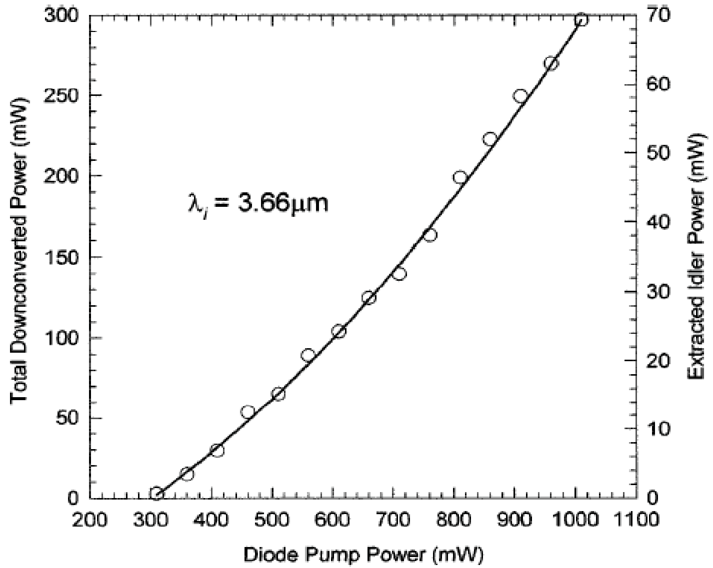


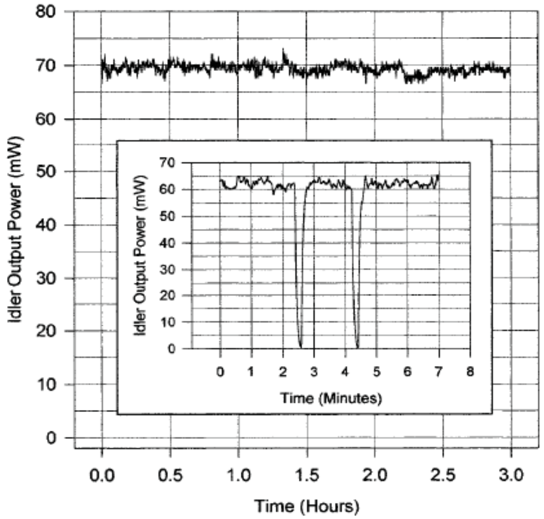
$E_{out,\ max} \approx$ 18.3 mJ

$d_{eff} \approx$ 8.1±1.2 pm/V

Intracavity CW-SRO







- 50 mm PPLN, w=70 µm
- M2 – HR for pump
- M2 - M3 – Hi-Q cavity for signal

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[D.J.M. Stothard etal Opt. Lett **23**, 1895 (1998)]

Tuning singly-resonant OPOs

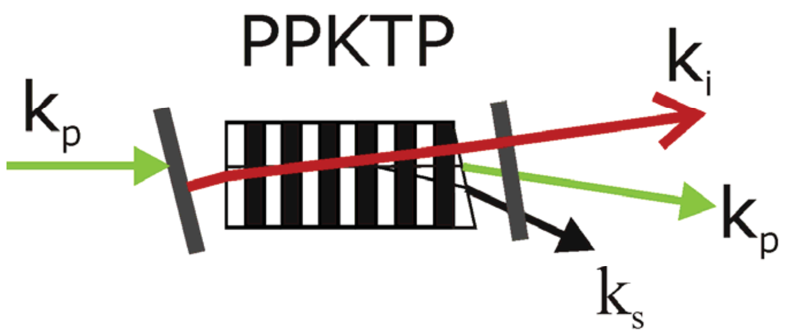
Manipulating the QPM-crystal

- Temperature
- Multigrating structures
- Fanned gratings
- rotation

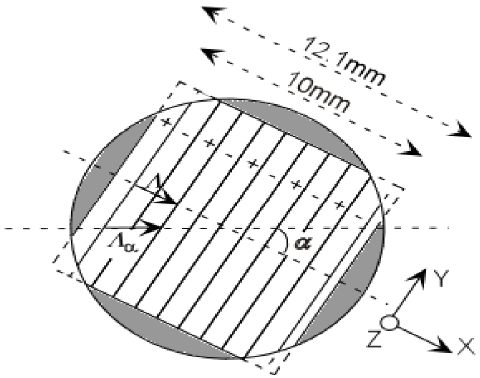
or

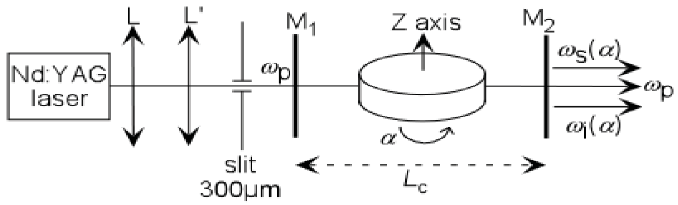
Noncollinear interaction

\+ Wider tuning range
\+ Fast tuning
\+ Separable signal, idler and pump beams
\+ Truly singly resonant
\+ Reduces back-conversion
\+ Single period grating
– Shorter interaction length



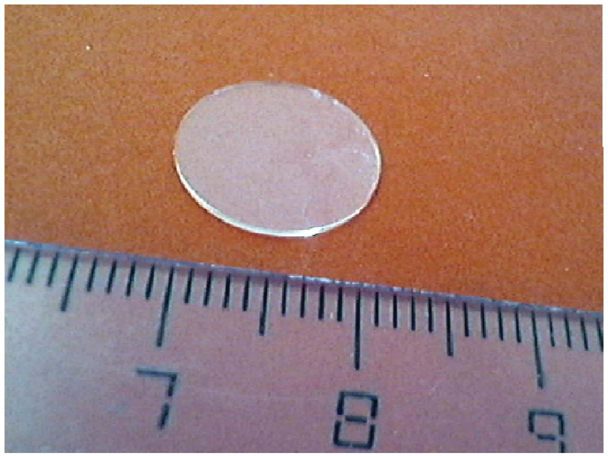
Widely tunable OPO with circular PPKTP

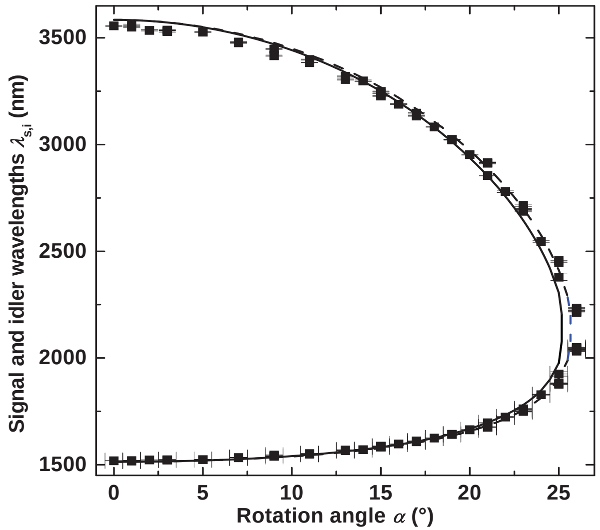




<u>The pump laser</u>
Nd:YAG, $\tau \approx 6$ ns, 10 Hz, $M^2 = 1.1$

<u>The PPKTP sample</u> 2.1 mm diameter, $\Lambda = 35.0$ µm poled area 10 by 10 mm^2, thickness 0.5 mm,

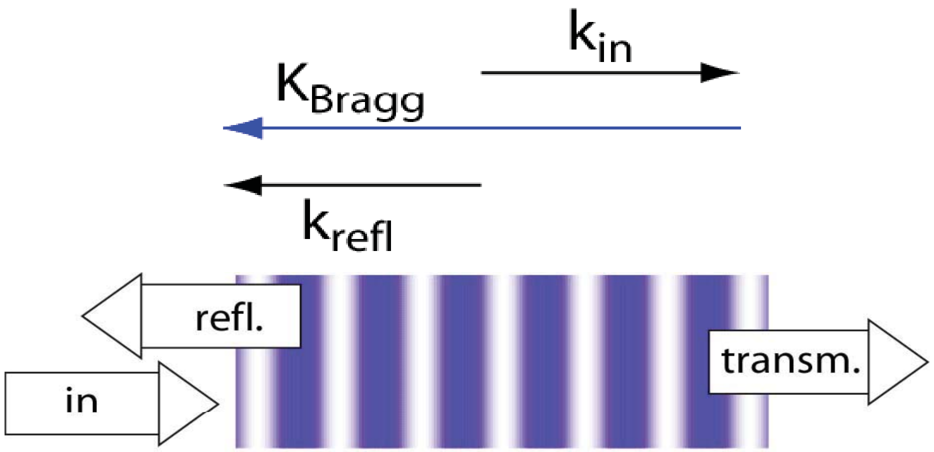




$\eta = 17.3\%$,
at $\alpha = 26°$.
$E_{tot} = 74$ µJ
$E_{pump} = 430$ µJ

Volume Bragg gratings

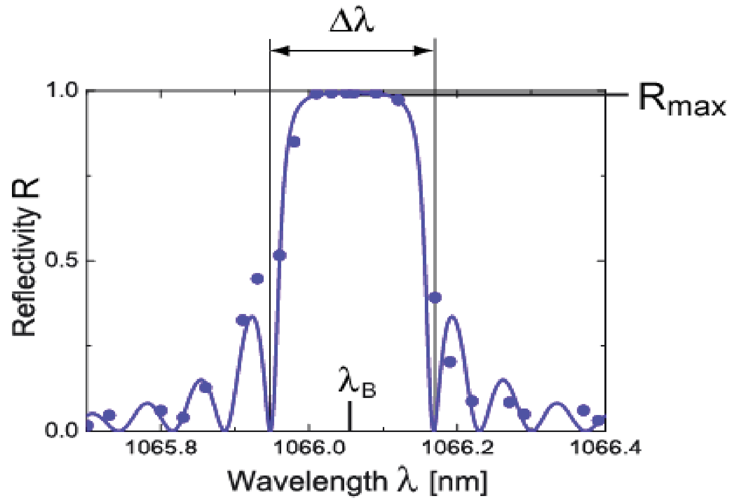
- Narrowband reflection peak
- Performance can be tailored to suit needs
- Made in durable and cheap glass



$$n = n_0 + n_1 \sin \frac{2\pi z}{\Lambda}$$

Material

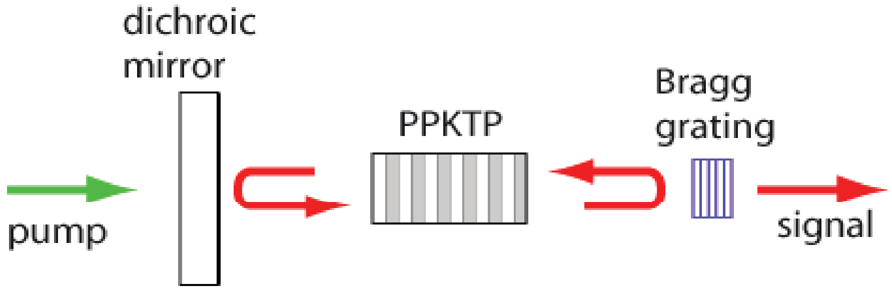
- Period, Λ
- Thickness, d
- Strength, n_1

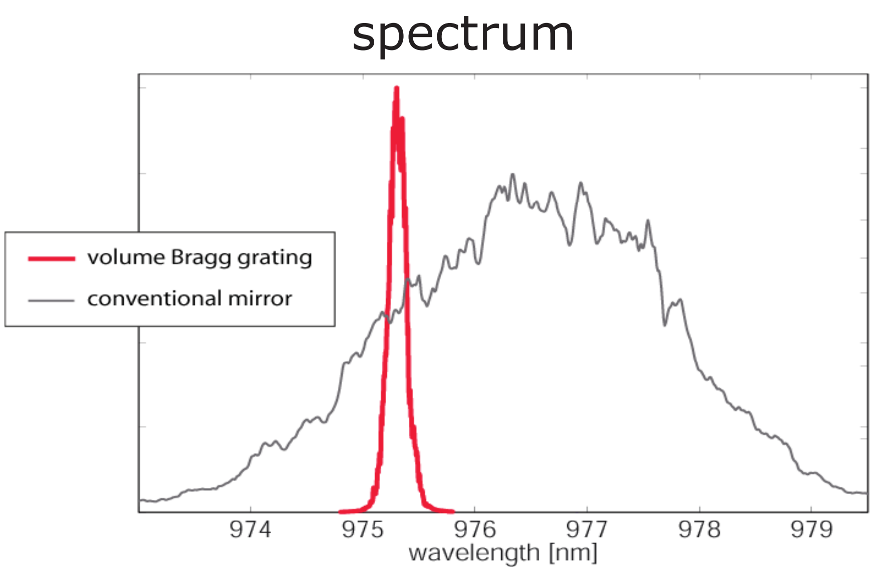


Optical

- $\lambda_B = 2n_0\Lambda$
- $R_{\max} = \tanh^2 \frac{\pi n_1 d}{\lambda_B}$
- $\Delta\lambda = \lambda_B \sqrt{\frac{4\Lambda^2}{d^2} + \frac{n_1^2}{n_0^2}}$

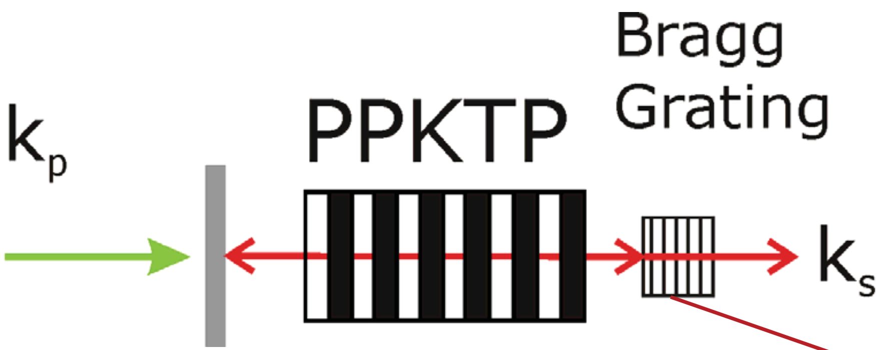
Narrowband OPO 975 nm

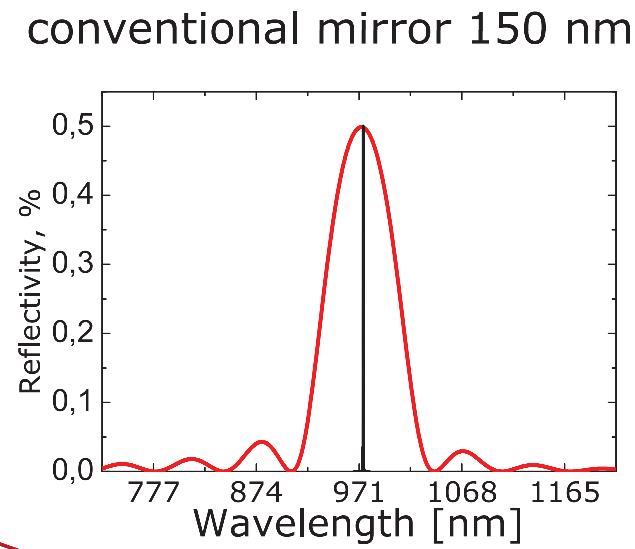


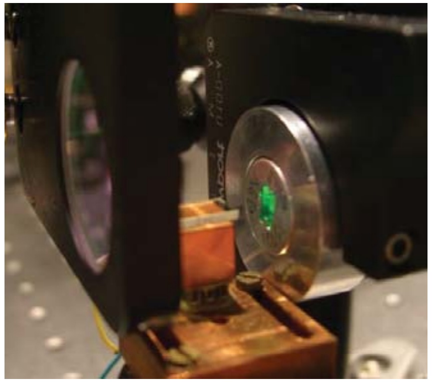


0.4 mJ signal
limited by pump

Cavity element – volume Bragg grating

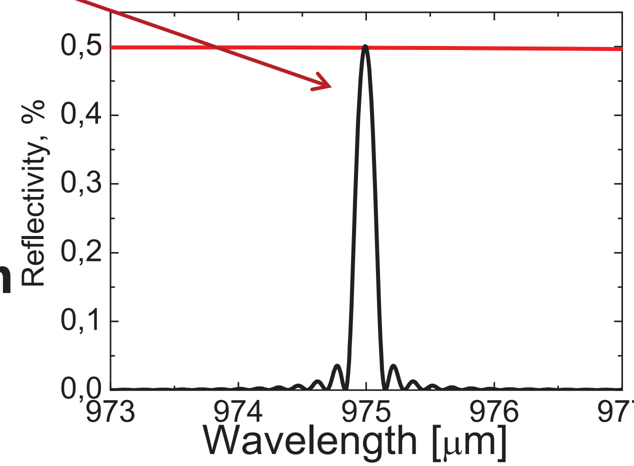




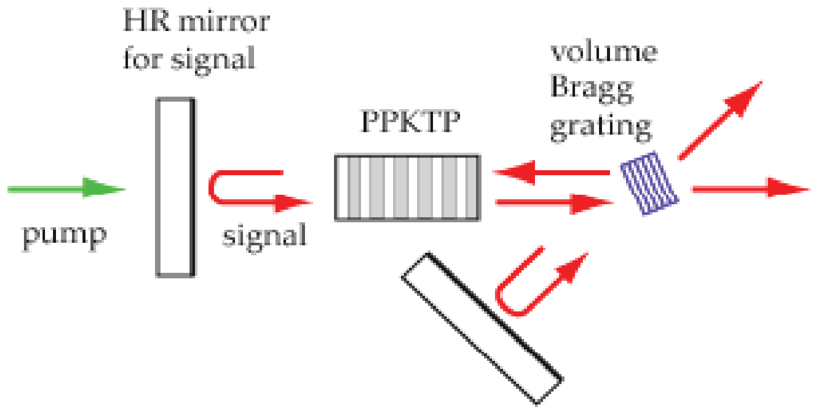


$\Delta\nu$ = 3.0 nm (950 GHz) @ 975nm

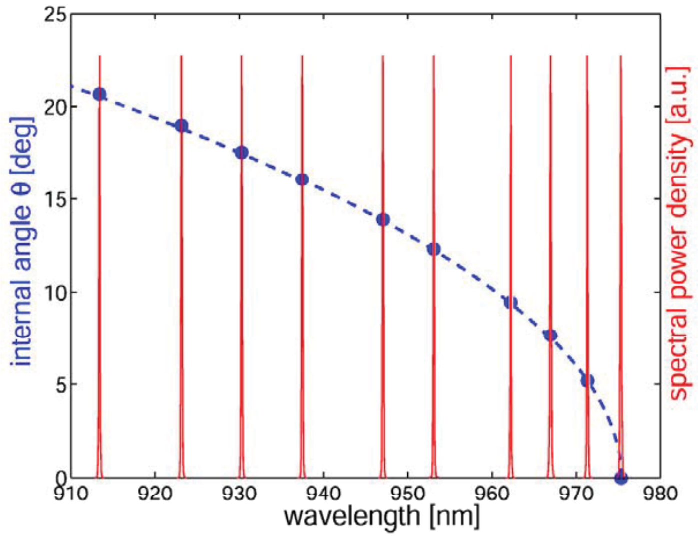
$\Delta\nu$ = 0.16 nm (50 GHz) @ 975nm

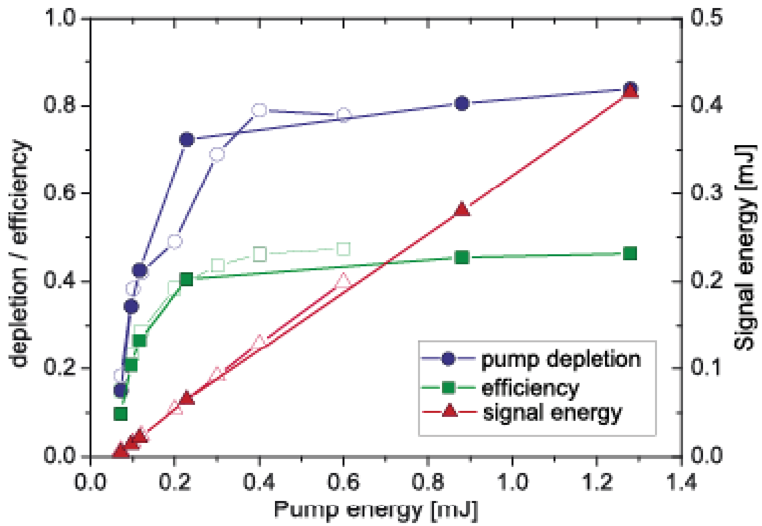


Angle tuning

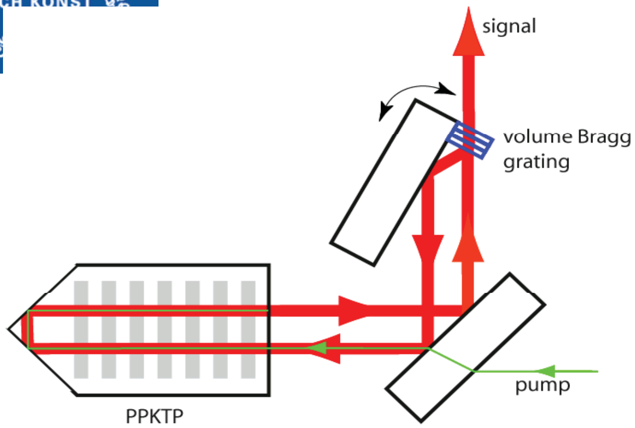


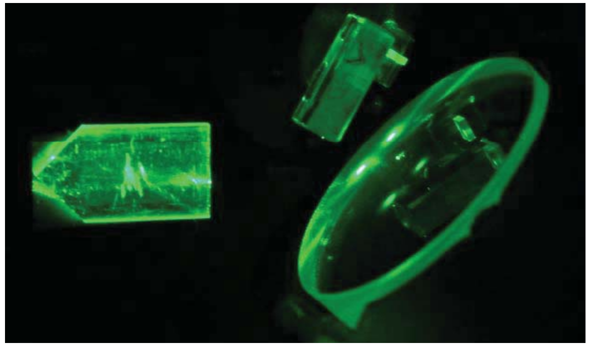
tuning spectra

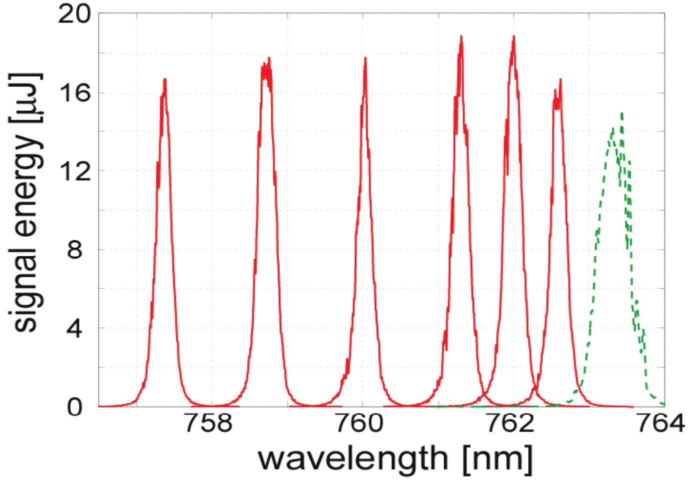




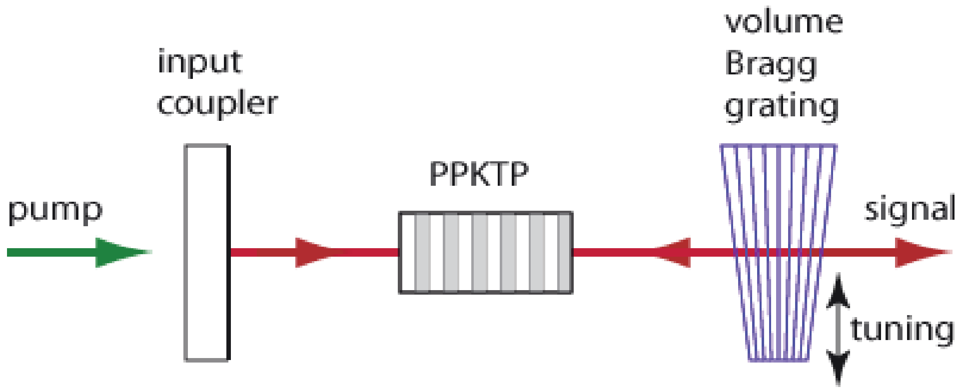
Angle tuning improved



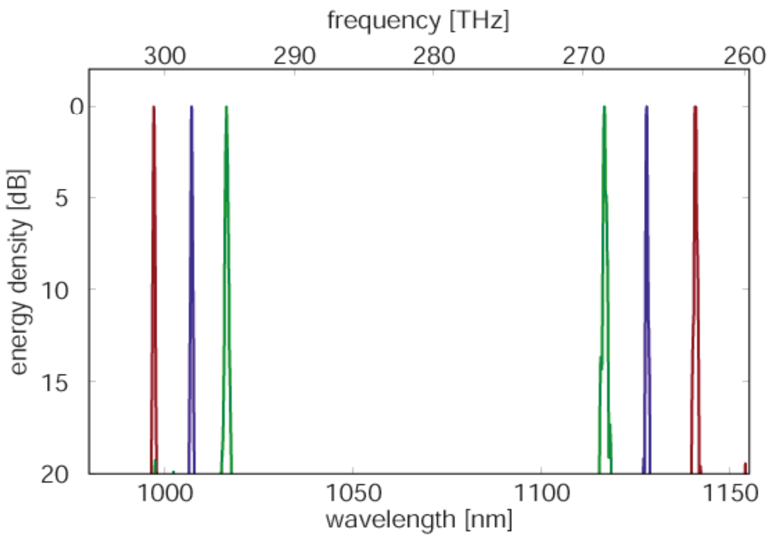




OPO with transversely chirped Bragg grating

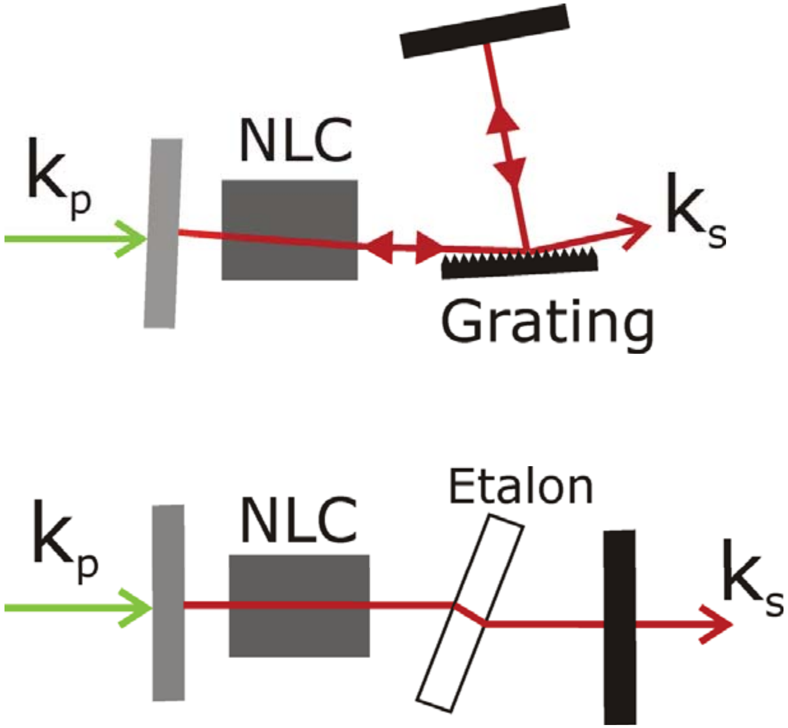


tuning spectra



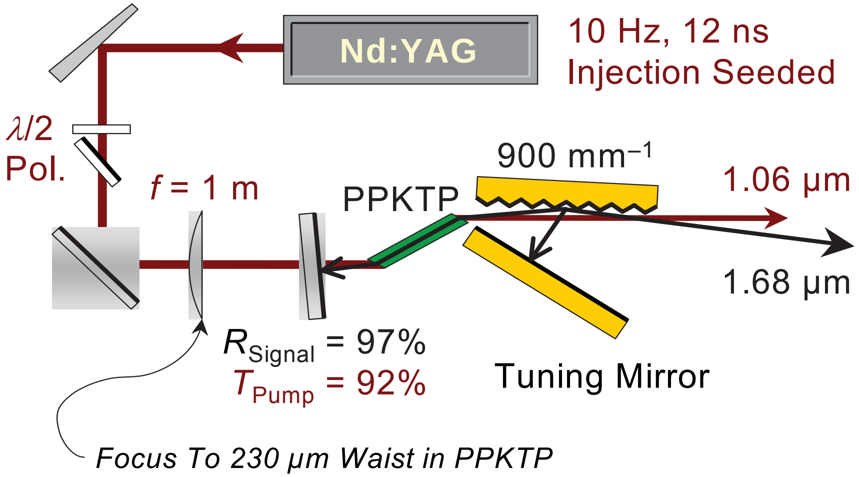
Linewidth narrowing - OPO

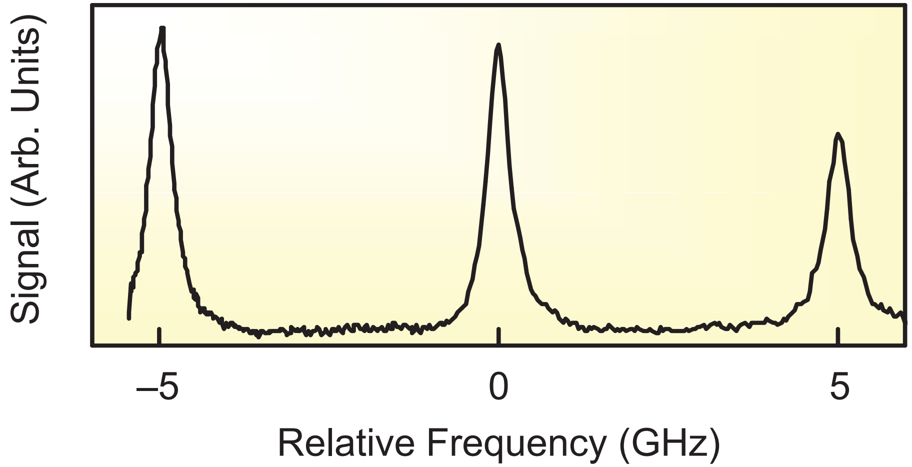
- Conventional techniques[1]
  - Folded cavity with grating
  - Inserting etalon
  - – Increased cavity length
  - – Higher thresholds



1. S. Brosnan and R.L. Byer, IEEE J. Quantum Electron. **15**, 415 (1979)

Narrow bandwidth OPO/OPA





The pump laser

Continuum Powerlite 7000, Nd:YAG, injection seeded, τ = 12 ns, 10 Hz, E_p = 20 mJ, M^2 = 1.1.

The OPO

PPKTP, 17 mm, Λ = 37.4 μm, T = 20 °C.
E_s = 0.37 mJ, η_s=11%, M^2 = 1.6, $\Delta\nu$ < 400 MHz

The OPA

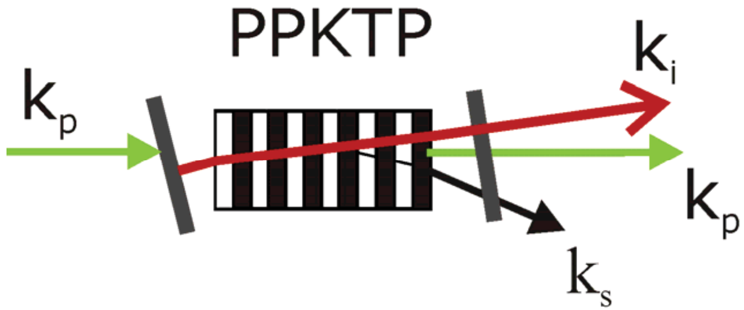
PPKTP, 20 mm, Λ = 37.4 μm, T = 20 °C
Output: E_s = 2.15 mJ, η_s = 19.7 %, E_i = 1.17 mJ, η_i = 10.7 % M^2 = 1.4, $\Delta\nu$ < 400 MHz

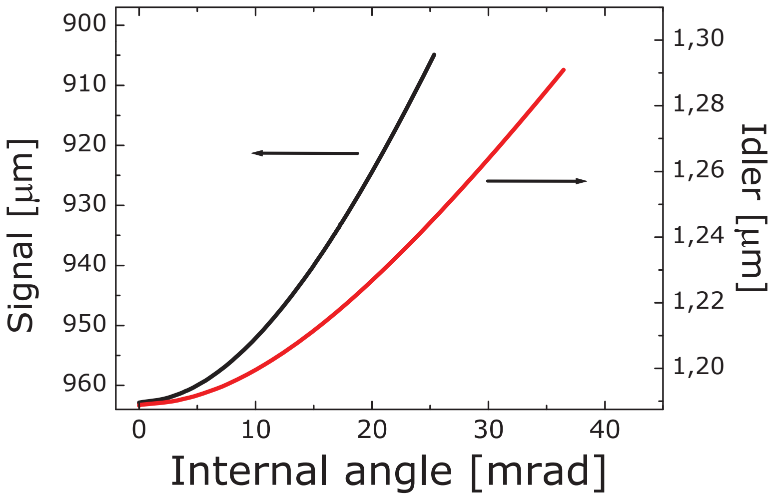
Strategies for spectral management in QPM OPOs

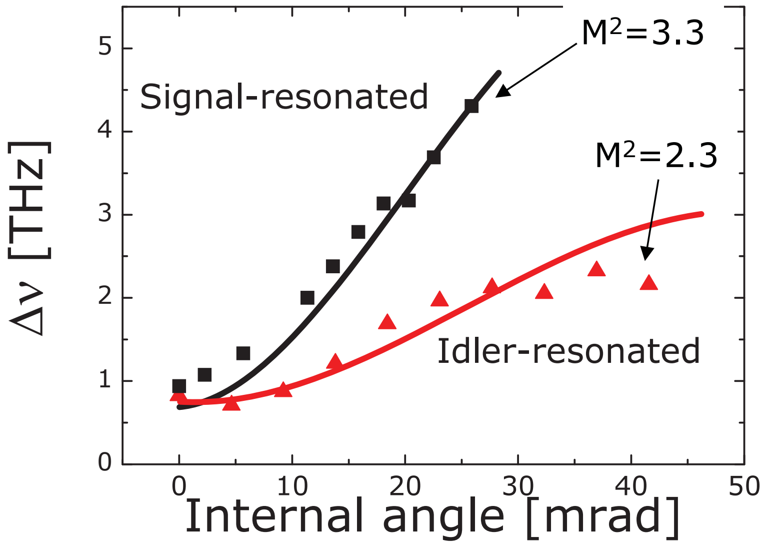
- **Inside PPKTP**
  - two coherent pump beams
  - angular dispersion
- **Cavity element**
  - intra-cavity grating
  - volume Bragg grating

Inside PPKTP – angular dispersion

- **Investigate noncollinear**
  Signal-resonant
  vs.
  Idler-resonant







Under equal pump conditions

$\Delta\upsilon_s > \Delta\upsilon_i$

Inside PPKTP – angular dispersion

Efficiency very high

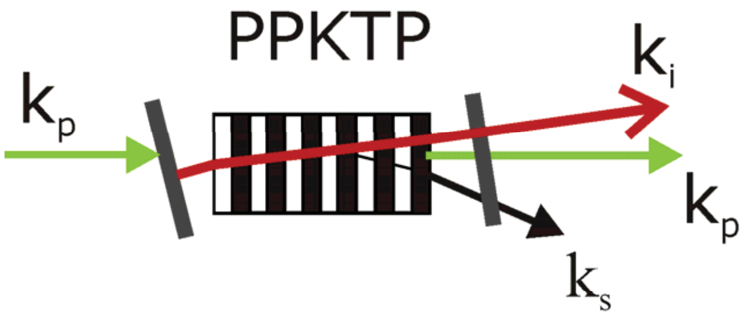
Increasing noncollincear angle

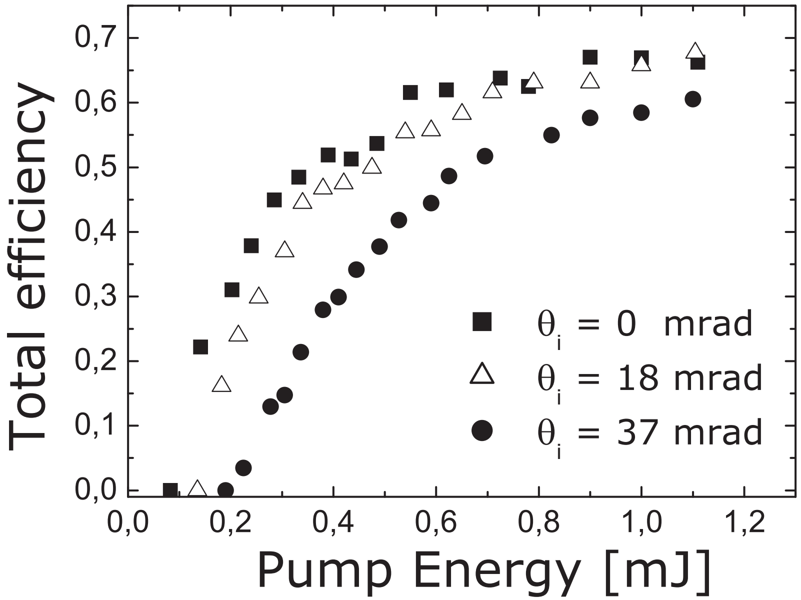
⇓

Decreasing beam overlap

⇓

Reduces the slope of efficiency growth





Cavity element – intra-cavity grating

Idler-resonant => better M^2, high efficiency and $\Delta\upsilon$ ↓

Self-seeding

access the resonant wave

↓

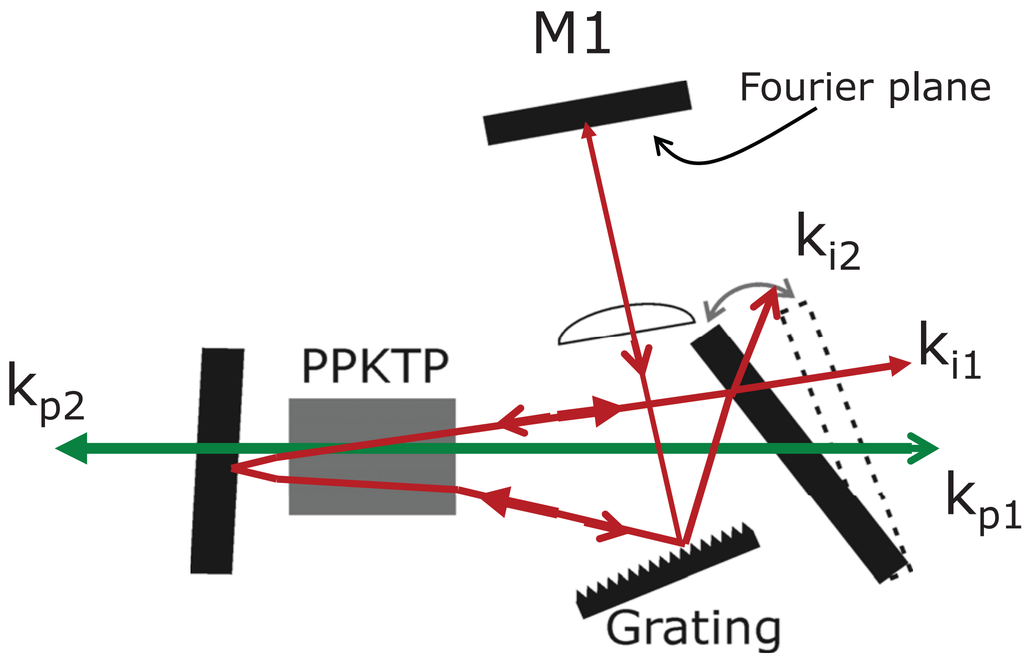
intra-cavity grating

↓

spectral manipulation

↓

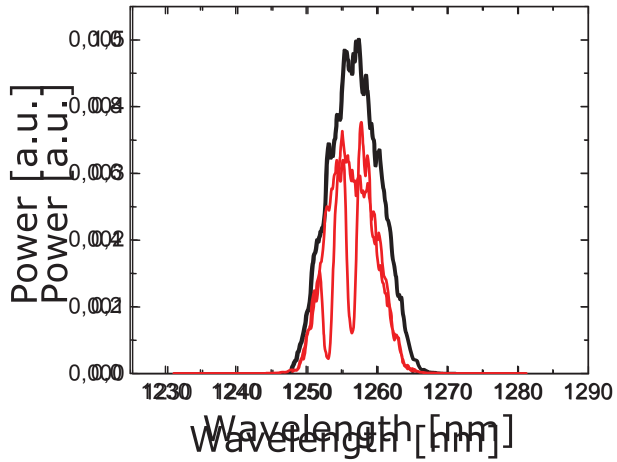
Send back into cavity
=> seed for k_{p2}



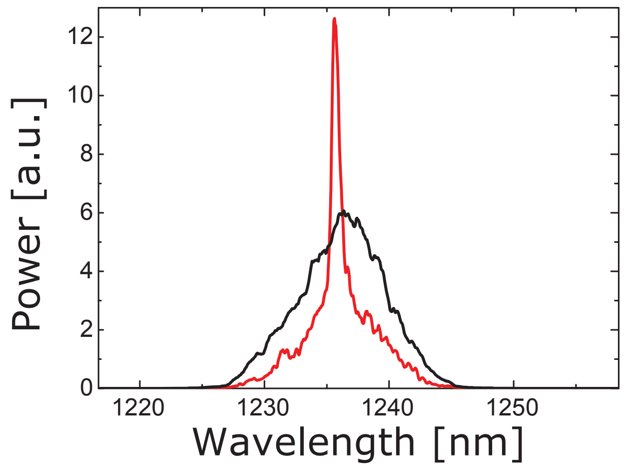
Cavity element – self-seeding

Spectral manipulation in the Fourier Plane

A 40µm diameter wire in the Fourier plane



A 20 µm wide stripe mirror in the Fourier plane

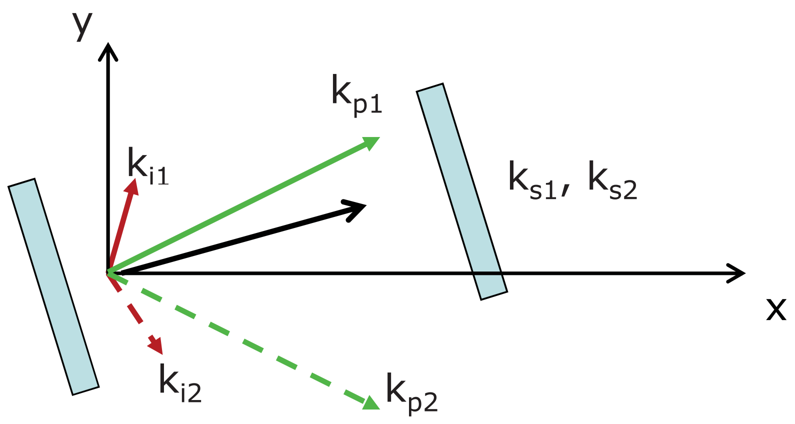


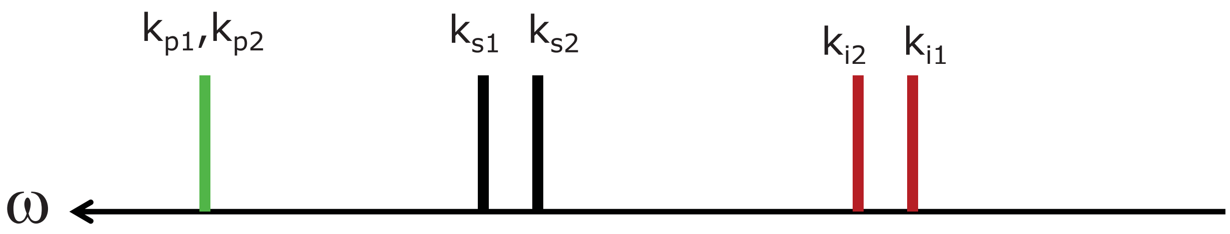
Inside PPKTP – two coherent pumps

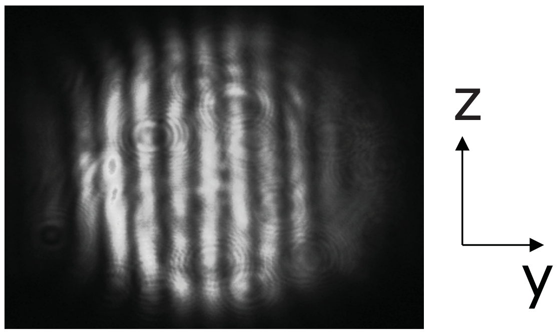
- Two coherent pump beams

  Intersects inside the PPKTP
  => Two signal-idler pairs

  Periodic interference pattern
  => Gain grating inside the PPKTP
  => 2D structure







Inside PPKTP – 2D-structure

- Two coherent pump beams

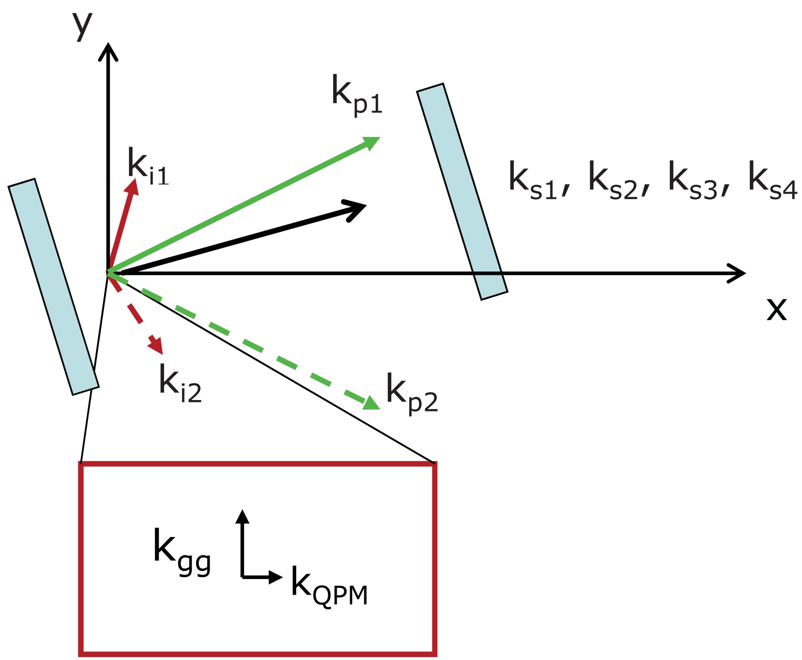
  Intersects inside the PPKTP

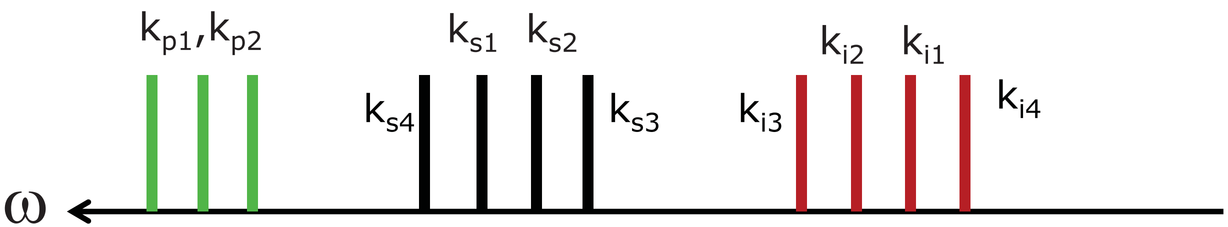
  => Two signal-idler pairs

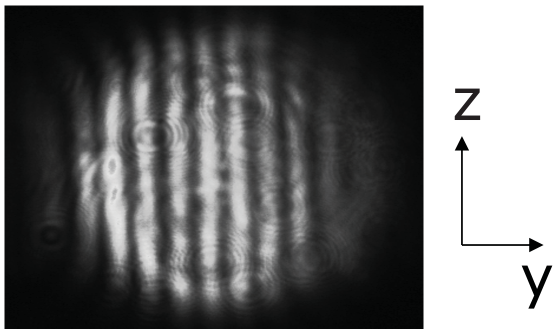
  Periodic interference pattern

  => Gain grating inside the PPKTP

  => 2D structure







Inside PPKTP – four-wave mixing

Energy conservation

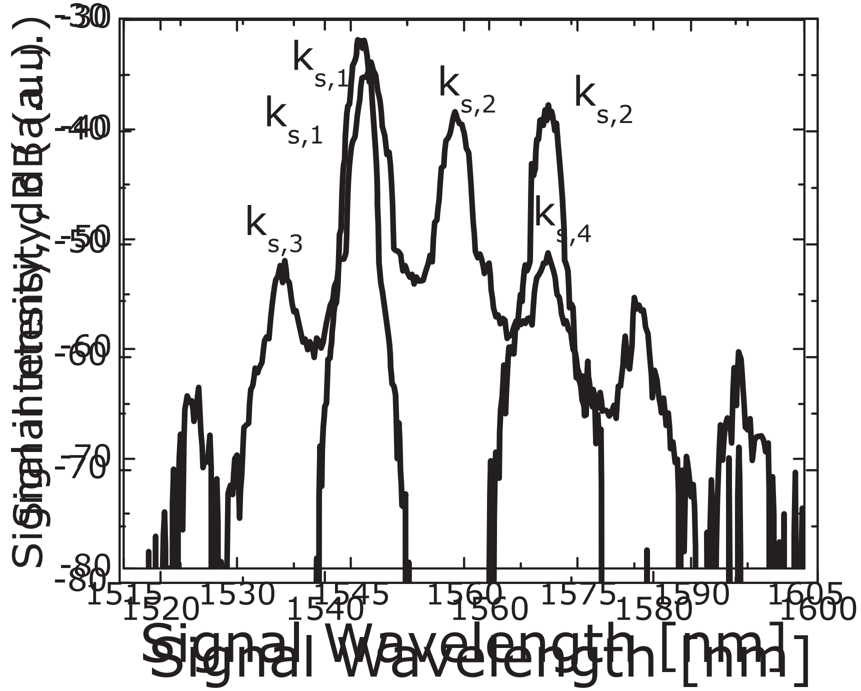
$$\omega_{s3} = \omega_{s1} + \omega_{i2} - \omega_{i1} = \omega_{s1} + \delta\omega$$

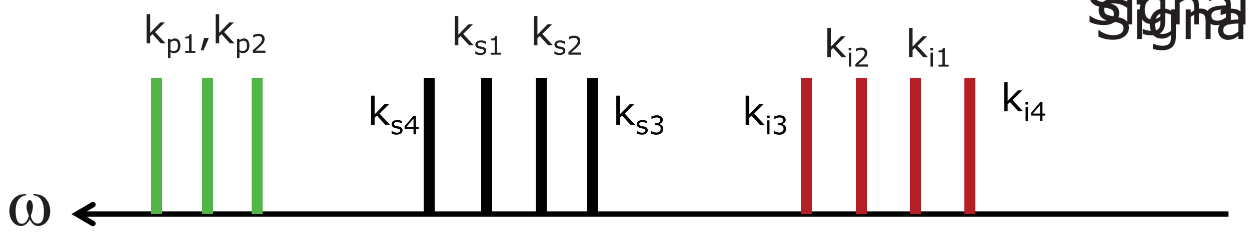
$$\omega_{s4} = \omega_{s2} + \omega_{i1} - \omega_{i2} = \omega_{s2} - \delta\omega$$

Momentum conservation

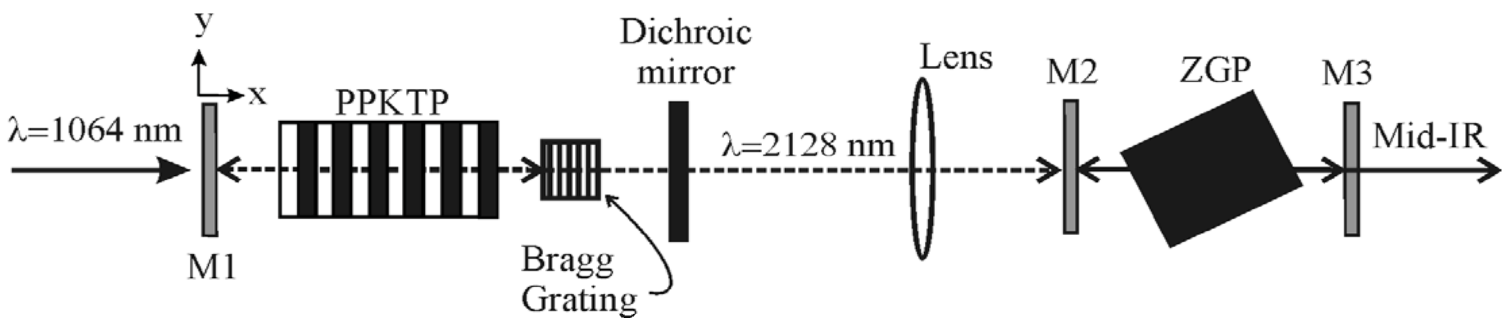
$$k_{s3} = k_{s1} + k_{i2} - k_{i1} \pm k_{gg}$$

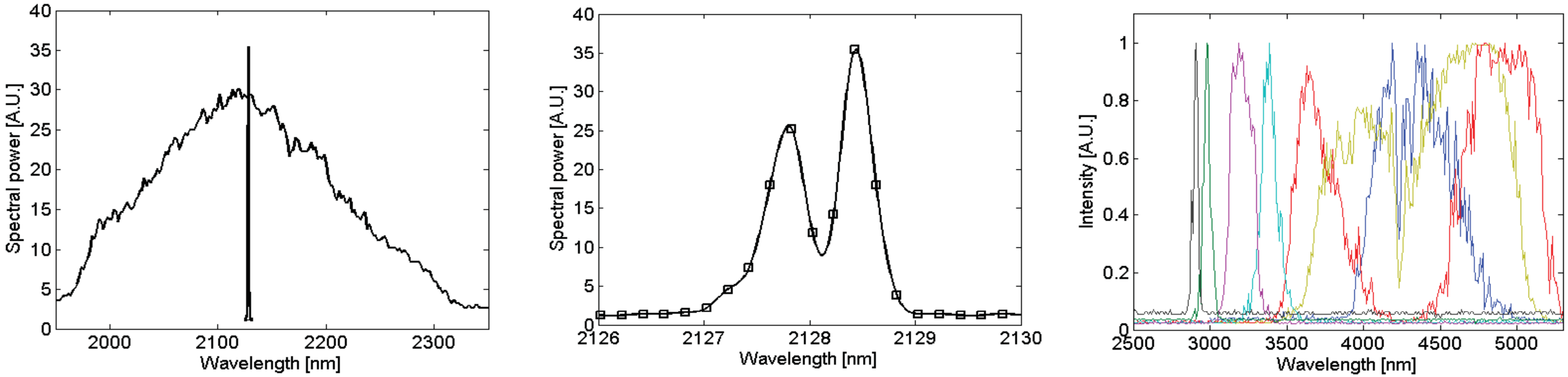
$$k_{gg} = k_{p1} - k_{p2}$$





Double stage OPO for mid-IR generation





Spectrum compared to regular output coupler

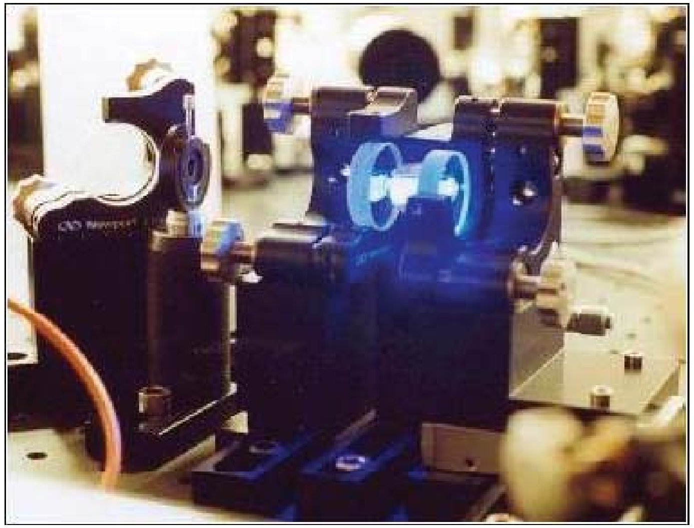
Spectrum first stage

Spectrum stage two

16 % total conversion efficiency

Tools for NLO

SNLO – a public domain software



SNLO . Public Domain Software for non-linear optics
http://www.sandia.gov/imrl/XWEB1128/xxtal.htm

OPO with focussed Gaussian beam.

- **Seminal paper:**

  ‘Parametric interaction of focussed Gaussian light beams’
  Boyd and Kleinman, J. Appl. Phys. 39, 3597, (1968)

- **Extension to non-degenerate OPO.**
  Relates treatments for plane-wave, collimated Gaussian and focussed Gaussian:
  ‘Focussing dependence of the efficiency of a singly resonant OPO’
  Guha, Appl. Phys. B, 66, 663, (1998)

Summary: Attractions of OPOs

- Very wide continuous tuning from a single device, via tuning the phase-match condition
- High efficiency
- No heat input to the nonlinear medium
- No analogue of spatial-hole-burning as in a laser, hence simplified single-frequency operation
- Very high gain capability
- Very large bandwidth capability

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