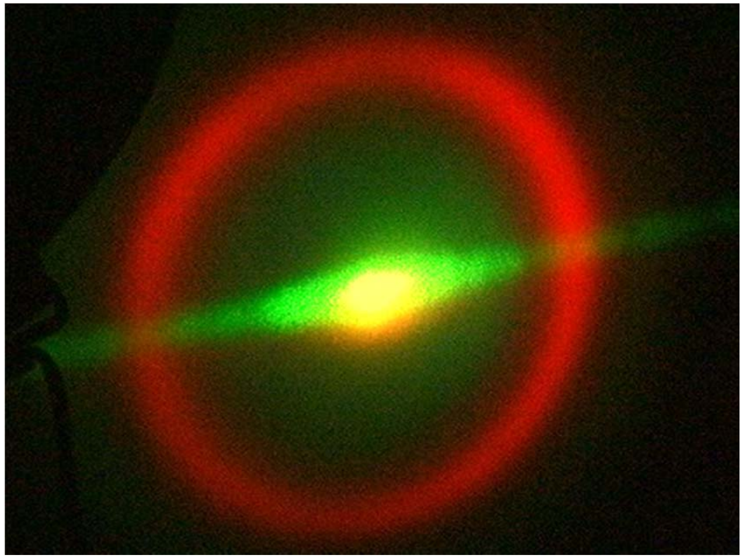
Nonlinear optics continued- waveguides and parametric devices

Fredrik Laurell



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Outline

- Optical waveguides – integrated optics
- Nonlinear integrated optics
- Introduction to parametric devices
- Optical parametric oscillators
    - Singly resonant OPOs vs. doubly resonant OPOs
    - Practical examples
- Summary

Planar Waveguides: Overview

- Similar function as optical fibers
- Easily fabricated on substrates with a mask

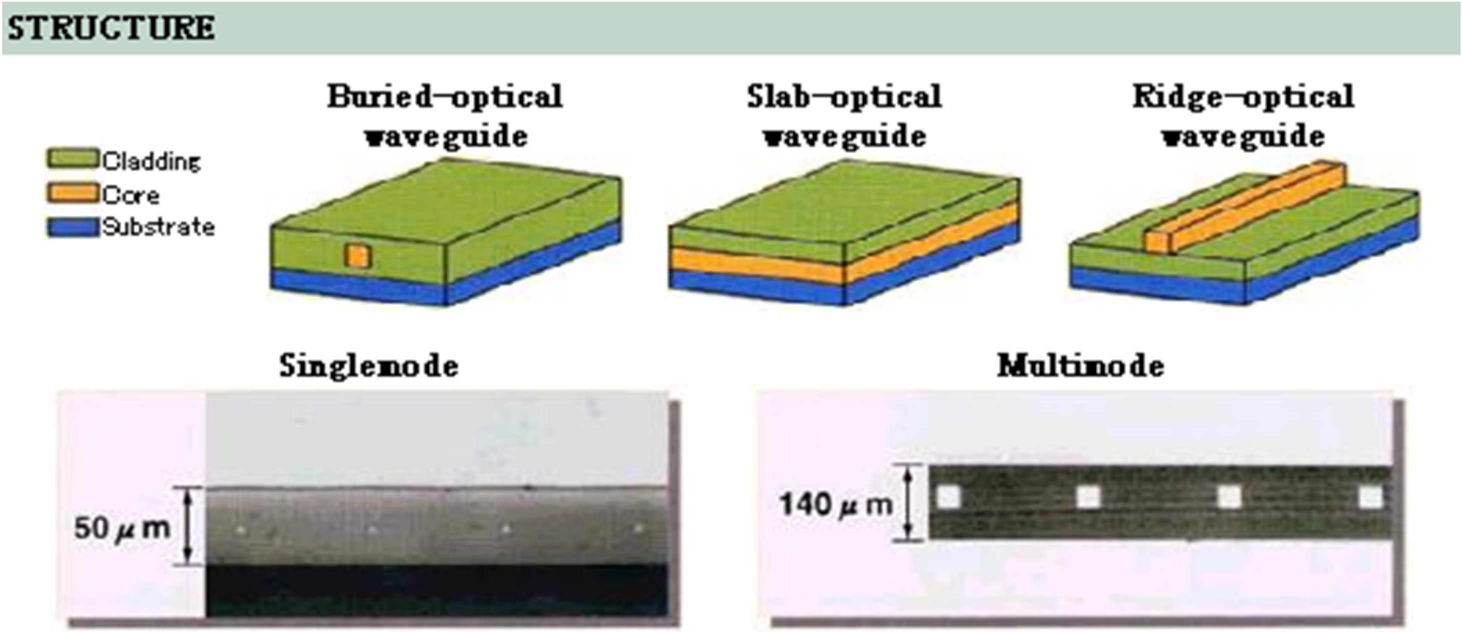
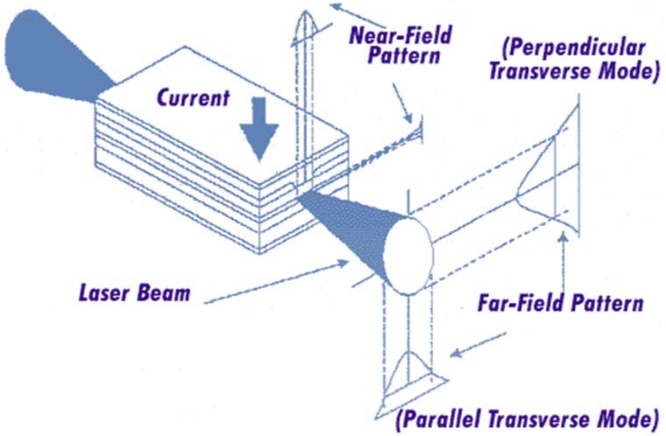
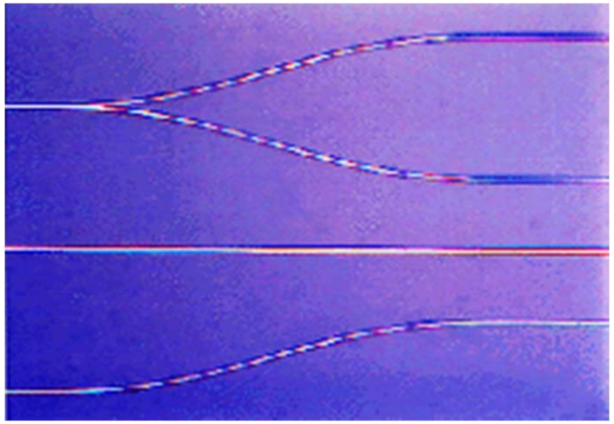


Image from NTT-AT (http://www.keytech.ntt-at.co.jp/optic2/prd_e0015.html)

Uses for planar waveguides

- Routing Light
- Devices
  - Modulators
  - Splitters
  - Erbium Doped Planar Waveguide Amplifiers (EDWA)
  - Resonators





http://www.netzartfedorov.com/clients/nanonics/newnanon/text-industry.html http://www.ee.ic.ac.uk/optical/Optics.html

Couplers – grating devices - integration

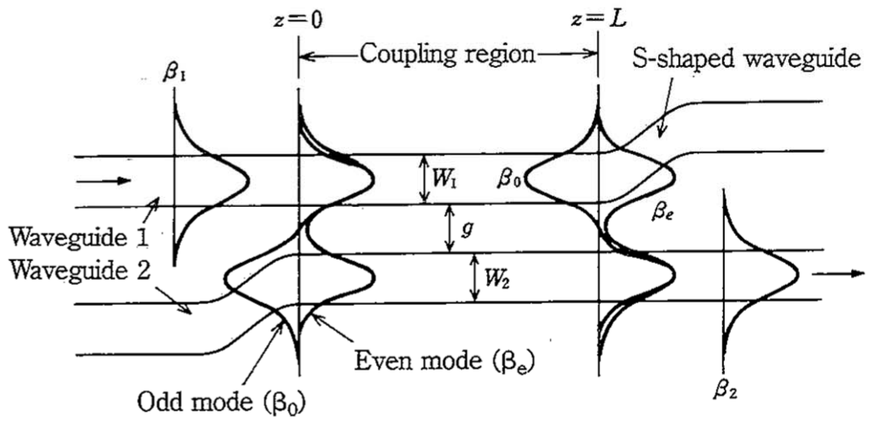
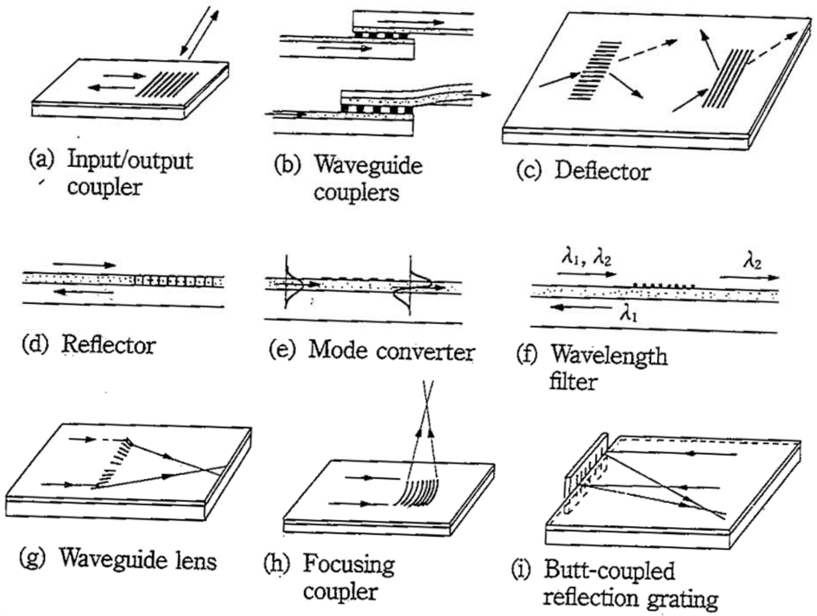
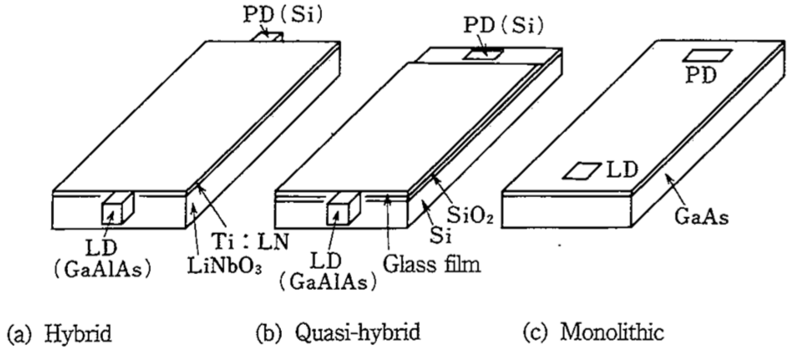


Fig. 2.27 Operating principle of waveguide directional couplers.



(a) Input/output coupler
(b) Waveguide couplers
(c) Deflector
(d) Reflector
(e) Mode converter
(f) Wavelength filter
(g) Waveguide lens
(h) Focusing coupler
(i) Butt-coupled reflection grating

Fig. 4.1 Passive grating components for optical integrated circuits.



(a) Hybrid
(b) Quasi-hybrid
(c) Monolithic

Fig. 1.1 Three types of optical integrated circuits.

Maxwells Equations in Slab Waveguide

- Maxwell's Equations

$$\nabla \times \tilde{\mathbf{E}} = -\mu_0 \frac{\partial \tilde{\mathbf{H}}}{\partial t},$$

$$\nabla \times \tilde{\mathbf{H}} = \varepsilon_0 n^2 \frac{\partial \tilde{\mathbf{E}}}{\partial t},$$

- Simplifications

$$\tilde{\mathbf{E}} = \mathbf{E}(x, y) e^{j(\omega t - \beta z)},$$

$$\tilde{\mathbf{H}} = \mathbf{H}(x, y) e^{j(\omega t - \beta z)}.$$

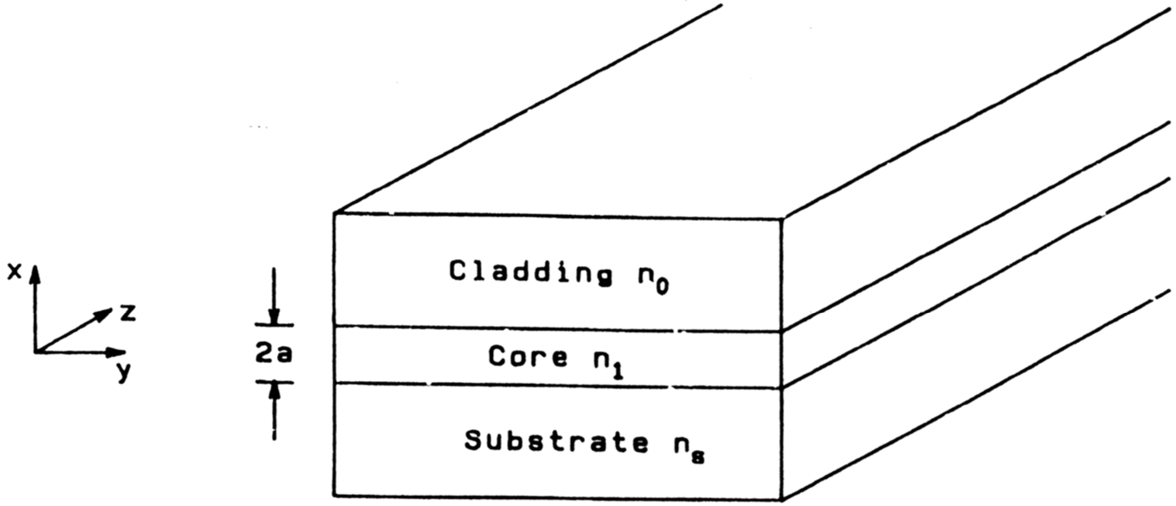


Figure 2.1: Slab optical waveguide.

TE and TM modes

- Dispersion Curves

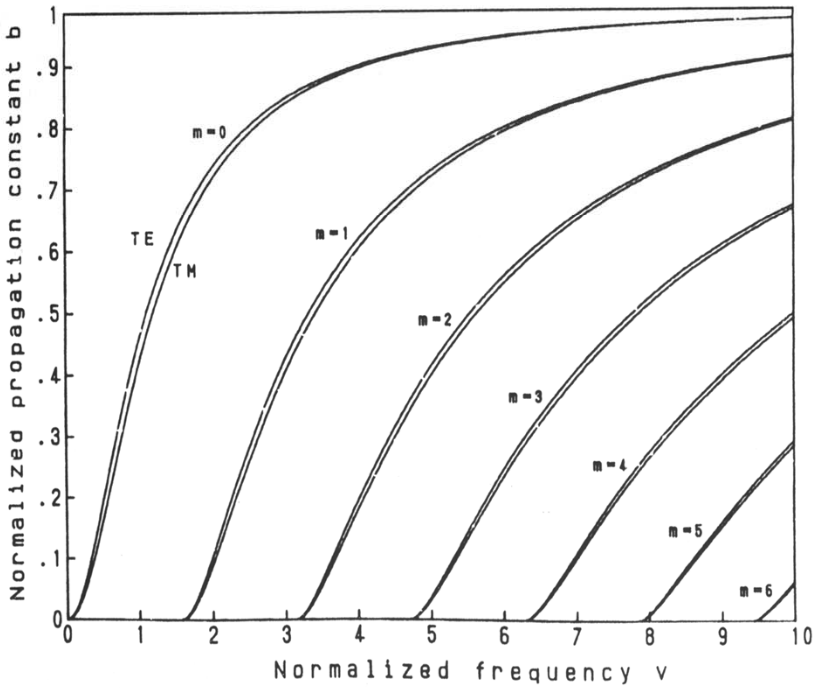


Figure 2.9: Dispersion curves for the TE and TM modes in the slab waveguide.

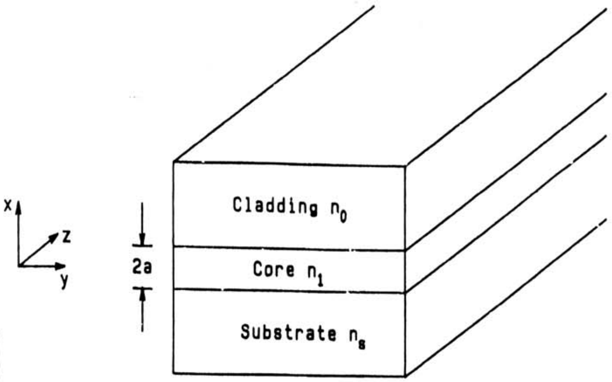


Figure 2.1: Slab optical waveguide.

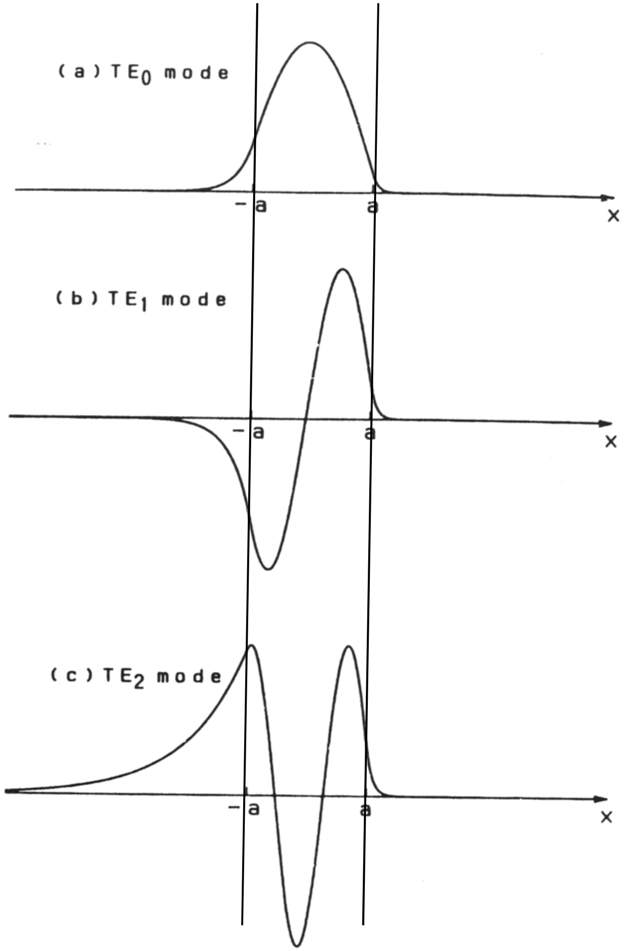
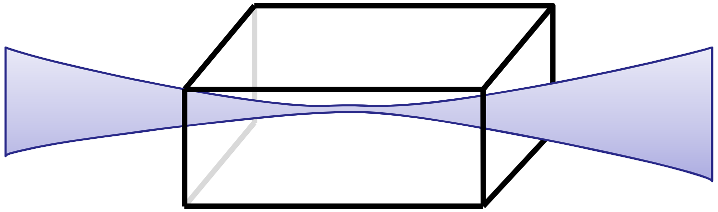


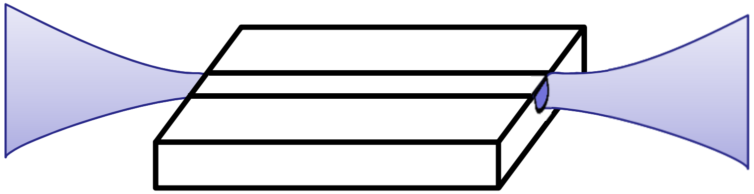
Figure 2.7: Electric field distributions in the slab waveguide.

Waveguide vs. Bulk for NLO

+ Waveguides provide high confinement and long interaction length – high efficiency
+ Fibers can be connected to the waveguide to provide robust sources
- Additional fabrication steps to create a good waveguide
- Power handling issues



SHG conversion efficiency for confocal focusing in the bulk



Conversion efficiency for SHG in waveguide

$$E(x,y,z)=\frac{1}{2}A(z)B(x,y)e^{i(\omega t-\beta z)}+c.c.,$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}B^2(x,y)dxdy=1,$$

$$I_{OVL}=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}B_F^2B_{SH}dxdy,$$

$$A_{OVL}=\frac{1}{I_{OVL}^2}$$

$$\eta_{Bulk}=\frac{P_{SH}}{P_F}=\frac{16\pi^2d_{eff}^2}{\varepsilon_0c\lambda_F^3n_Fn_{SH}}P_Fl$$

$$\eta_{WG}=\frac{P_{SH}}{P_F}=\frac{8\pi^2d_{eff}^2}{\varepsilon_0c\lambda_F^2N_F^2N_{SH}A_{OVL}}P_Fl^2$$

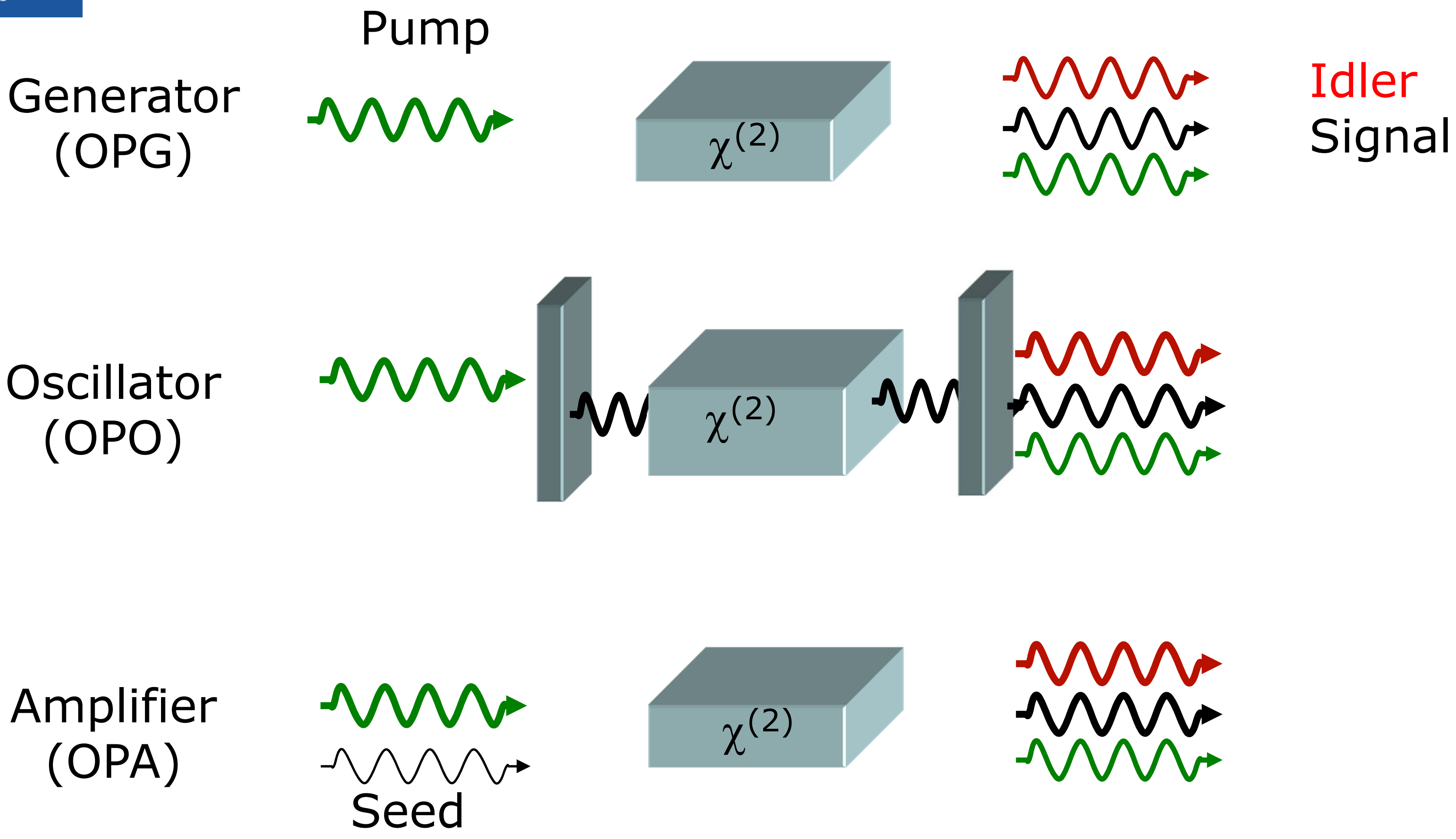
Normally 10 to 1000 X improvement in efficiency with waveguide vs. bulk

$$\frac{\lambda l}{2N_{eff}A_{OVL}}$$

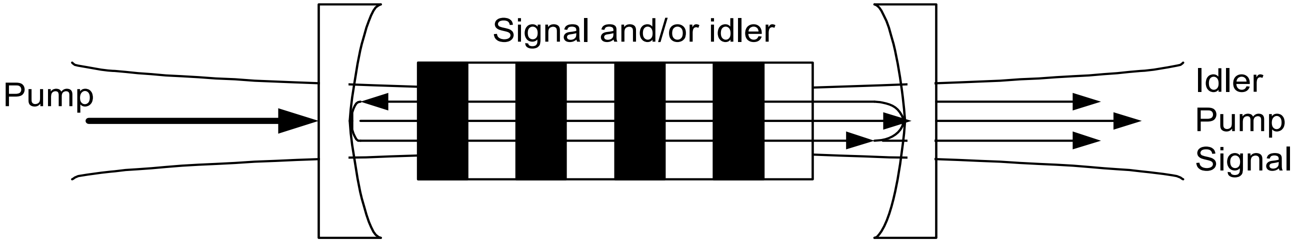
Why optical parametric devices?

- Very wide continuous tuning from a single device, via tuning of 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

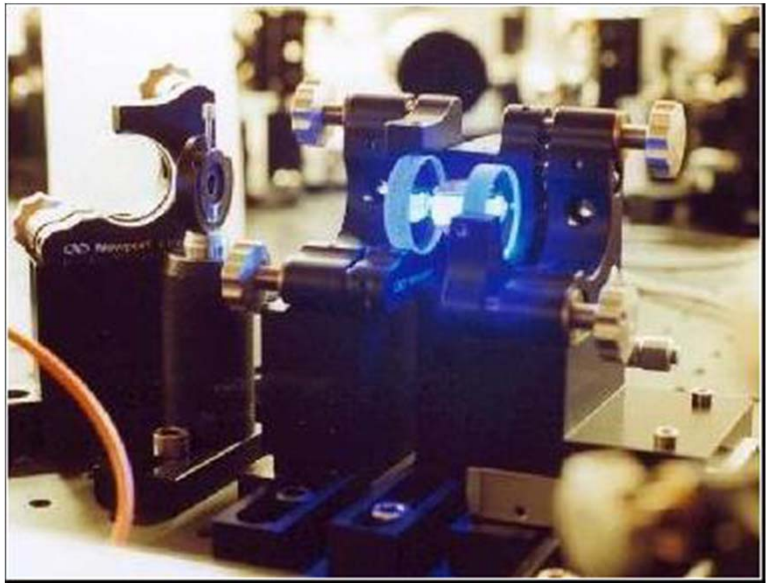
Nonlinear processes – optical parametric devices



Optical parametric oscillation (OPO)

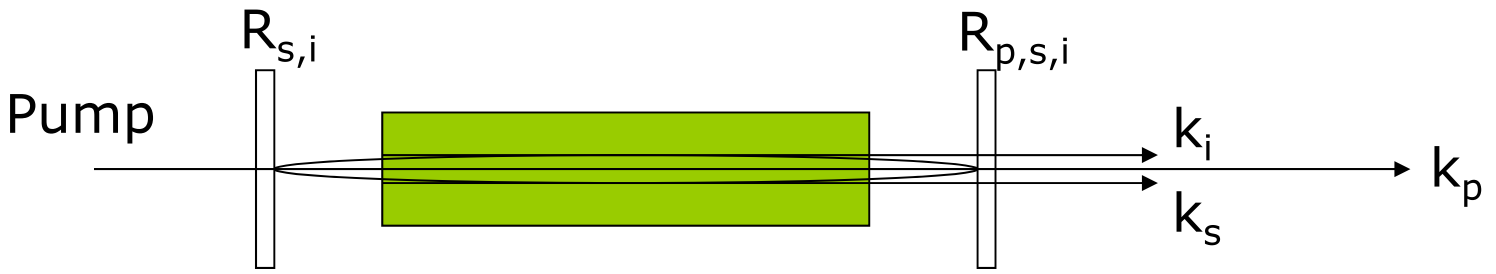


Singel or double resonant OPO
(SRO or DRO)

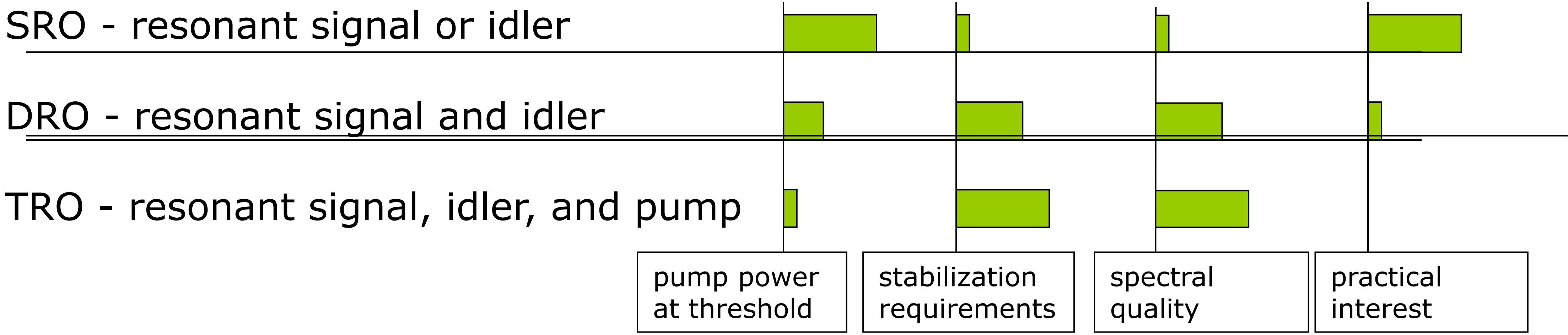


The Optical Parametric Oscillator

Add feedback to OPG → 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

Manley-Rowe relations

Integrals of the coupled equations

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

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

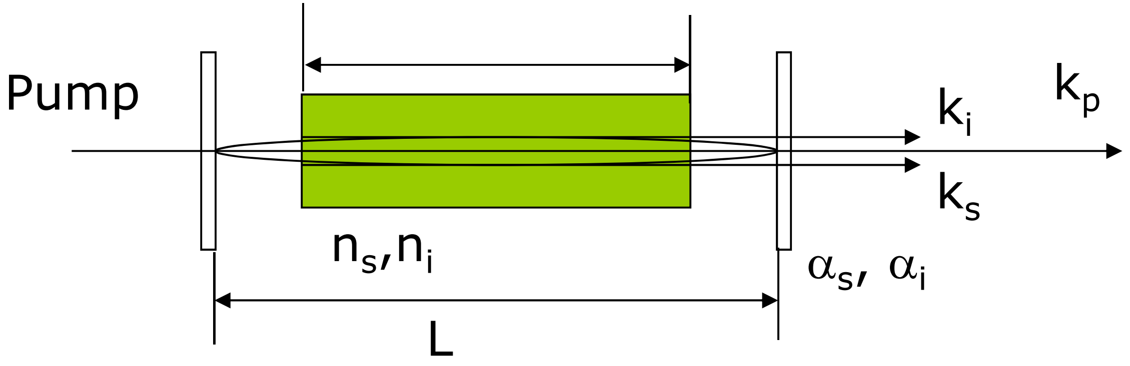
$$n_2|E_2(z)|^2/\omega_2 - n_1|E_1(z)|^2/\omega_1 = \text{const}$$

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

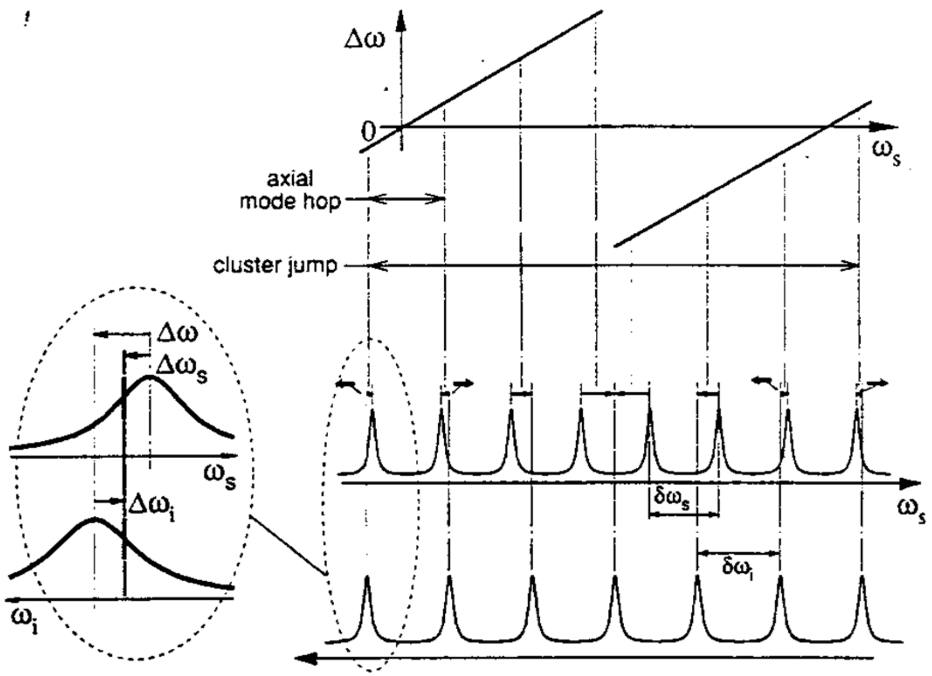
Free-spectral range: $$\delta\omega_j = \frac{\pi c}{L_j + (n_j - 1)l}$$

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

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

Cavity resonance:

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

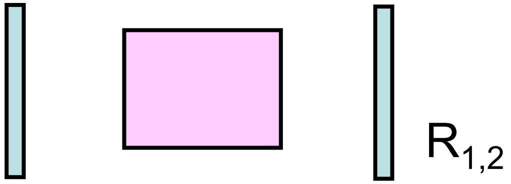


The OPO threshold

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)

$$\cosh gL = \frac{1 + (R_1R_2)^{1/2}}{R_1^{1/2} + R_2^{1/2}}$$

g = gain coefficient

OPO threshold: SRO vs DRO

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

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

SRO ⇒ $g^2 L^2 = 1 - R_2$

DRO ⇒ $g^2 L^2 = (1 - R_2)(1 - R_1)/4$

Advantage of DRO is low threshold:

Example:

DRO with $R_1 = 98\%$

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

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

Parametric gain
Plane-wave, phase-matched

If gain is small, ($gL \ll 1$) , gain increment is

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

Note: incremental gain proportional to pump intensity

~ proportional to ω_3^2

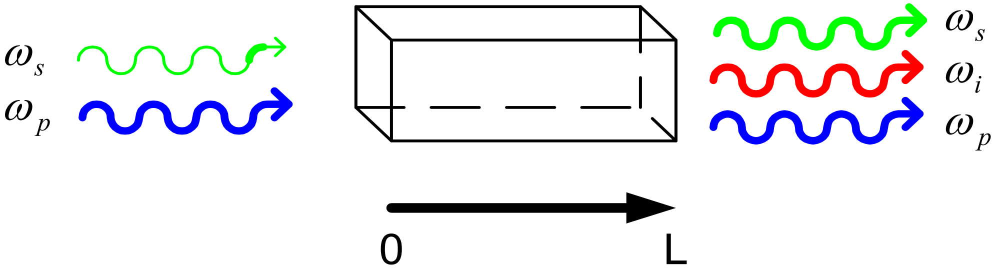
proportional to d^2 / n^3 (NL Figure Of Merit)

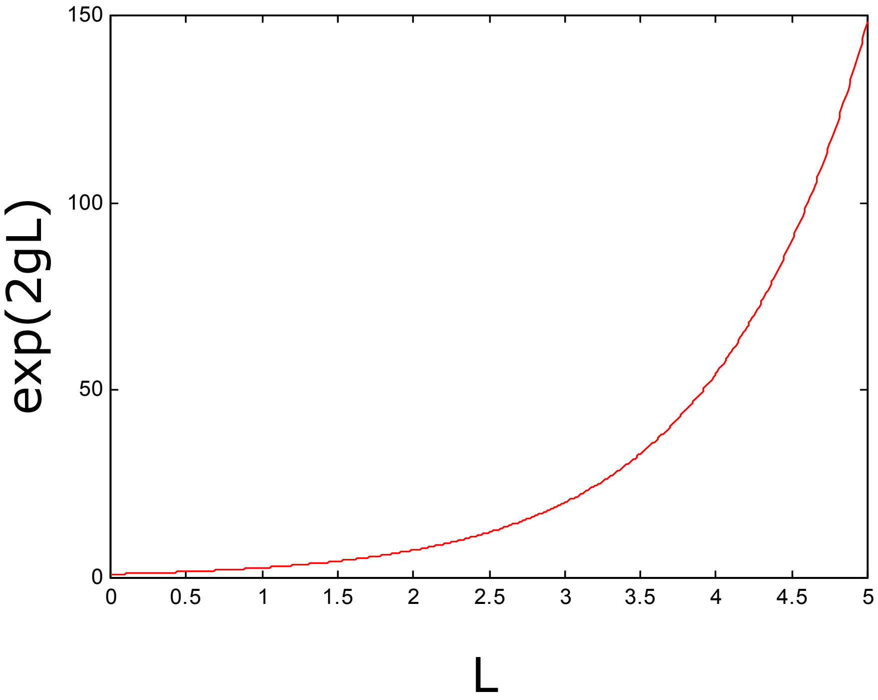
Optical parametric amplification (OPA)

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

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

$\Delta k=0$





g = gain coefficient, G = gain

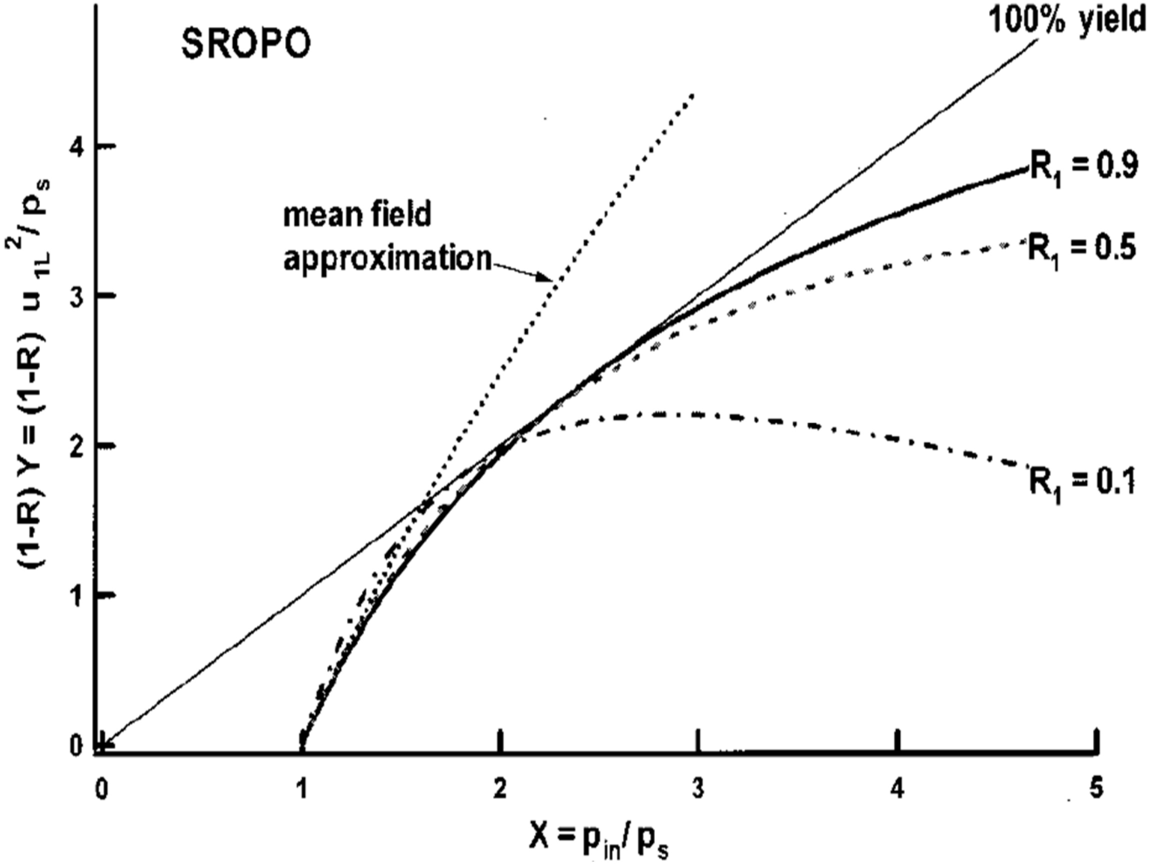
Typical OPO conversion efficiencies

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

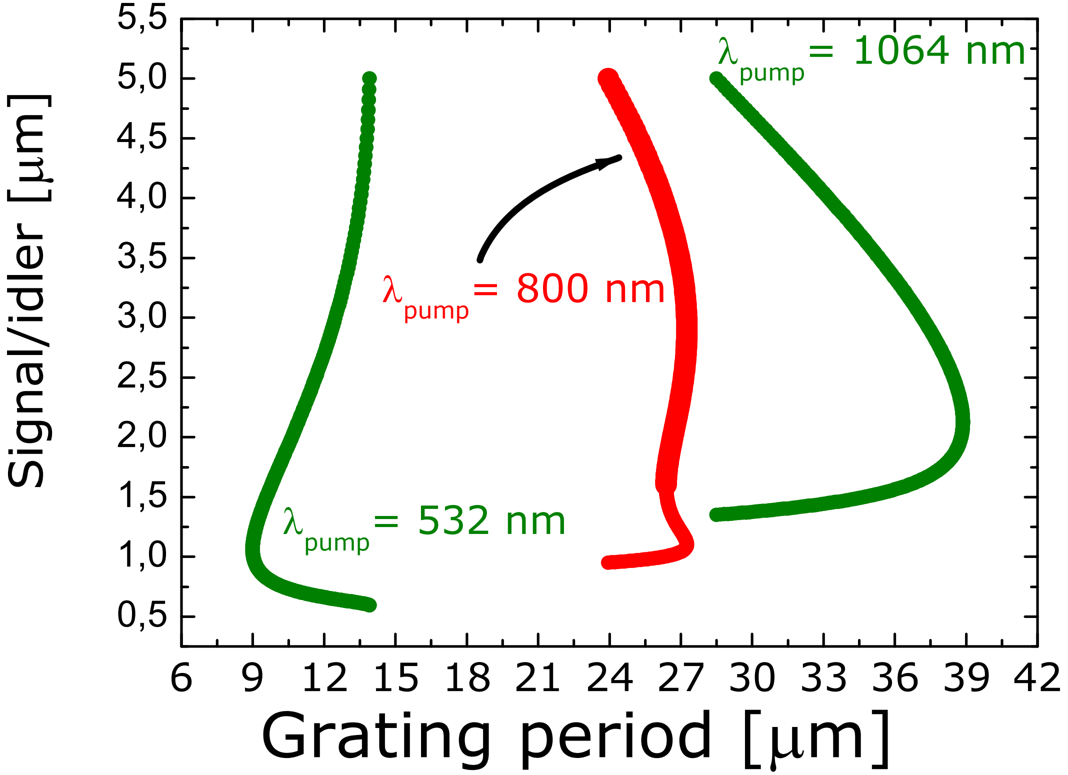


(p_s is normalised pump threshold intensity)

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

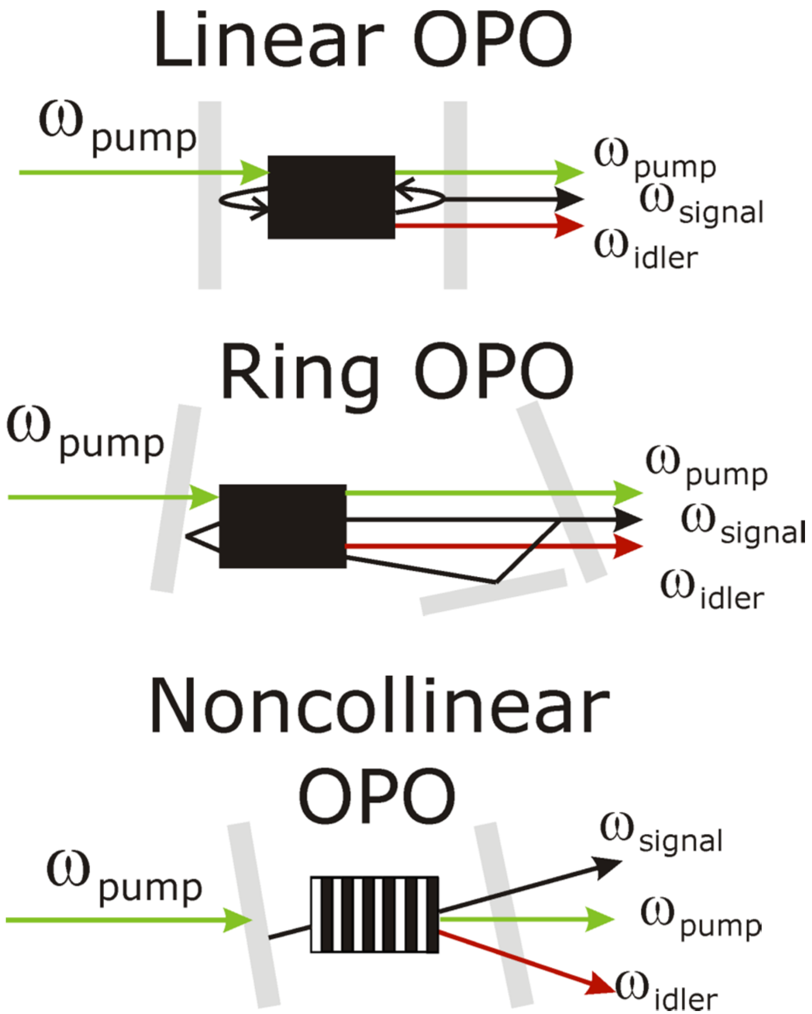
Advantages with nanosecond QPM-OPOs

Low threshold

Increased interaction length

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

Easy tunability



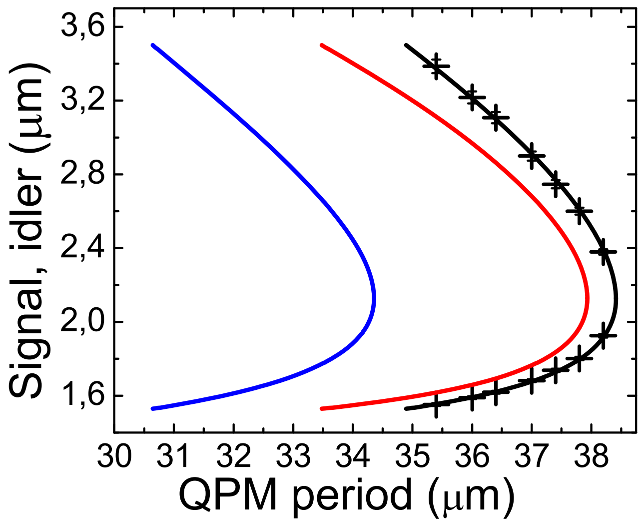
Quasi-Phase-Matching
OPO Tuning Techniques

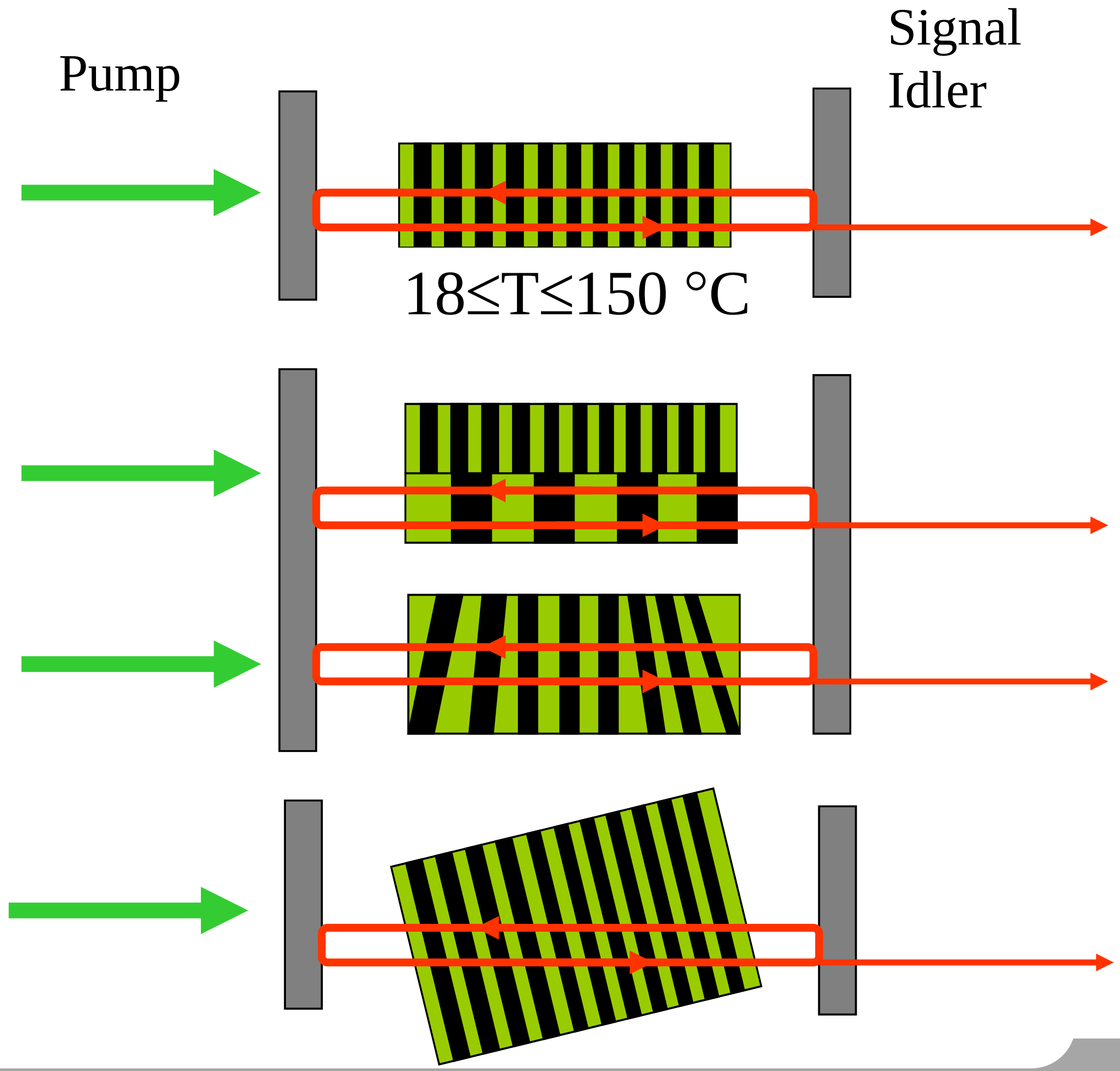
Temperature tuning

Multigrating structures

Fanned grating

Non-collinear configuration





Pump

Signal

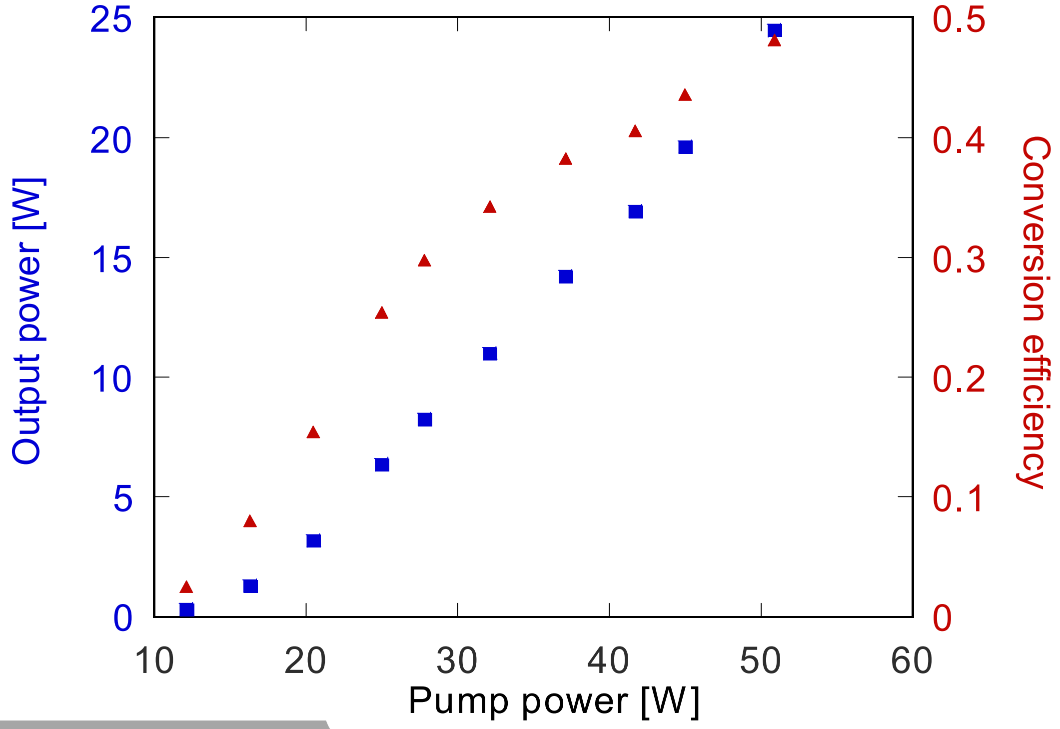
Idler

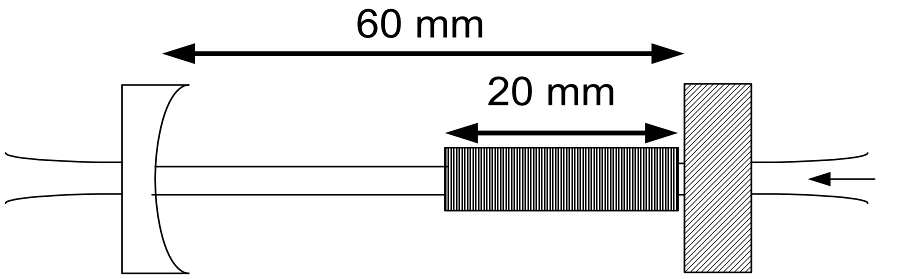
18≤T≤150 °C

High repetition rate DRO

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

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





R = 35 %, signal+idler
R = 100 %, pump
ROC = -2 m

R = 99 %, signal+idler
AR for pump
Flat

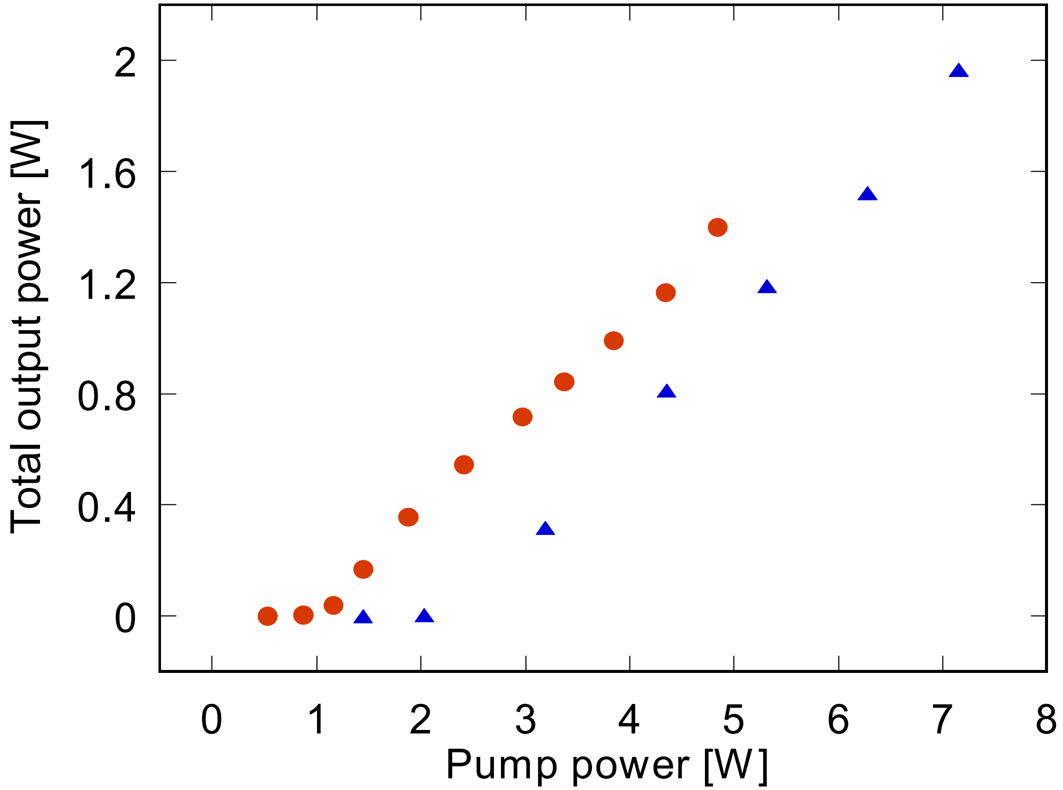
w_0 = 0.25 mm

η = 48 %

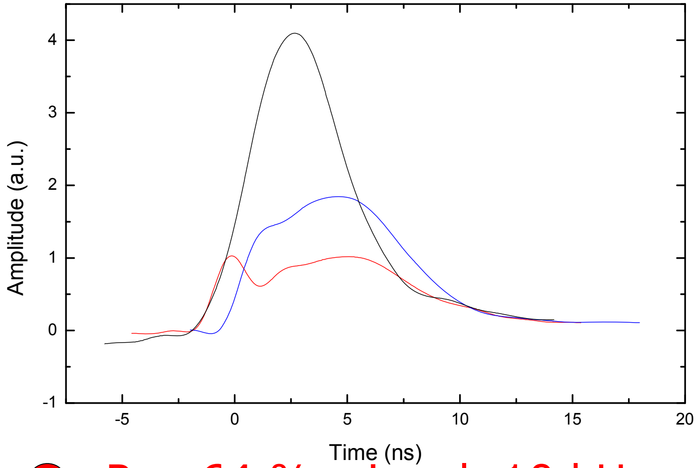
$P_{\text{out,max}} \approx$ 24 W

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

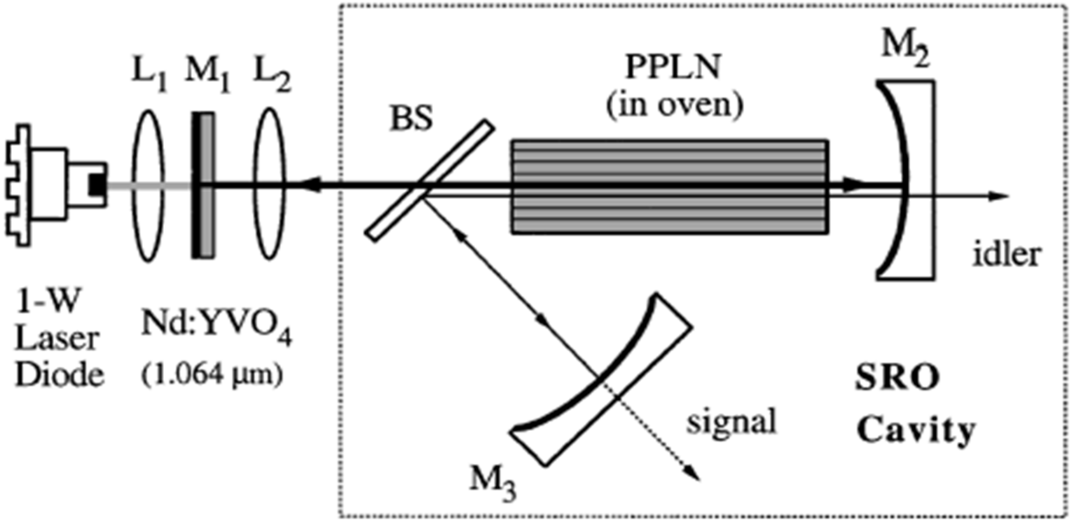
$\eta_{20kHz} = 28\ \%$

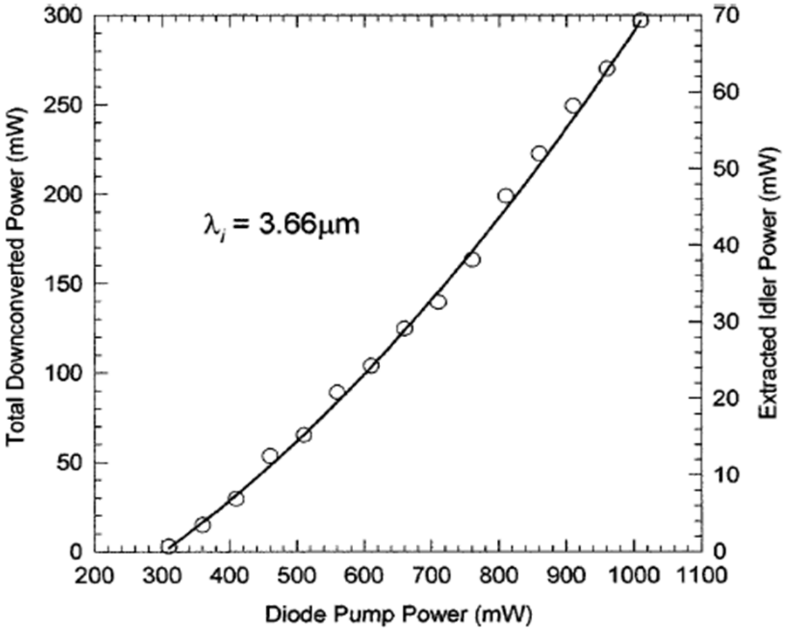
$\eta_{10kHz} = 28\ \%$

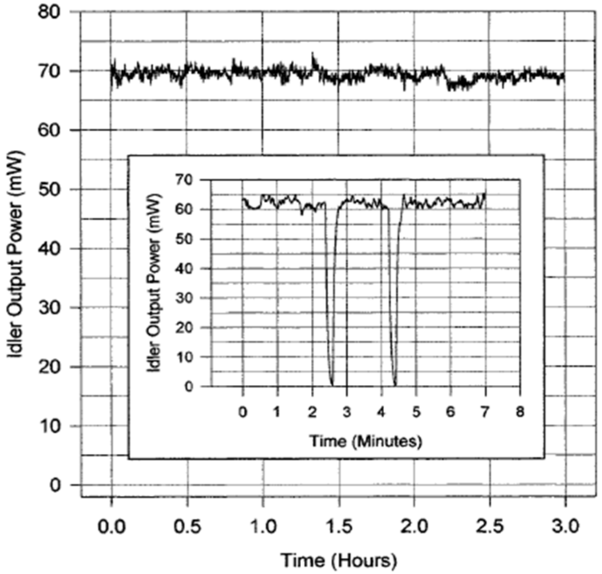
$P_{out,max} \approx 2$ W

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

Intracavity CW-SRO







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

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

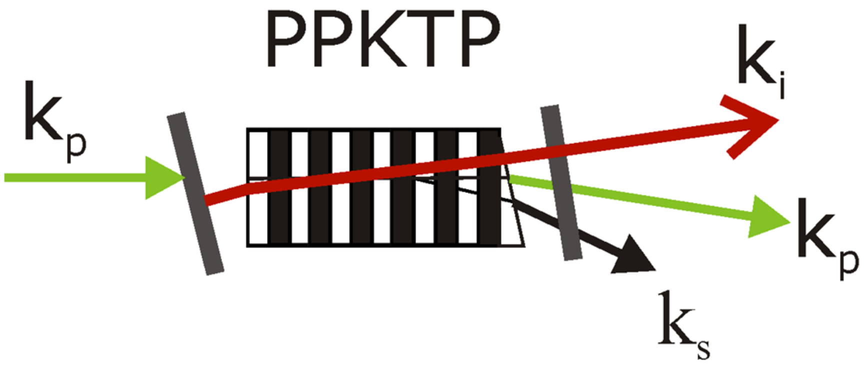
Tuning singly-resonant OPOs

Manipulating the QPM-crystal

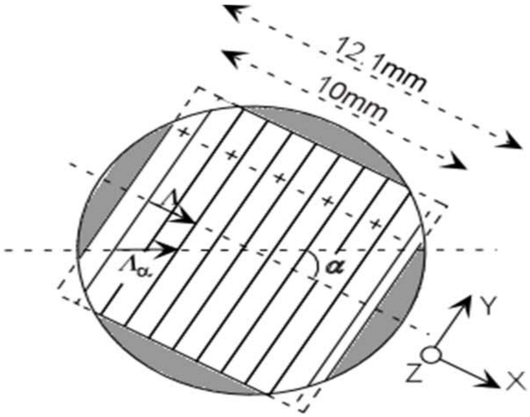
- Temperature
- Multigrating structures
- Fanned gratings
- Rotation
- Noncollinear interaction

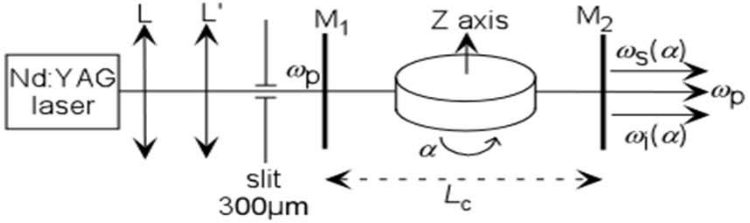
Noncollinear interaction

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



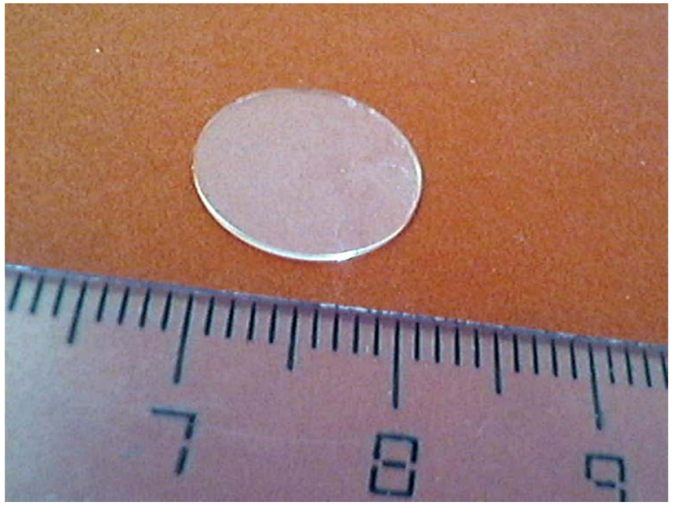
Widely tunable OPO with circular PPKTP

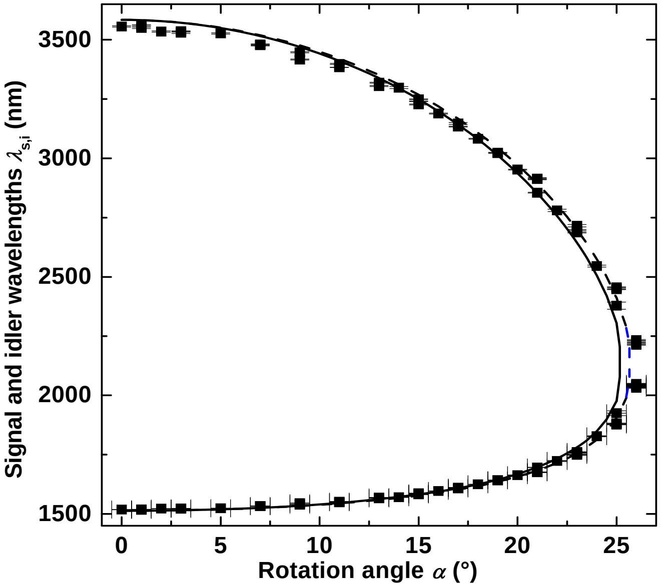




The pump laser
Nd:YAG, $\tau \approx 6$ ns, 10 Hz, $M^2 = 1.1$

The PPKTP sample 2.1 mm diameter, $\Lambda = 35.0$ µm
poled area 10 by 10 mm², thickness 0.5 mm,

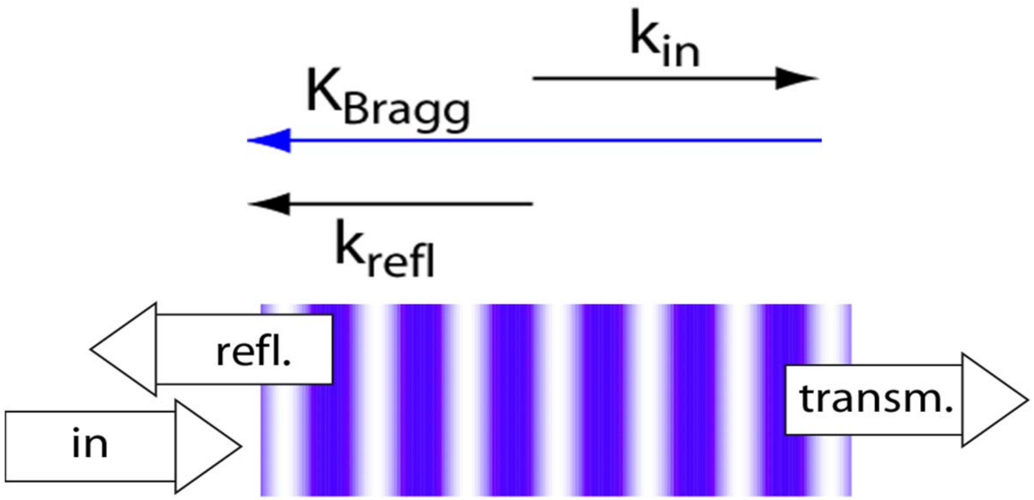




$\eta = 17.3\%$,
at $\alpha = 26°$.
$E_{tot} = 74$ µJ
$E_{pump} = 430$ µJ

Volume Bragg gratings

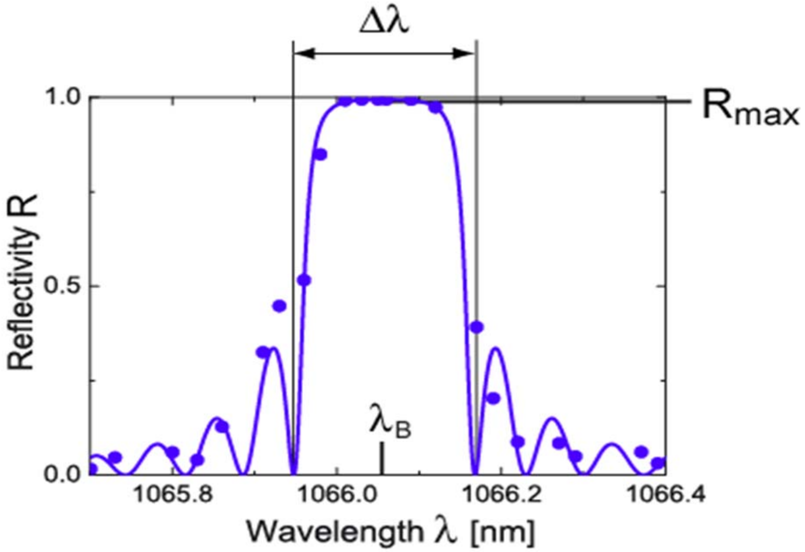
- Narrowband reflection peak
- Performance can be tailored to suit needs
- Made in durable and cheap glass



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

Material

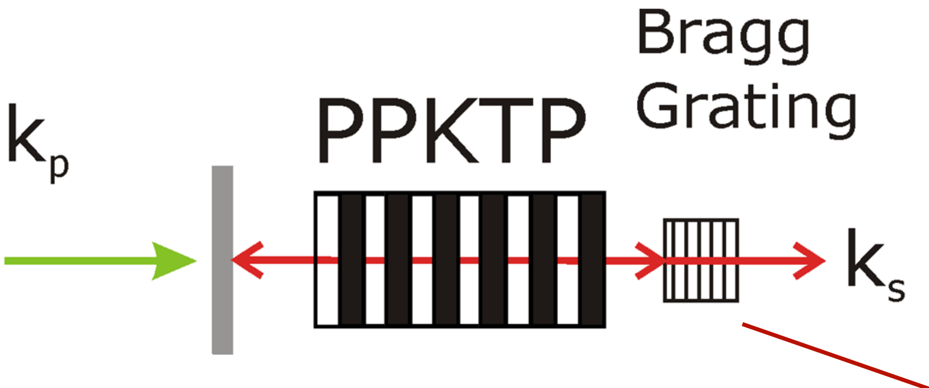
- Period, Λ
- Thickness, d
- Strength, n_1



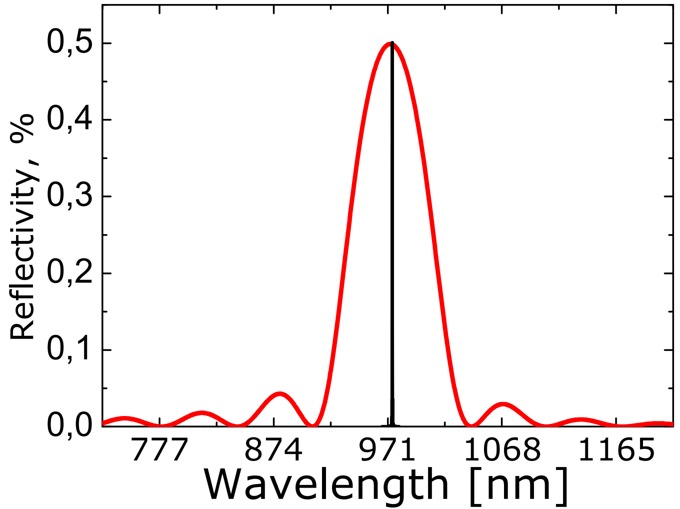
Optical

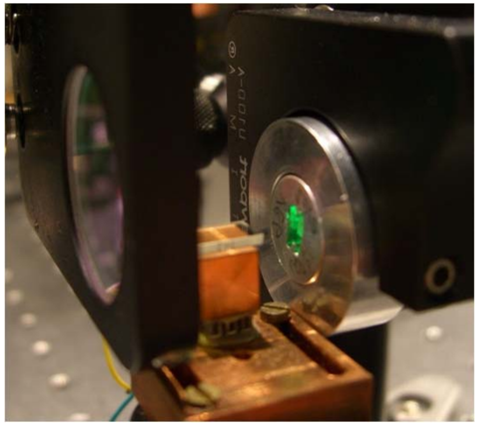
- $\lambda_B = 2 n_0 \Lambda$
- $R_{\max} = \tanh^2 \frac{\pi n_1 d}{\lambda_B}$
- $\Delta\lambda = \lambda_B \sqrt{\frac{4\Lambda^2}{d^2} + \frac{n_1^2}{n_0^2}}$

Cavity element – volume Bragg grating



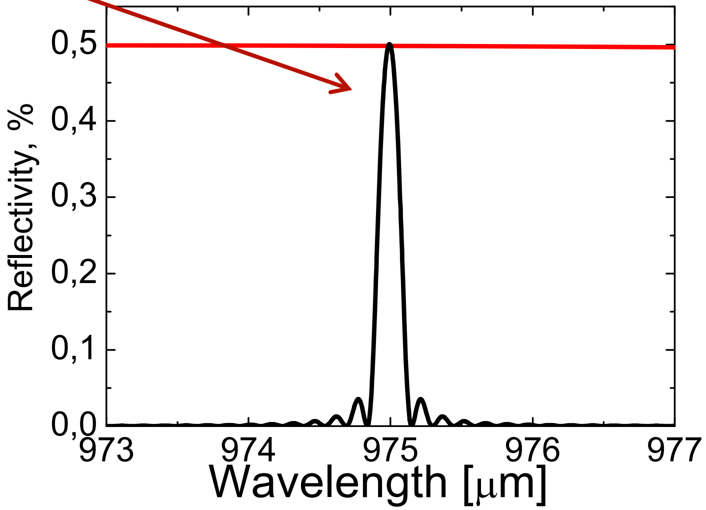
conventional mirror 150 nm



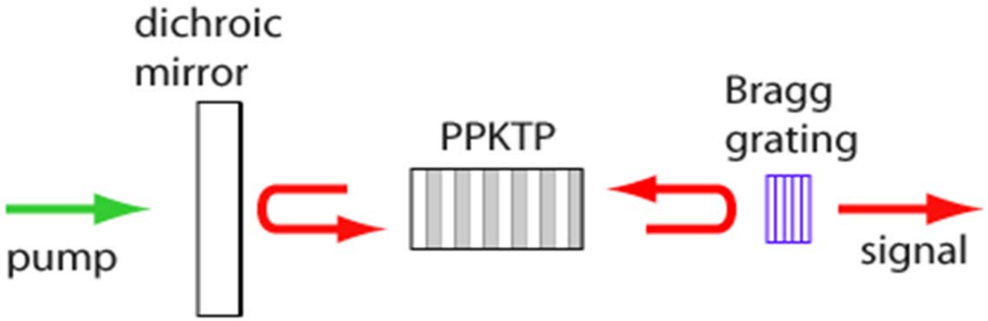


$\Delta\nu$ = 3.0 nm (950 GHz) @ 975nm

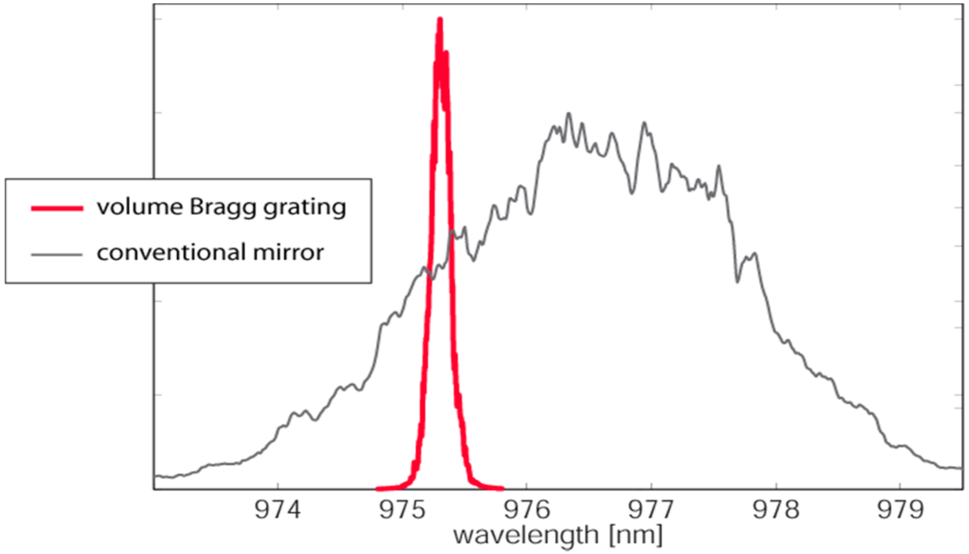
$\Delta\nu$ = 0.16 nm (50 GHz) @ 975nm



Narrowband OPO at 975 nm

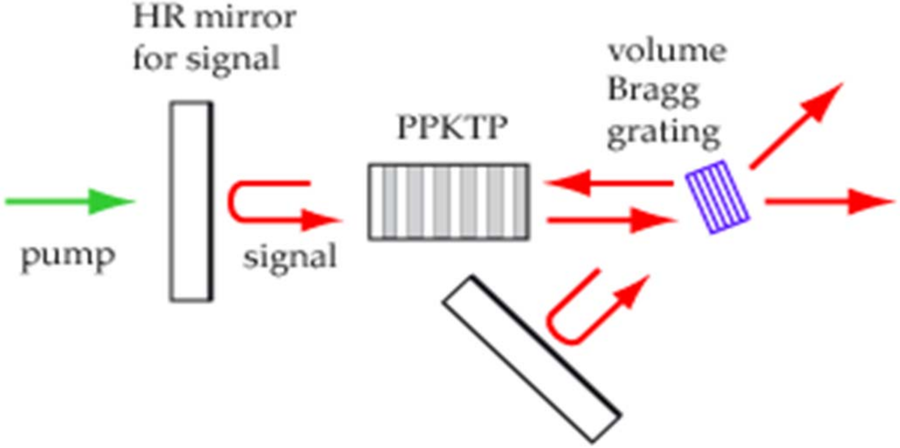


spectrum

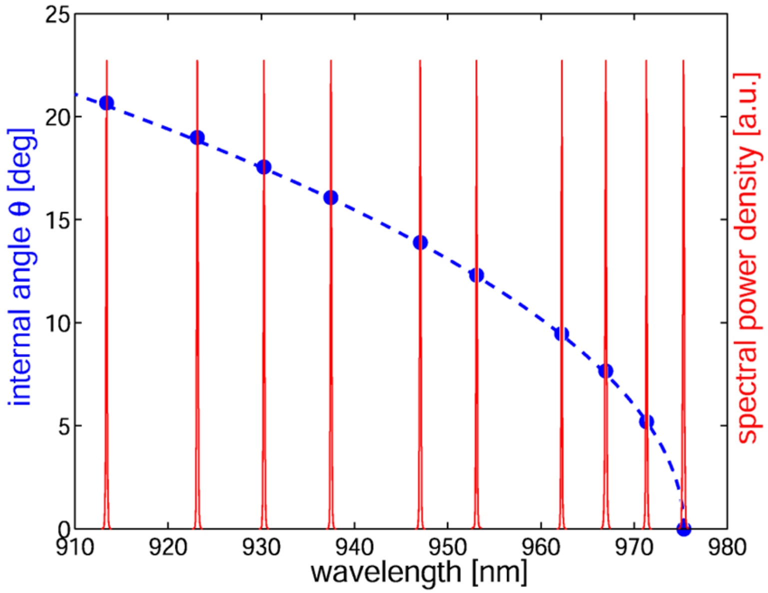


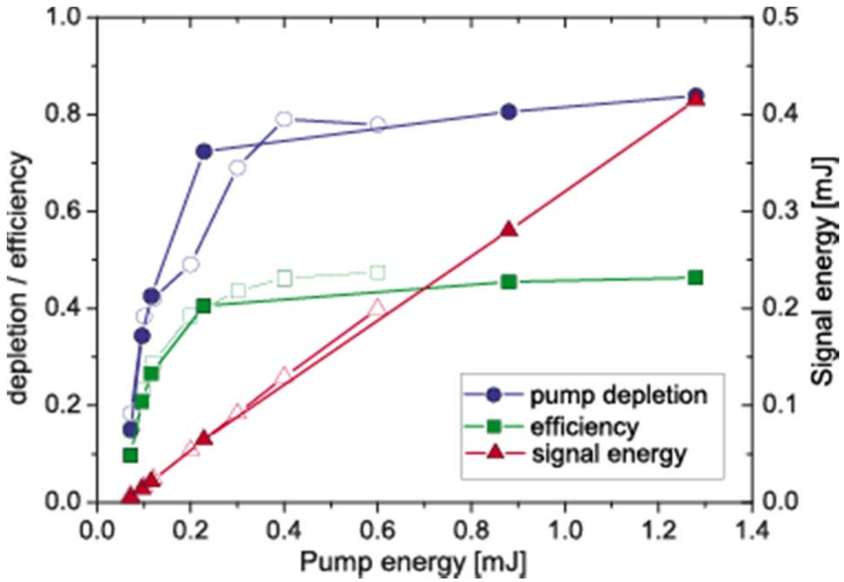
0.4 mJ signal
limited by pump

Angle tuning

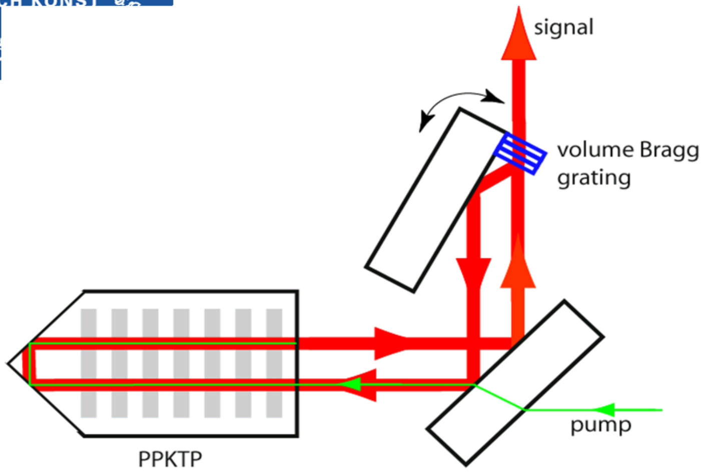


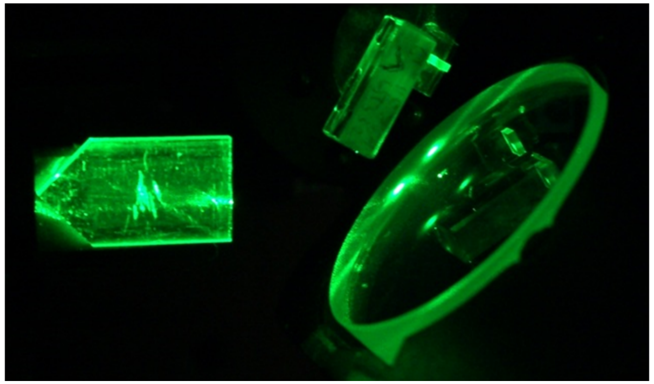
tuning spectra

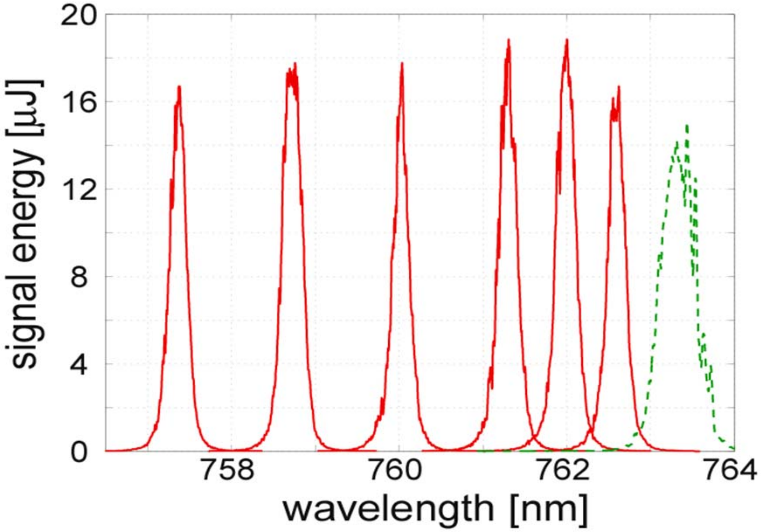




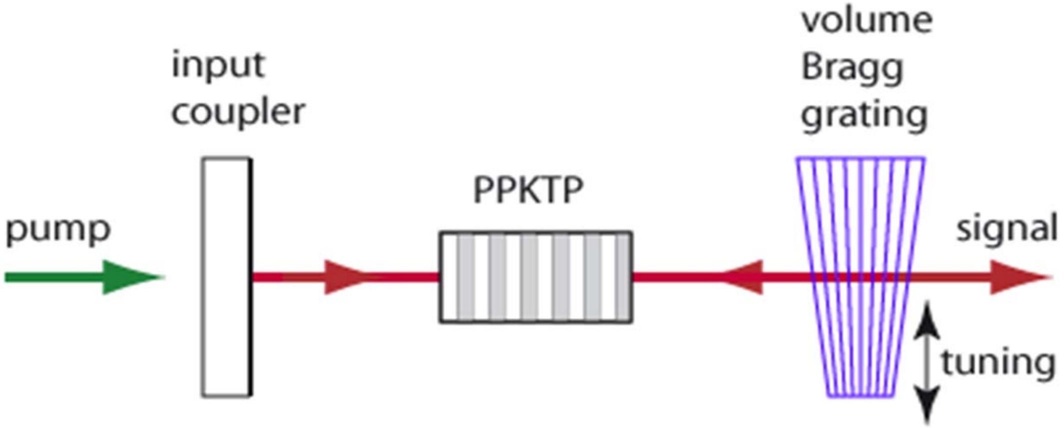
Angle tuning improved



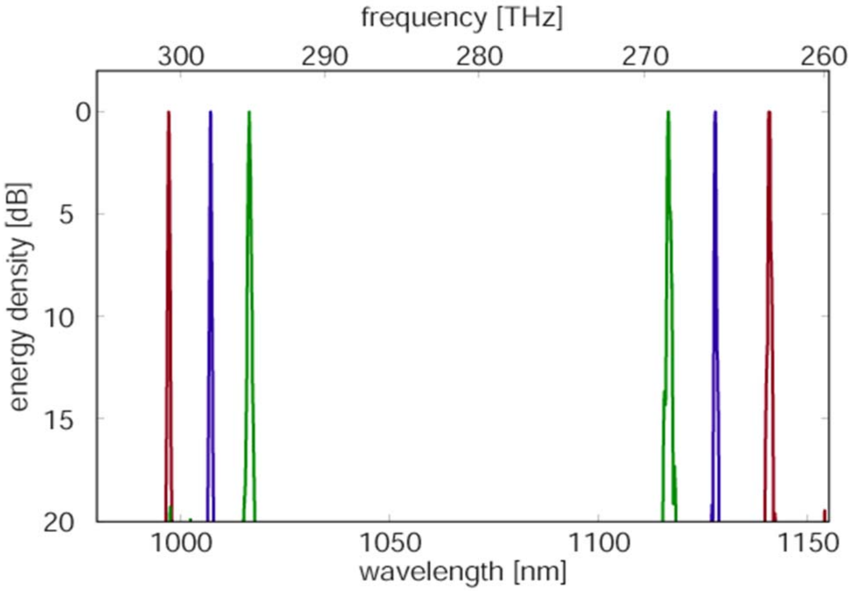



tuning spectra

OPO with transversely chirped Bragg grating

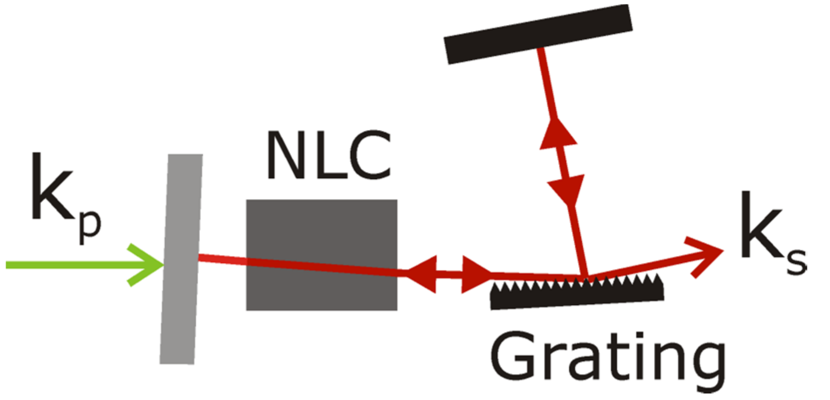


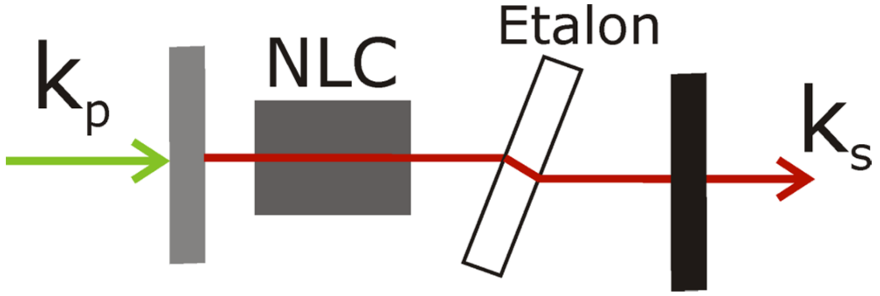
tuning spectra



Linewidth narrowing - OPO

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





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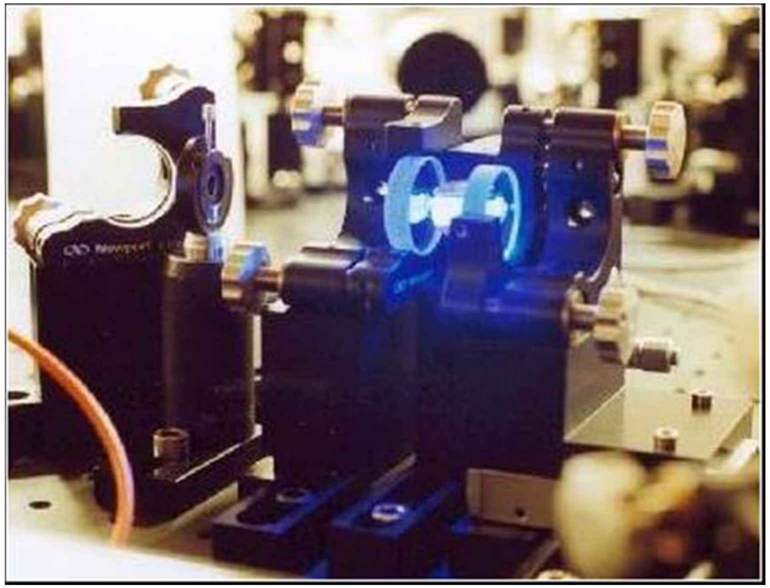
1. S. Brosnan and R.L. Byer, IEEE J. Quantum Electron. **15**, 415 (1979)

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