Tunable Coherent Optical Sources for Gamma-Ray Generation

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Outline

- The Laser
- Optical Parametric Oscillator (OPO)
- OPO Advantages
- OPOs for γ-Ray Generation
- Device Formats
- Costs
- Conclusions

The Laser

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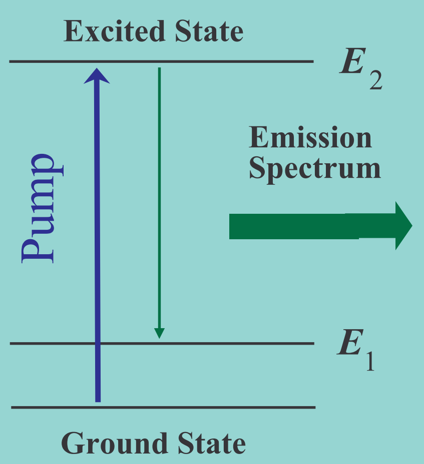
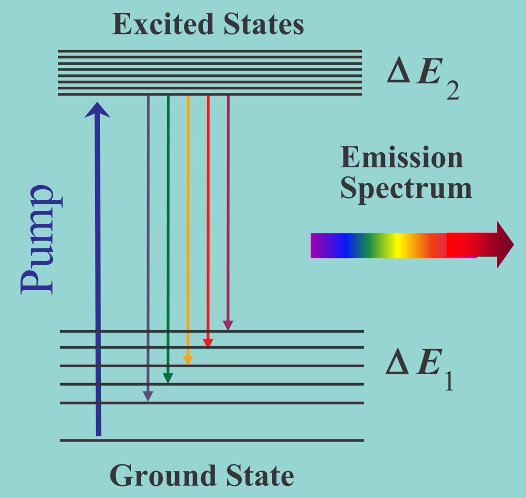
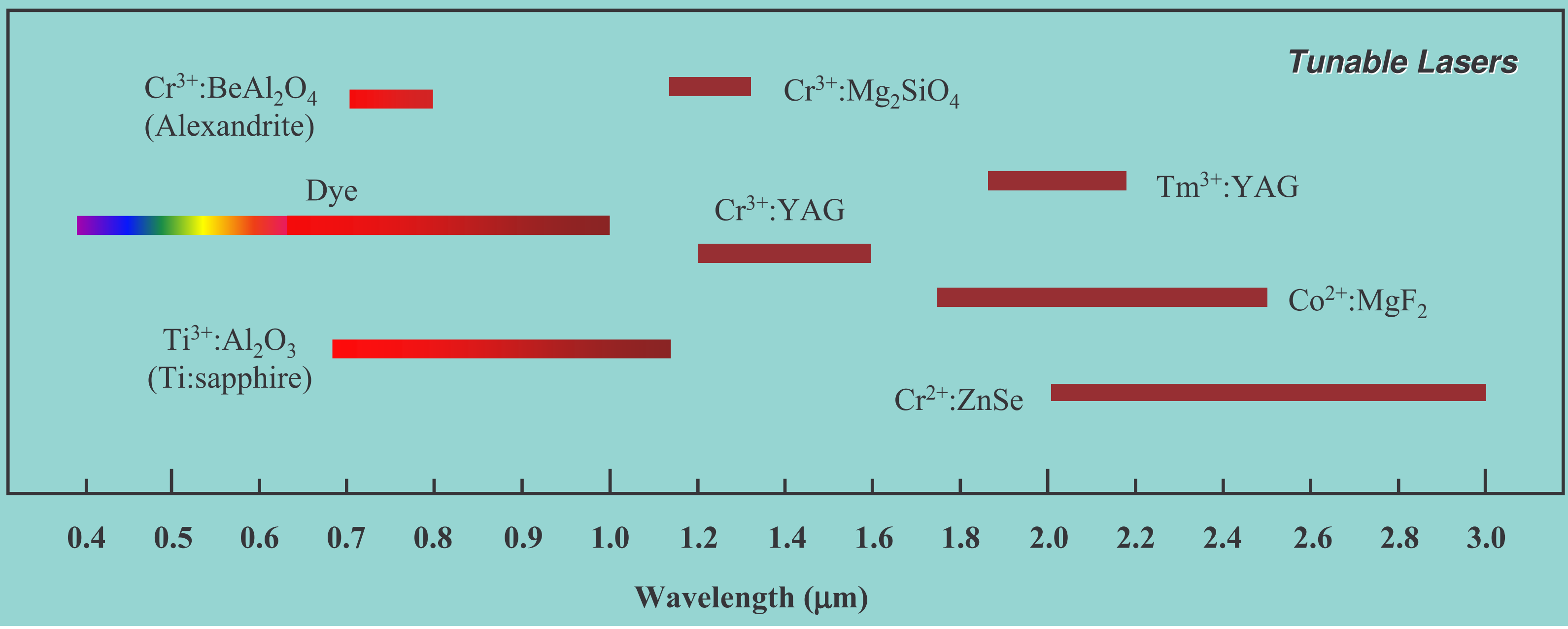
"Traditional" Laser

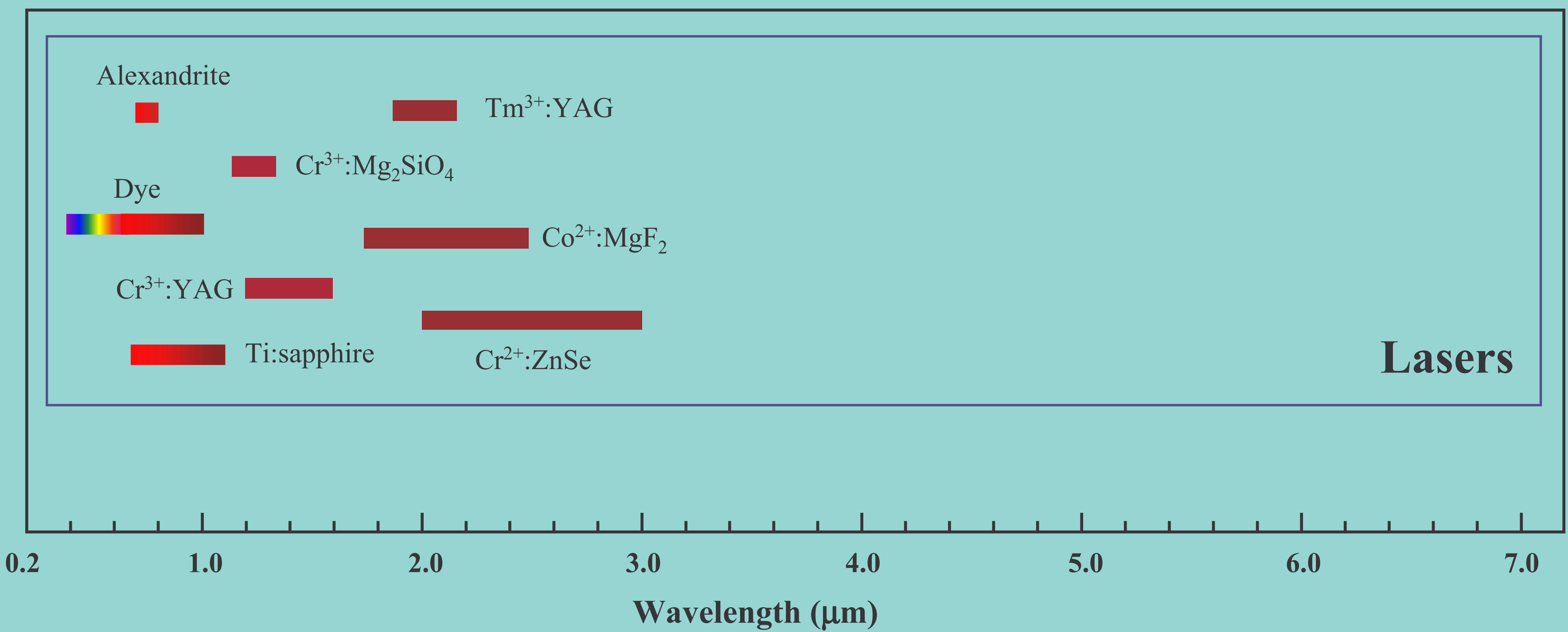


"Tunable" Laser

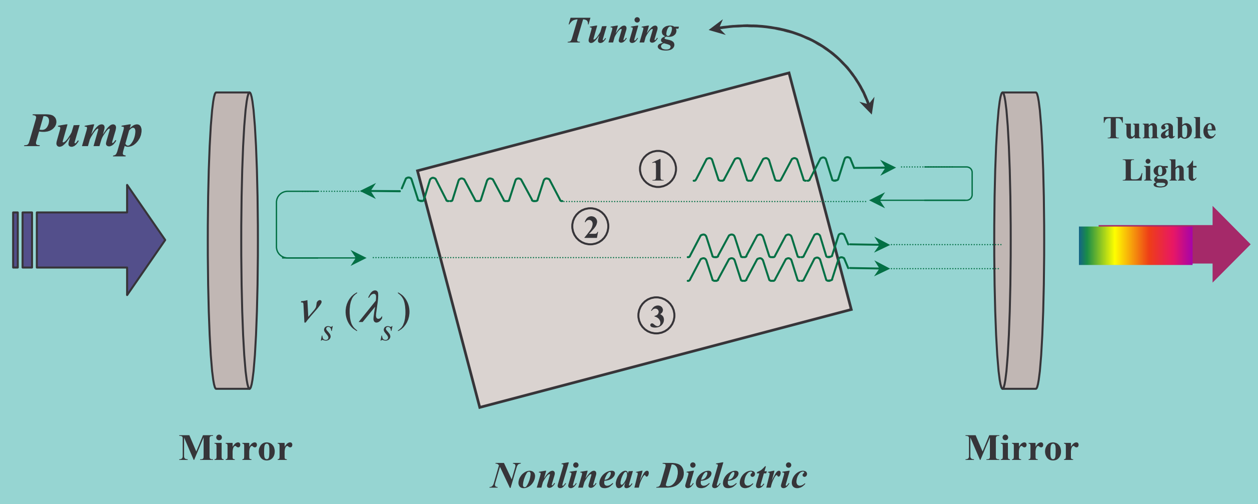


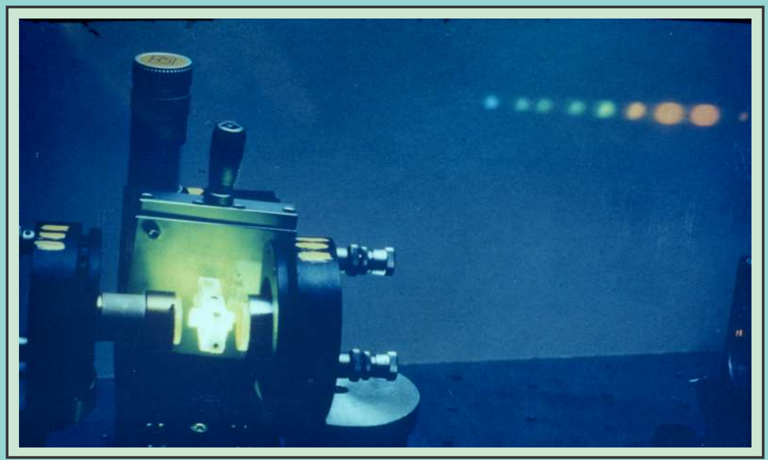


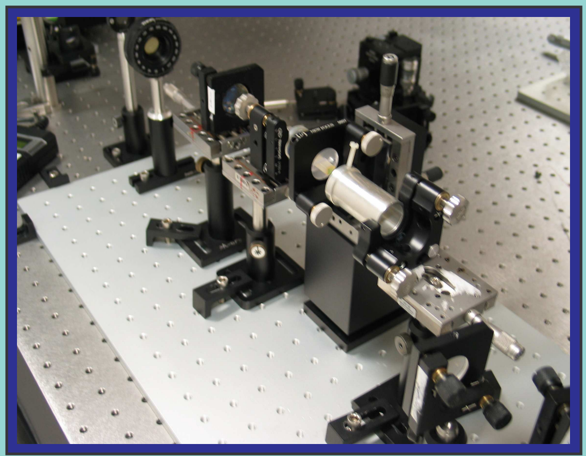
Spectral Coverage



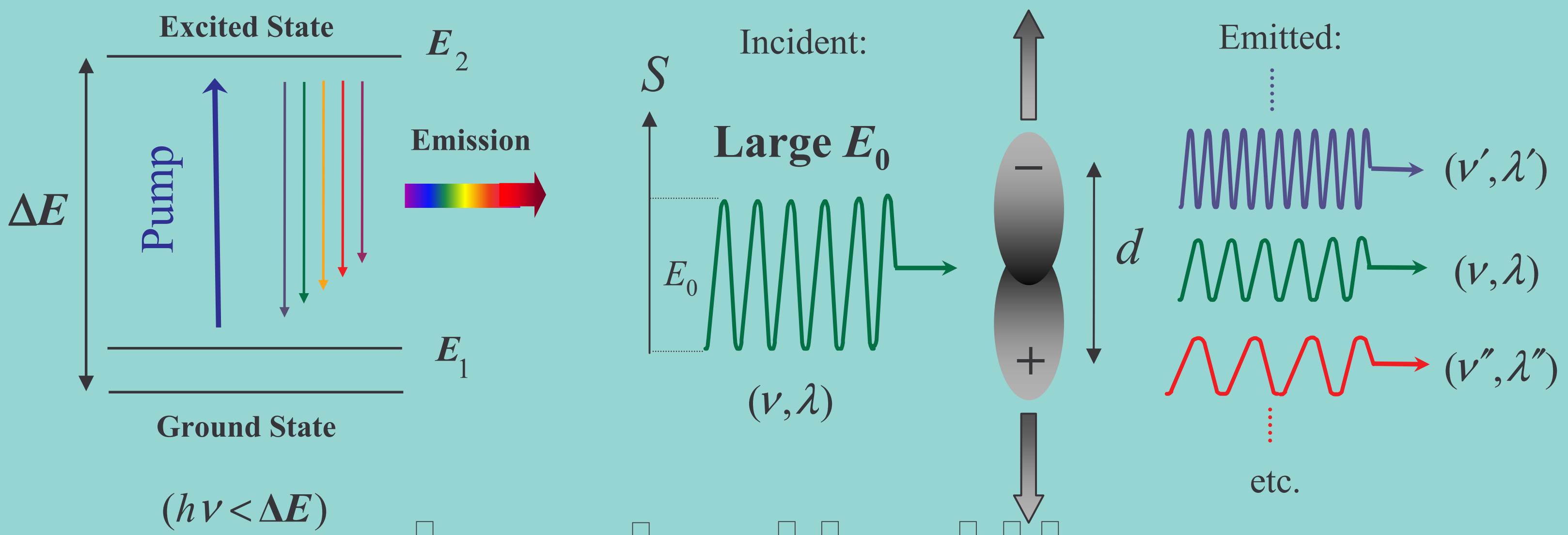
Optical Parametric Oscillator (OPO)



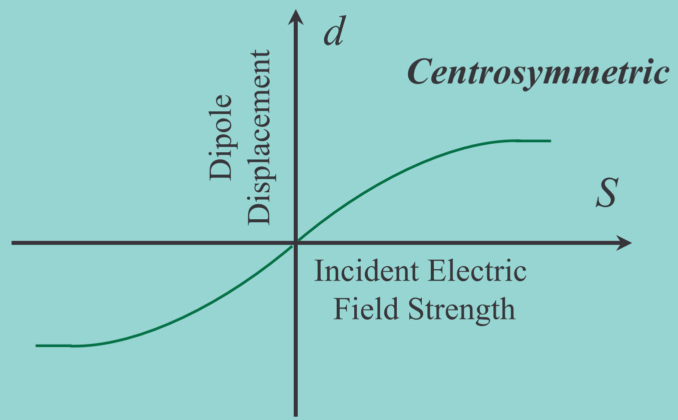


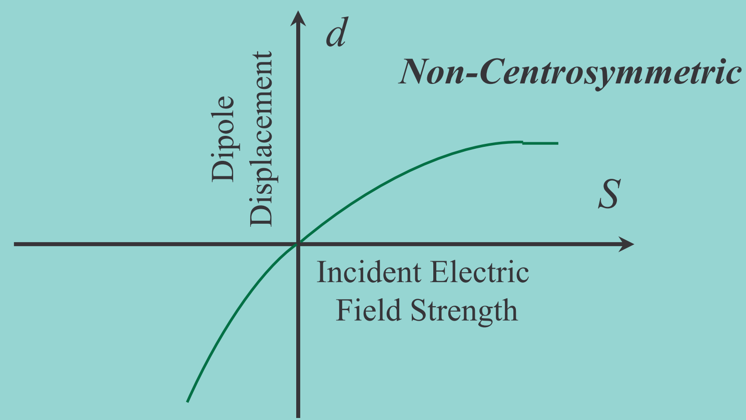


Operating Principle



$$\vec{P} = \varepsilon_0 \left[\chi^{(1)}.\vec{E} + \chi^{(2)}.\vec{E}.\vec{E} + \chi^{(3)}.\vec{E}.\vec{E}.\vec{E} + \cdots \right]$$





$$\vec{P} = \varepsilon_0 \left[\chi^{(1)}.\vec{E} + \chi^{(3)}.\vec{E}.\vec{E}.\vec{E} + \cdots \right]$$

$$\vec{P} = \varepsilon_0 \left[\chi^{(1)}.\vec{E} + \chi^{(2)}.\vec{E}.\vec{E} + \chi^{(3)}.\vec{E}.\vec{E}.\vec{E} + \cdots \right]$$

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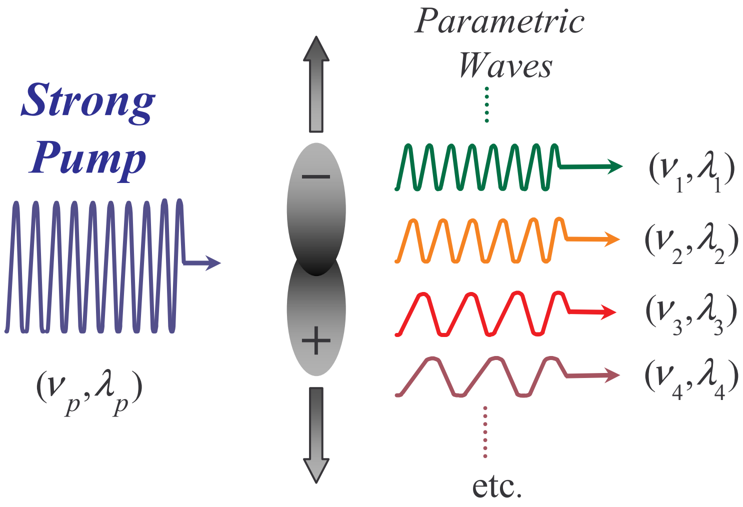
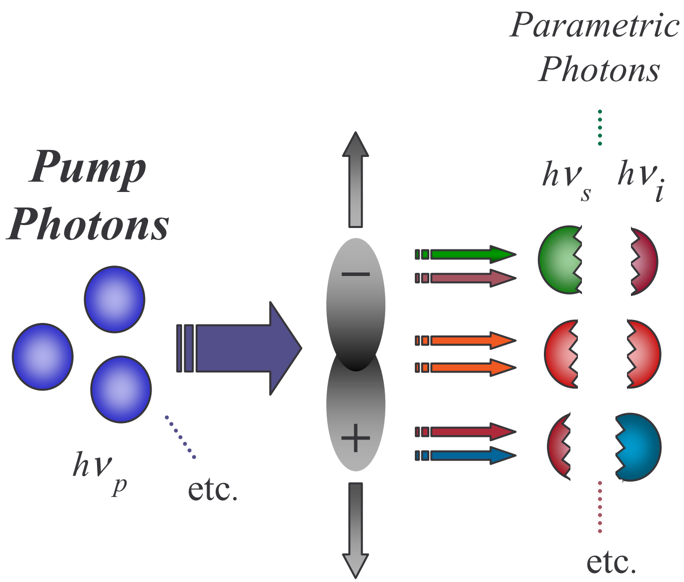
Optical Parametric Generation



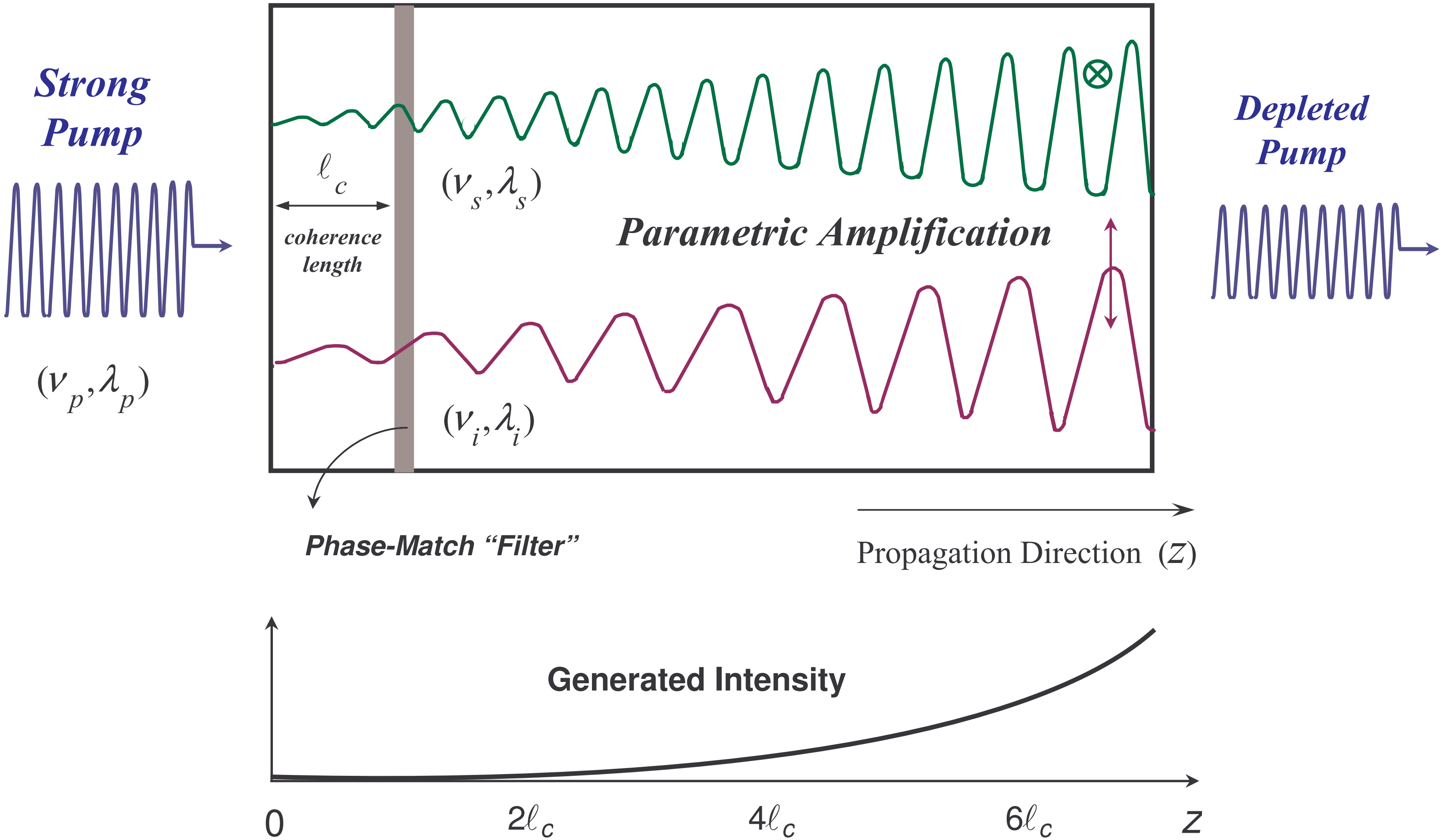
Wave Picture

Photon Picture



Birefringent Phase-Matching

Nonlinear Material : Anisotropic



Quasi-Phase-Matching

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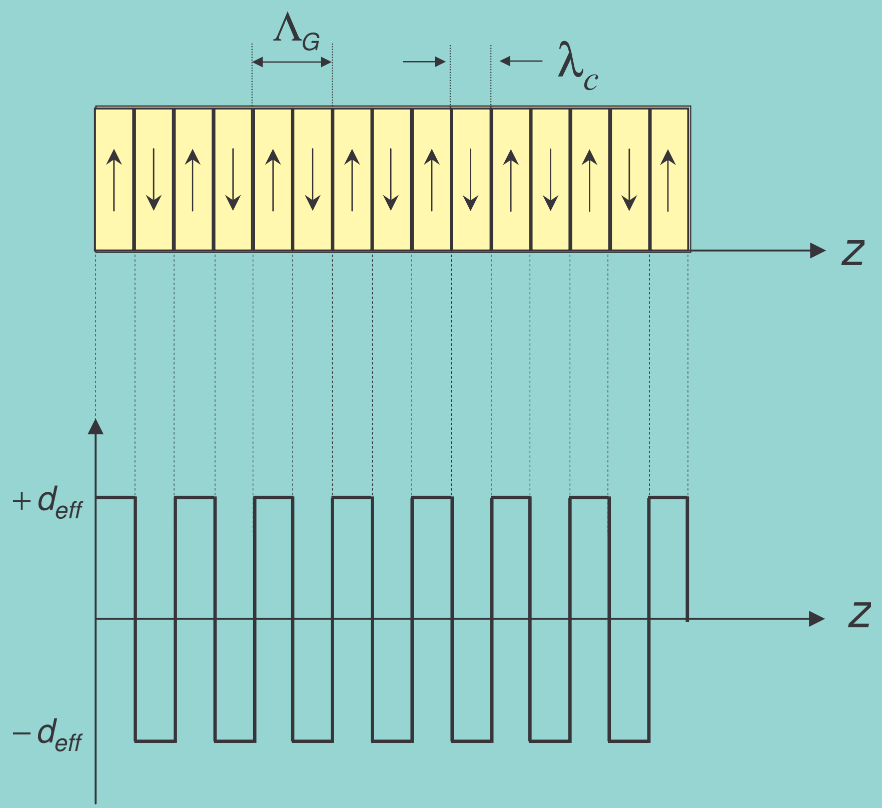
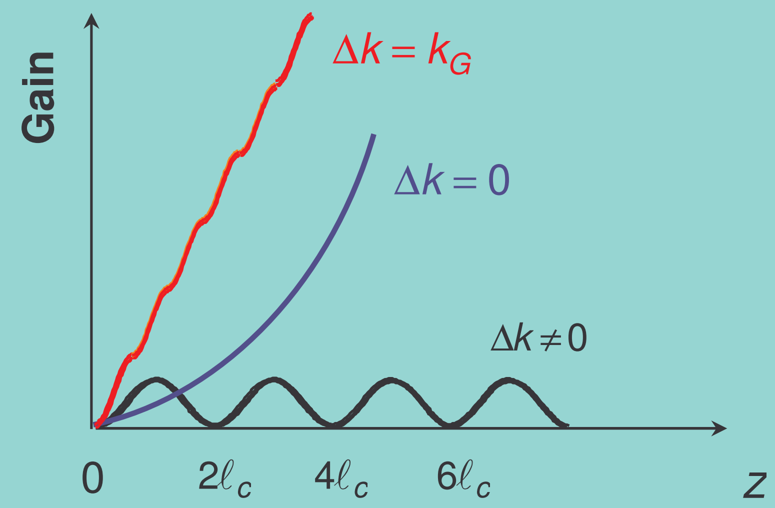


$$\Delta k \rightarrow \Delta k_Q = k_3 - k_2 - k_1 - k_G$$

Phase-Match Condition: $\Delta k_Q = k_3 - k_2 - k_1 - k_G = 0$

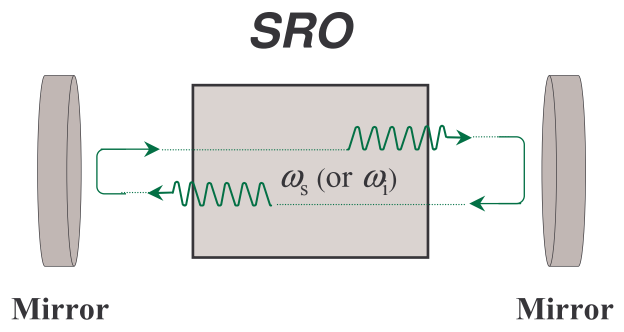
$$k_G = 2\pi / \Lambda_G$$



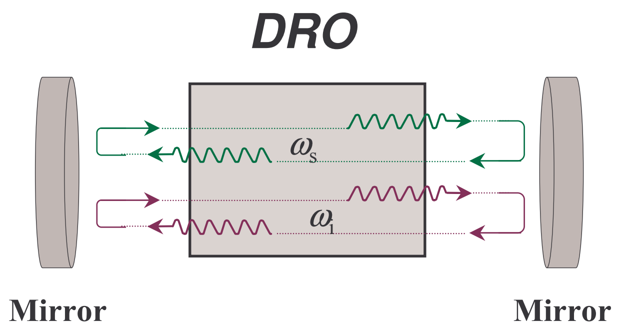
$$d_{eff}(\text{QPM}) = \left(\frac{2}{m\pi}\right) d_{eff}$$

OPOs: Basic Resonance Configurations

Singly Resonant Oscillator

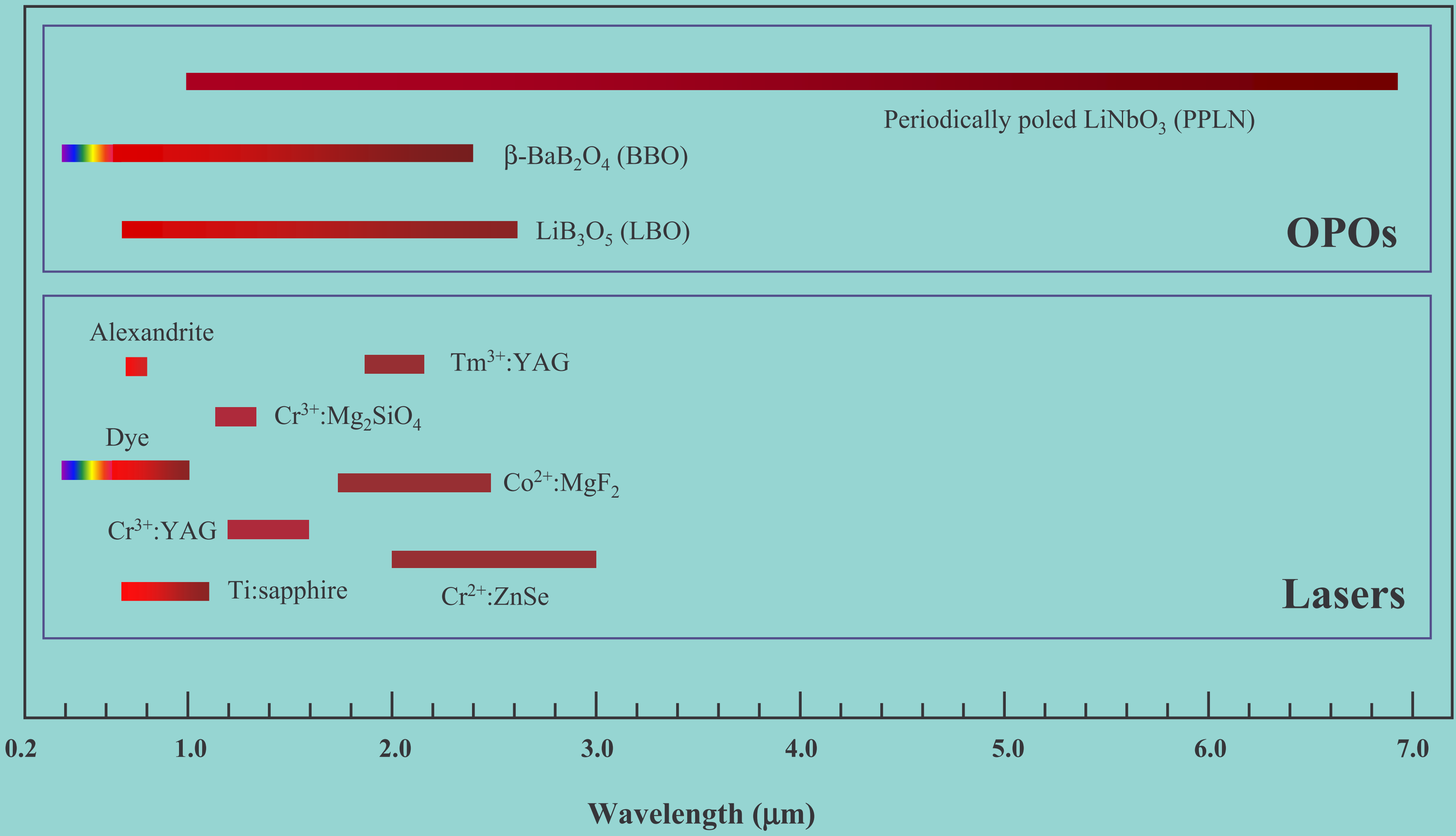


Doubly Resonant Oscillator



OPO Advantages

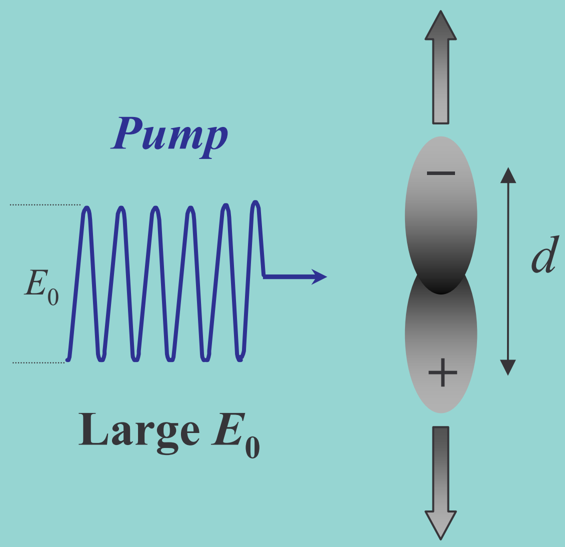
Spectral Versatility

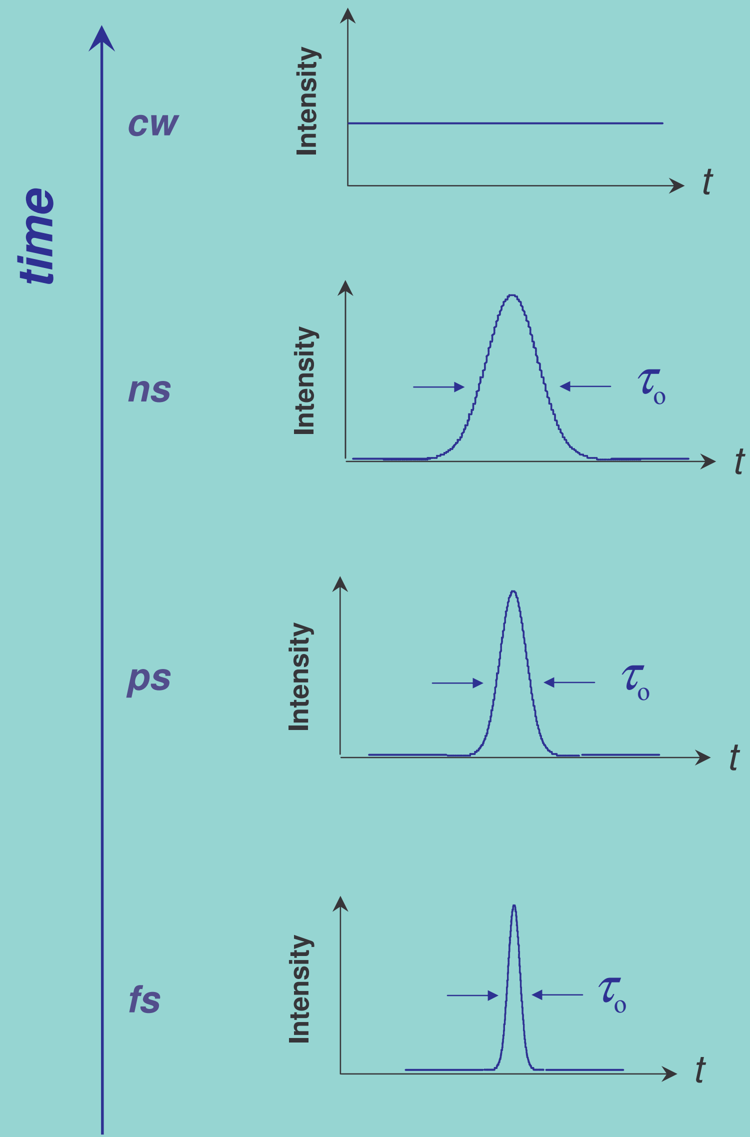


Temporal Versatility

Electronic Susceptibility

(<< 10^{-15} seconds)





Optical Parametric Oscillators (OPOs)

- **Wavelength Versatility: Ultraviolet ⟶ Mid-Infrared / THz**
- **Temporal Versatility: CW ⟶ Femtosecond**
- **Operation: > Room Temperature**
- **High Powers / Energies: 30 W, 200 mJ**
- **High Efficiencies: Typically > 50%**
- **Compact, All-Solid-State Design**

Resurgence

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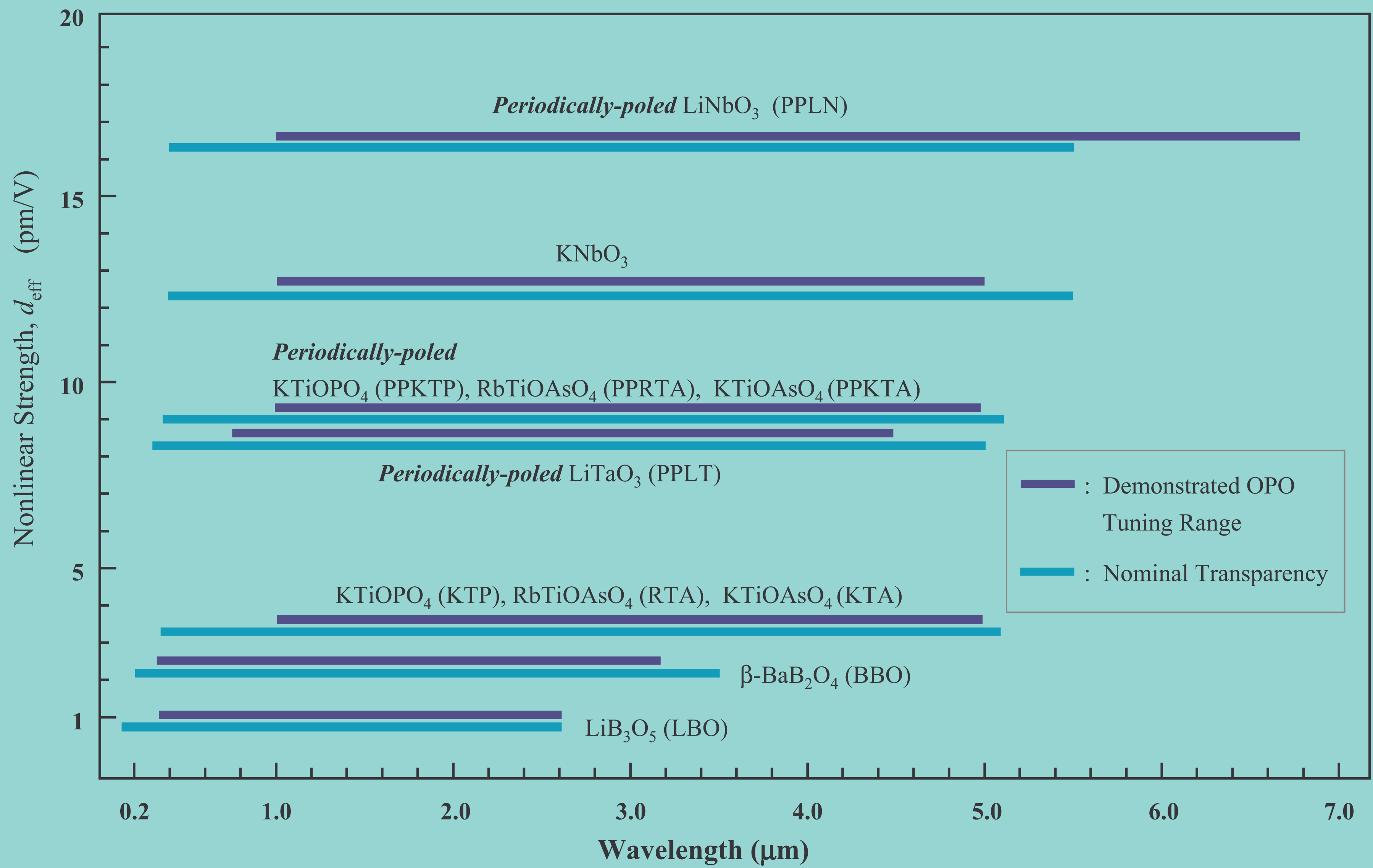
Nonlinear Materials	*Laser Sources*	*Device Innovations*
• Birefringent: (BBO, LBO, KTP, ZGP,..) • Quasi-Phase-Matched (PPLN, PPKTP, PPRTA,..)	• Crystalline • Semiconductor • Fiber	• Intracavity • Pump-Resonant • Dual-Cavity, etc.

↓ ↓ ↓

New Generation of OPO Devices

- Low-Threshold, Low-Power (mW) ⟶ High-Threshold, High-Power (Watts)
- CW ⟶ Femtosecond; nJ ⟶ mJ; Hz ⟶ GHz
- High Spatial and Spectral Coherence; High Frequency Stability
- Exceptional Tunability (Coarse and Fine)
- High Efficiency (>50%)
- Compact; All-Solid-State
- Novel Applications

New Nonlinear Materials



Device Formats

High-Power CW OPO

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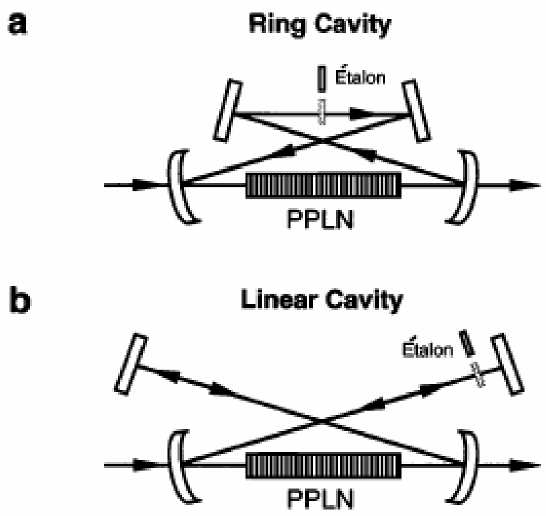
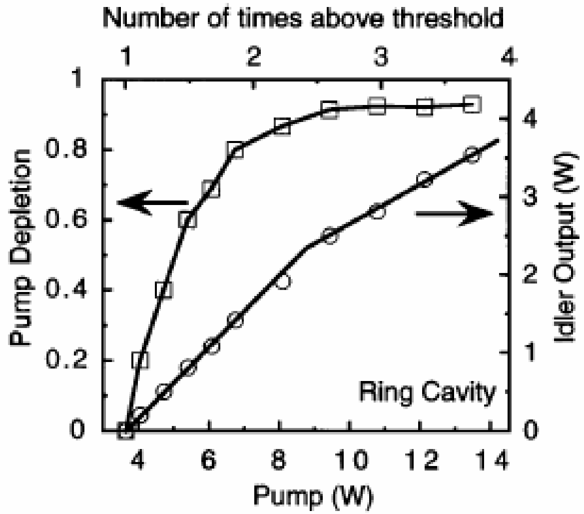
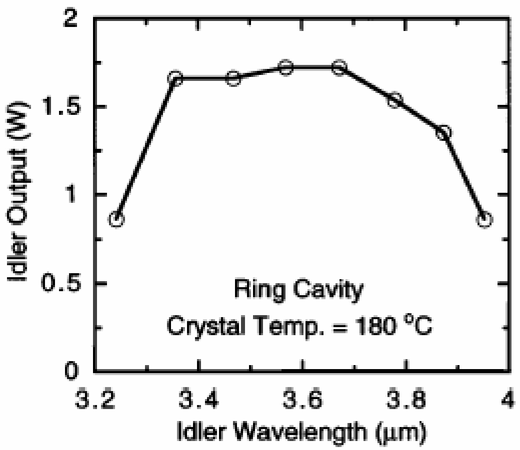
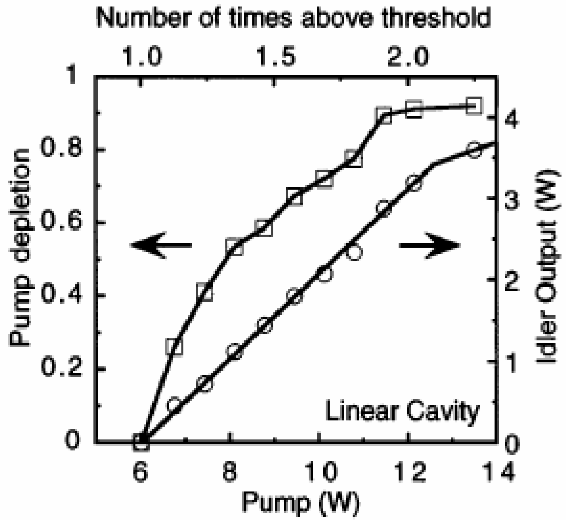




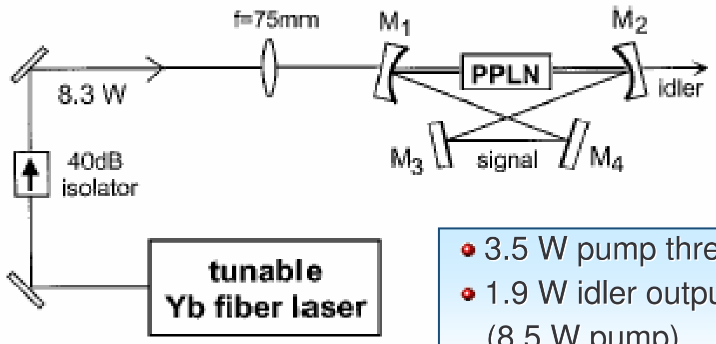
- P_{th} ~ 4-6 W
- P_{idler} ~ 3.5 W (8.5 W pump)
- λ_{idler} ~ 3-4 μm



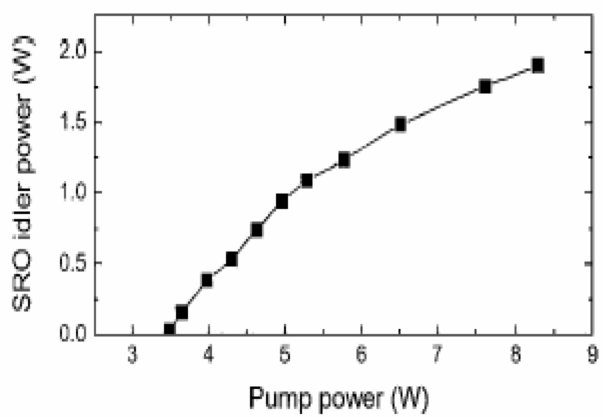


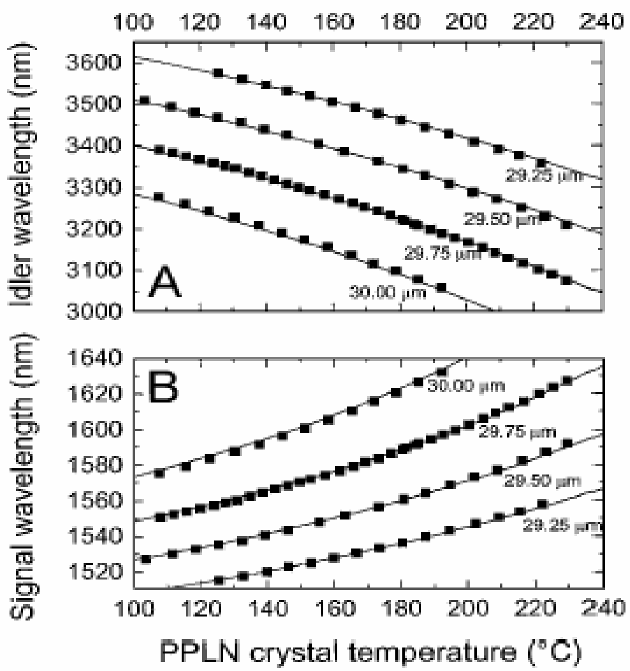
W. R. Bosenberg *et al.*, *Opt. Lett.* 21, 1336-1338 (1996).

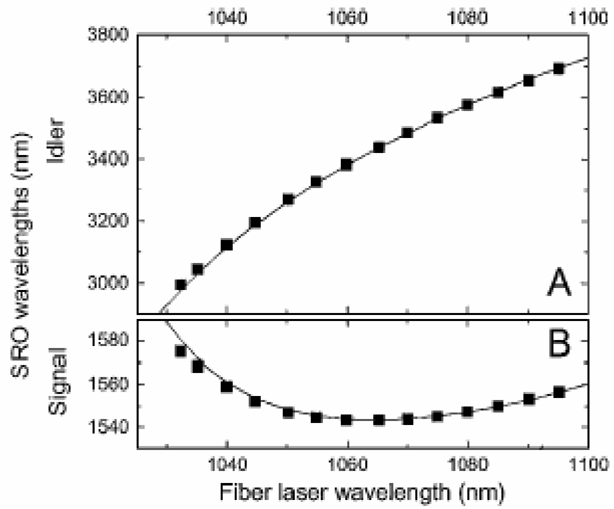
Fiber-Laser-Pumped High-Power CW OPO



- 3.5 W pump threshold
- 1.9 W idler output (8.5 W pump)
- 3.0-3.7 µm idler tuning

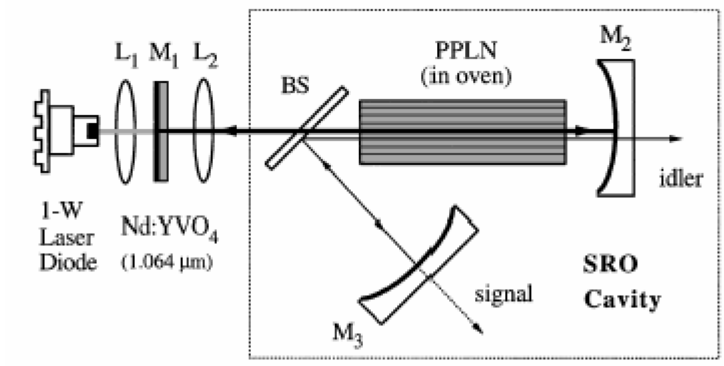




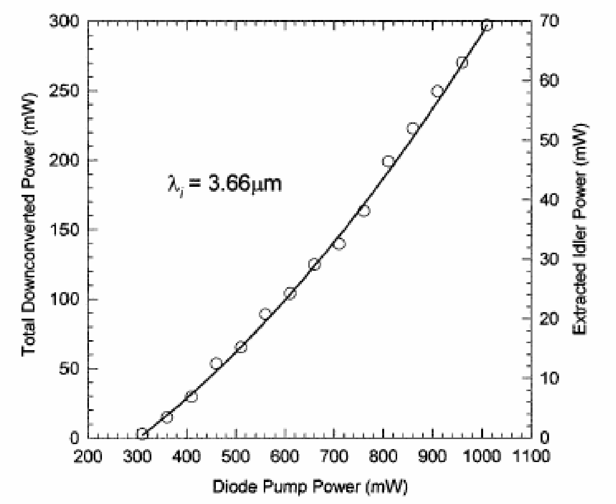


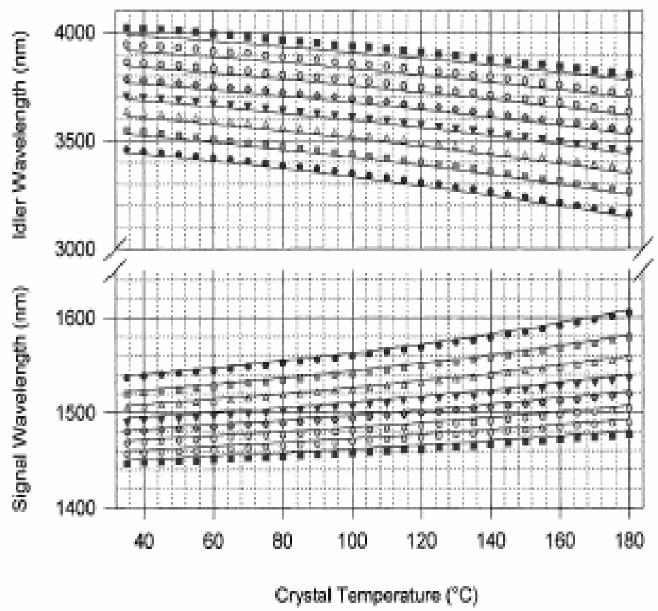
P. Gross *et al.*, *Opt. Lett.* 27, 418-420 (2002).

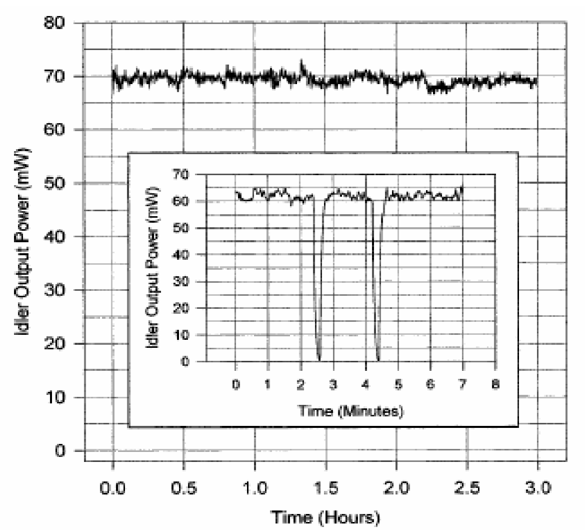
Miniature CW Intracavity OPO



- P_{th} = 300 mW (diode power)
- P_{idler} ~ 70 mW (1 W diode power)
- λ_{idler} ~ 3.1-4.1 μm

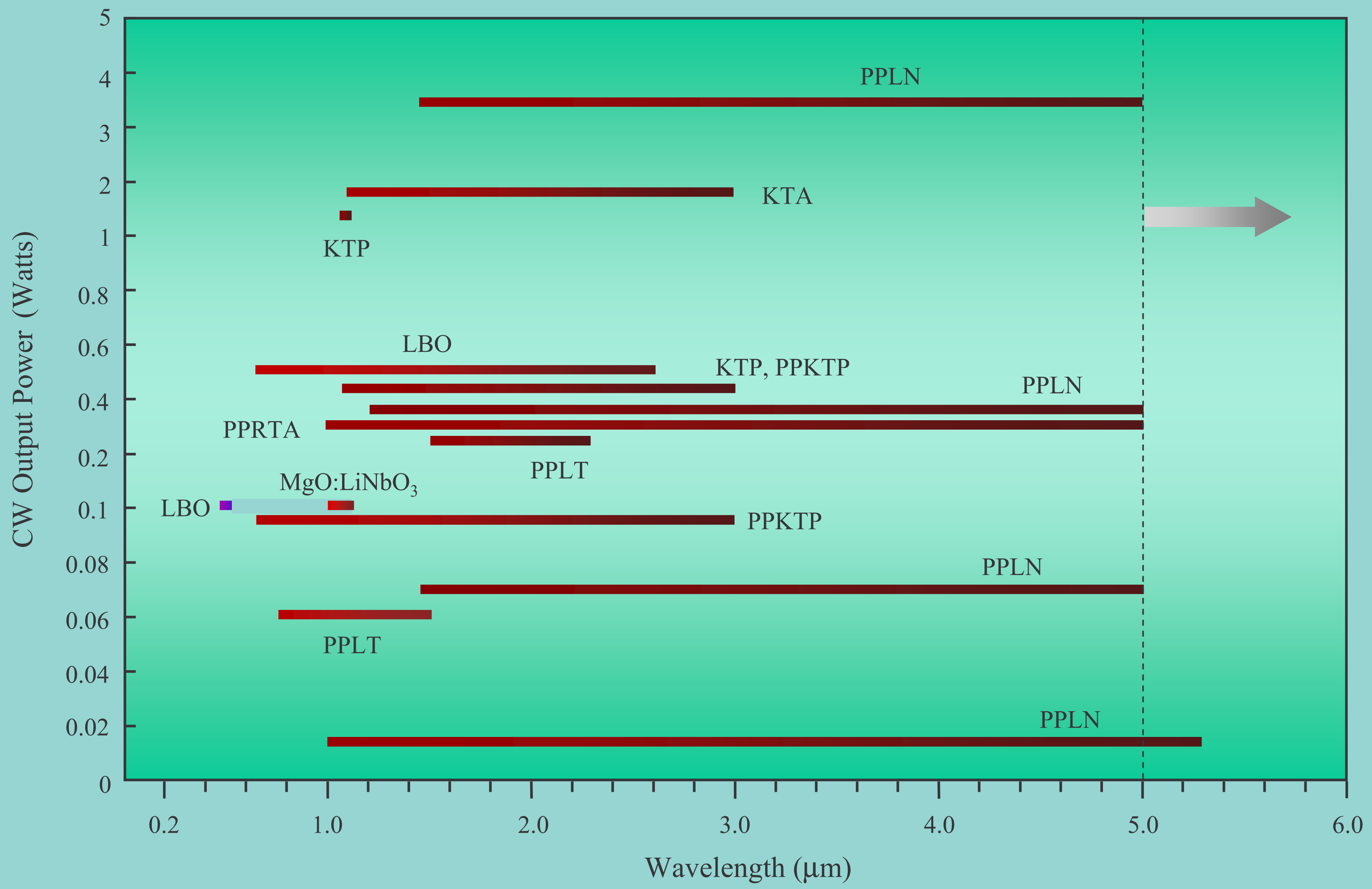






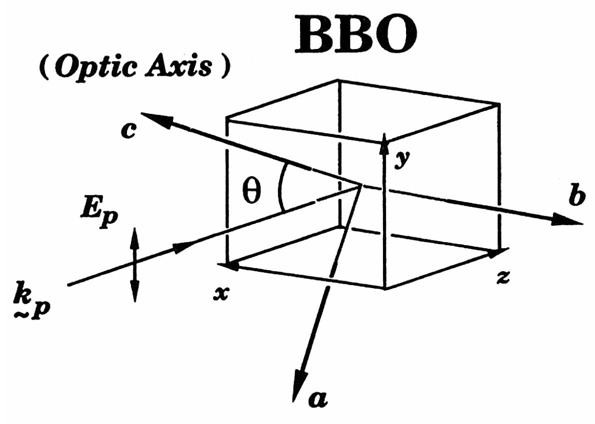
D. J. M. Stothard *et al.* , *Opt. Lett.* 23, 1895-1897 (1998).

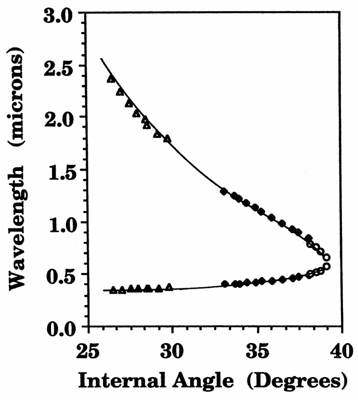
CW OPOs

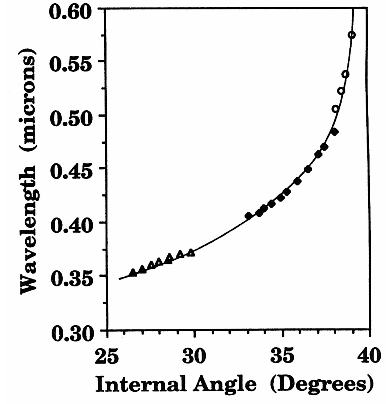


PPLN
KTA
KTP
LBO
KTP, PPKTP
PPLN
PPRTA
PPLT
MgO:LiNbO$_3$
LBO
PPKTP
PPLN
PPLT
PPLN
CW Output Power (Watts)
5
4
3
2
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0
0.2
1.0
2.0
3.0
4.0
5.0
6.0
Wavelength (µm)

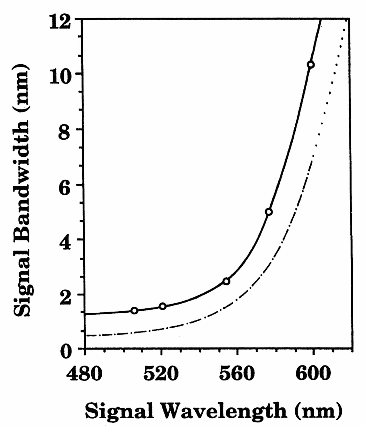
Nanosecond OPOs

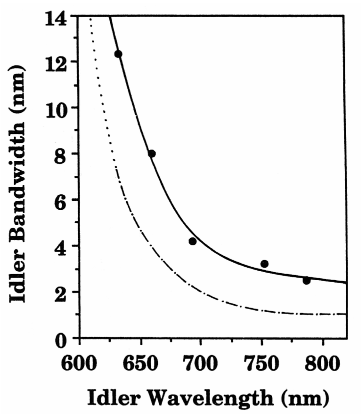


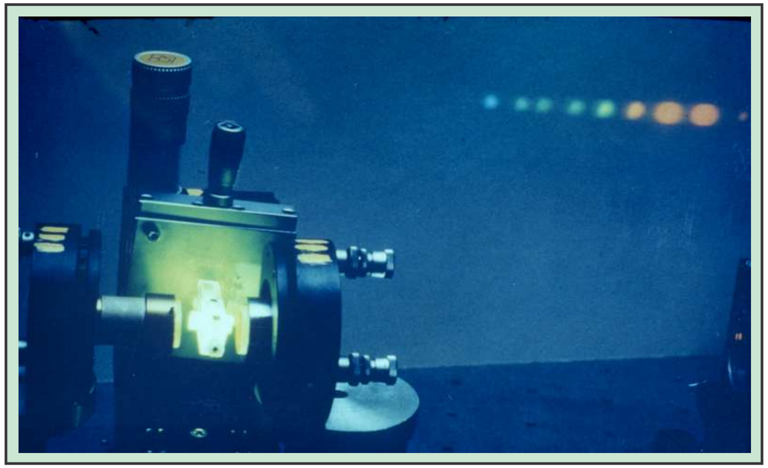




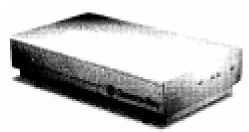
Tuning Range: 0.35-2.4 µm







Commercial System:



MOPO Series Optical Parametric Oscillator
MOPO-HF

Pulsed Mid-IR OPO (4-12 μm)

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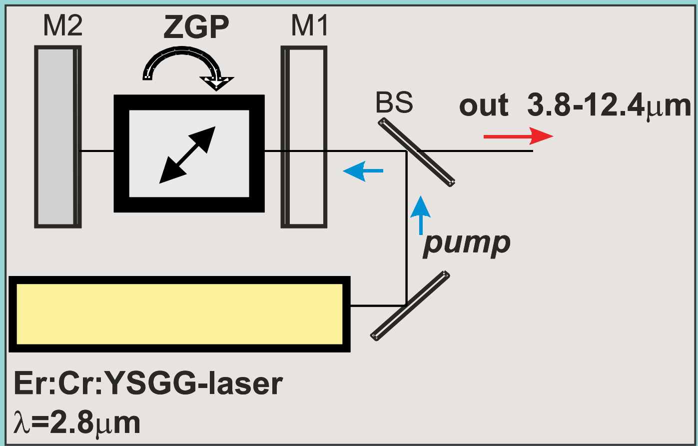
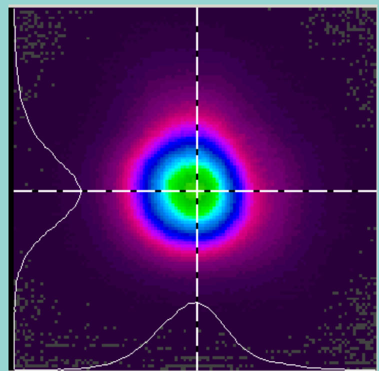
Erbium (2.8 μm) laser pumped ZGP OPO

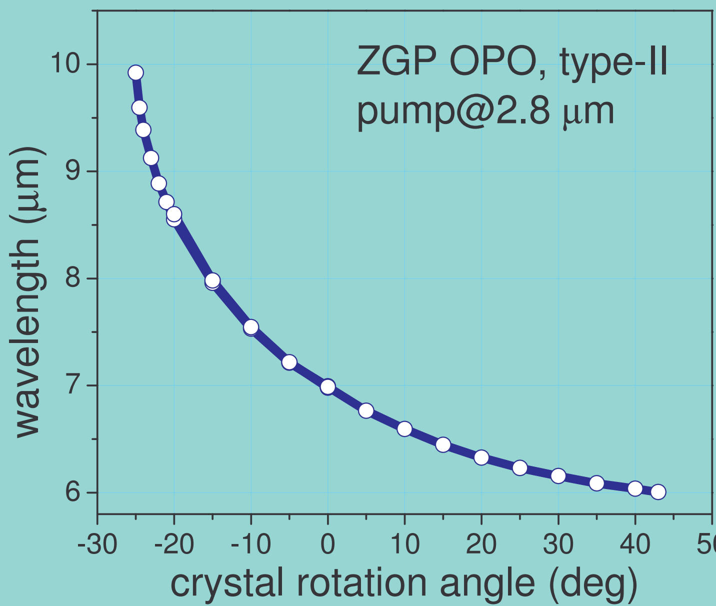
Pump: 2.8 μm, 3 mJ, 100ns, 25 Hz

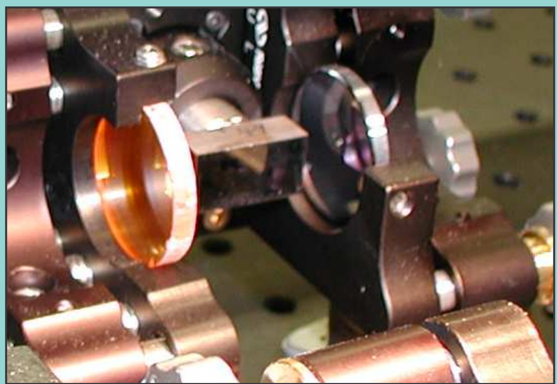


Far Field
FWHM 3.6 mrad
λ= 7 μm



Tuning curve



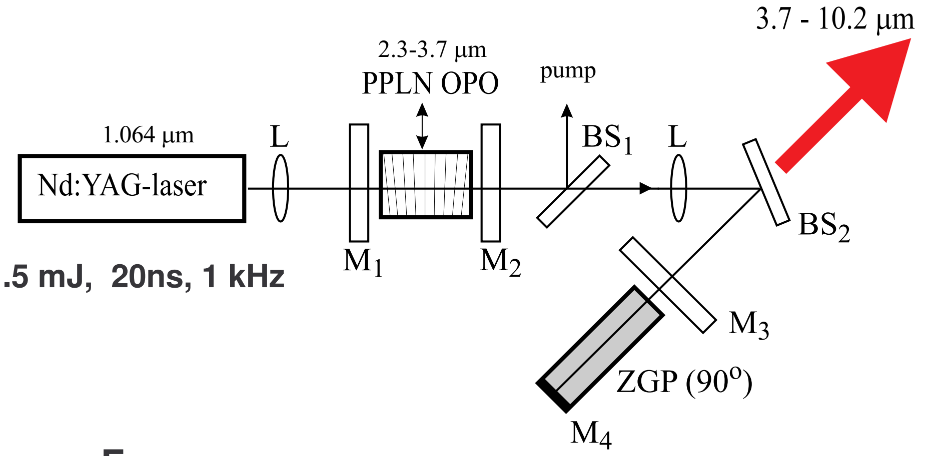


Idler tuning range:	**3.8-12.4 μm**
Linewidth:	**1- 2 cm^{-1}**
Quantum efficiency:	**40-50 %**
Pulse duration:	**70 ns**
Beam quality:	**M^2 = 1.5**
Rep. Rate:	**25 Hz**

K. L. Vodopyanov *et al.*, *Opt. Lett.* 25, 841 (2000).

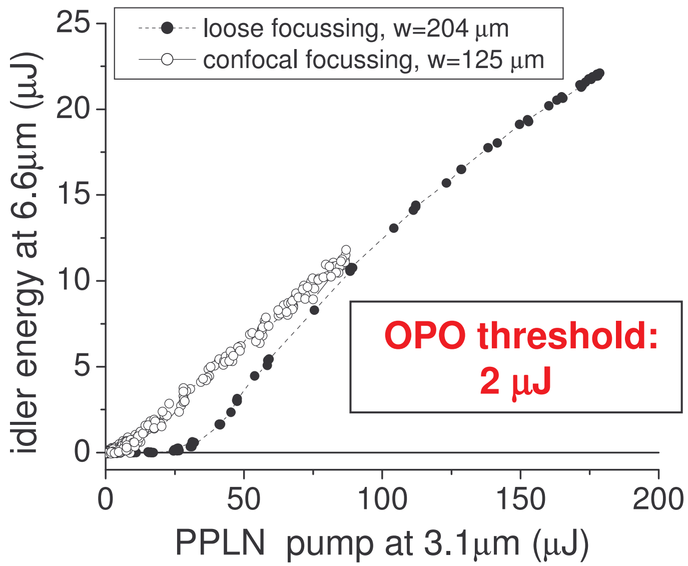
Pulsed Mid-IR OPO (4-10 μm)

Compact noncritically phase-matched cascaded PPLN-ZGP OPO

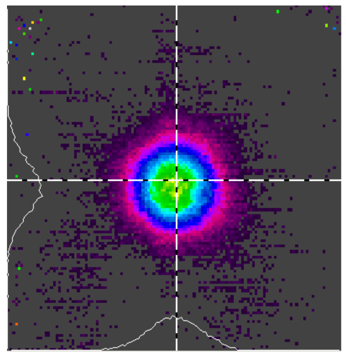


1.5 mJ, 20ns, 1 kHz

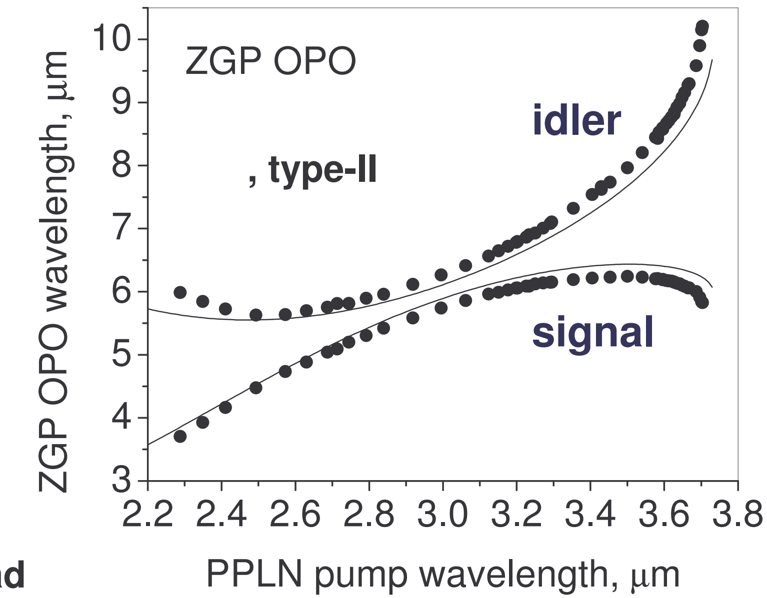
Energy curve



Far Field
FWHM 8.3 mrad
λ= 6 μm



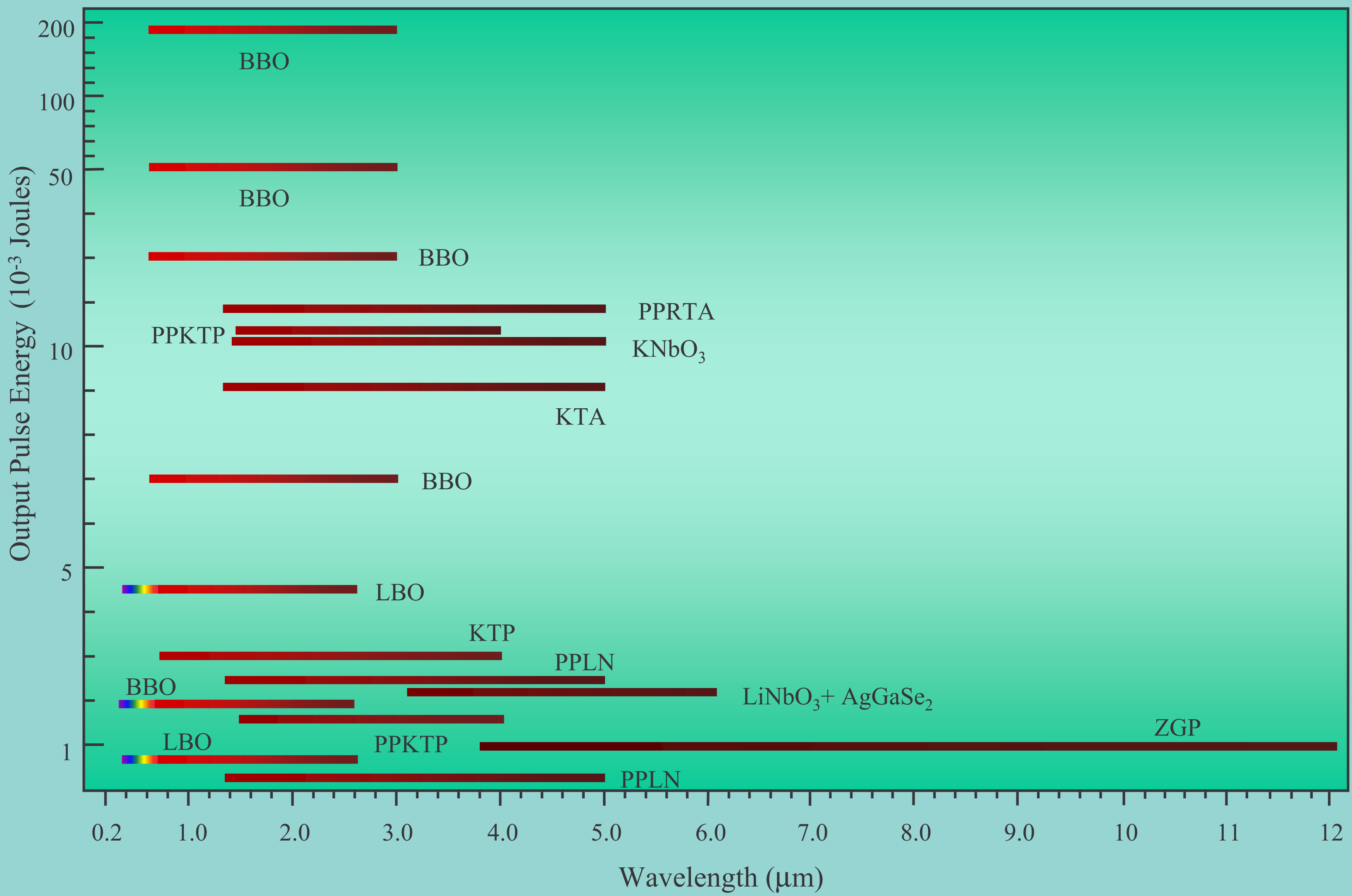
Tuning curves ZGP 90-deg



Tuning range: 3.7-10.2 μm
Linewidth: ~ 5 cm^{-1}
ZGP OPO quantum efficiency: 30 %
Pulse duration: 20 ns
Beam quality: M^2 = 1.75
Energy stability: 2%
Rep. Rate: 100Hz - 10 kHz

K. L. Vodopyanov and P. Schunemann, *Opt. Lett.* 28, 441 (2003).

Pulsed ns OPOs



Pulsed OPOs: High-repetition-rate

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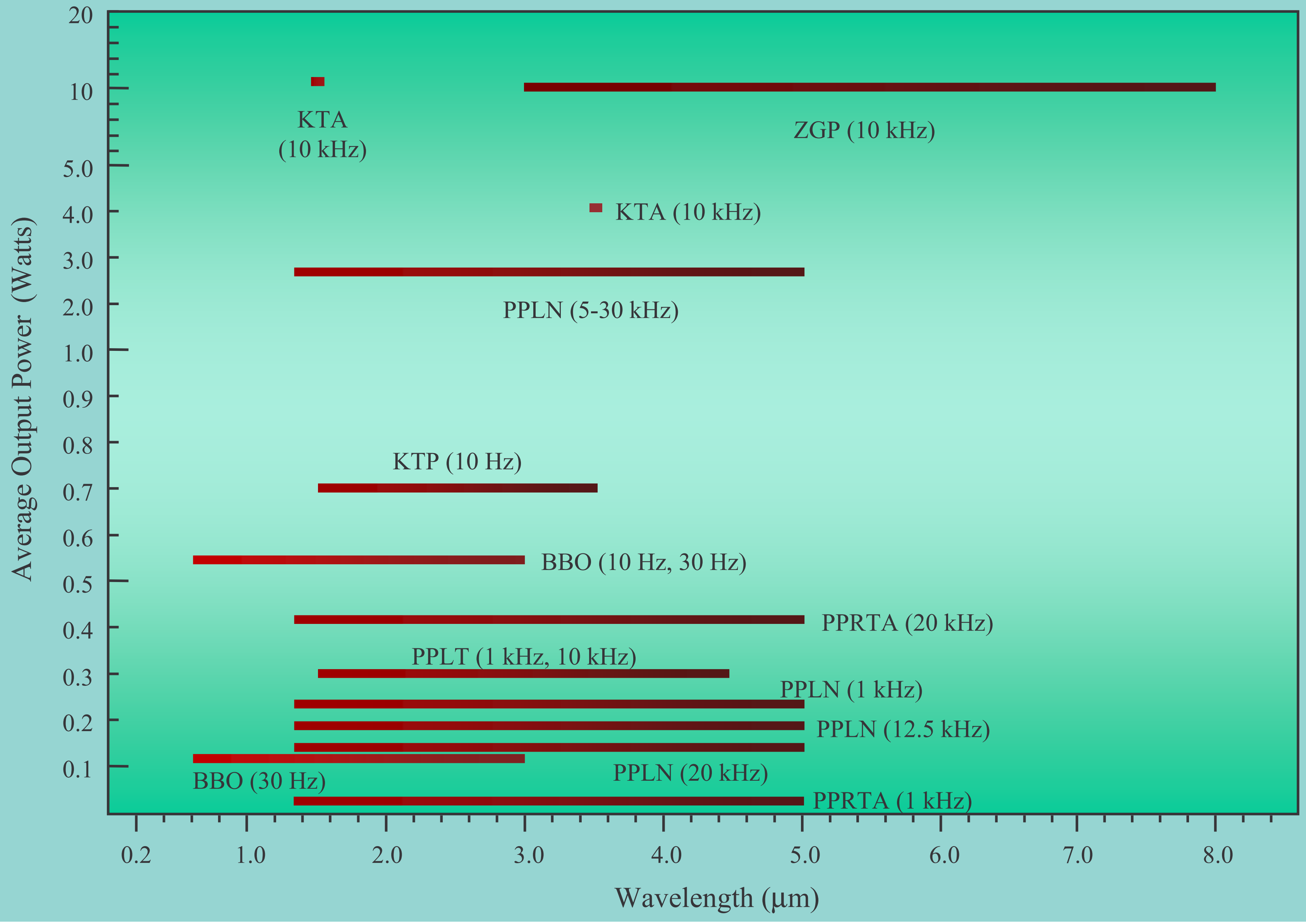

OPOs Advantages

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- Gamma-ray generation through laser backscattering

- Tunability control of photon energy on either side of the maximum gamma-ray energy, $E\gamma$ (max)=37.5 MeV. Useful for the experimental verification of theoretical calculations near $E\gamma$ (max), which will be of interest for some studies.

- Longer mid-IR wavelengths ⟶ lower photon energies ⟶ higher gamma-ray intensities (at lower gamma-ray energies) compared to ALL other laser backscattering facilities (except HIGS), which use Nd:YAG or argon-ion lasers.
  (Makes LLS a particularly useful facility for lower-energy/higher-intensity gamma-ray experiments.)

- Large optical powers (several watts). Therefore, under similar operating parameters (σ_c, I_e, L, S), the OPO will be able to provide higher gamma-ray intensities.

- Excellent spatial quality (diffraction-limited optical beam, minimum divergence, suitable cross-section ⟶ collimation, manipulation, and propagation over long distances with standard optical elements.

- Compact, all-solid-state design excellent output beam stability, with minimum variations in optical power, spatial beam quality, temporal stability, beam size and shape, and beam positioning over long distances.

- A new optical instrument, which has not been previously deployed in any other accelerator facilities throughout the world. Therefore, in addition to it usability, it will represent a world-first addition to such a facility, which will also enable novel scientific advances in high-energy accelerator physics.

- Indigenous to Spain.

CW OPO (1.5-5 μm)

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OPO Design	Singly Resonant (PPLN)
Wavelength Coverage	1.5-5 μm
Photon Energy	0.82-0.25 eV
Output Power	2-10 W
Spatial Quality	$M^2 \sim 1$
Spatial Profile	Gaussian (TEM_{00})
Polarization	>99% Linear
Footprint	30 x 40 cm

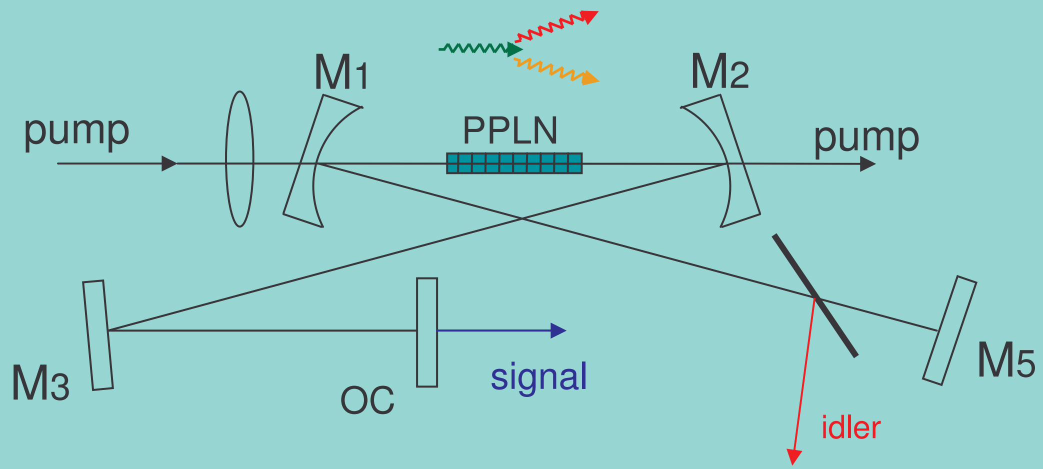
Pump Laser	Nd:YAG (cw)
Wavelength	1.064 μm
Output Power	30-100 Watts

Pulsed ns OPO (1.5-5 μm)

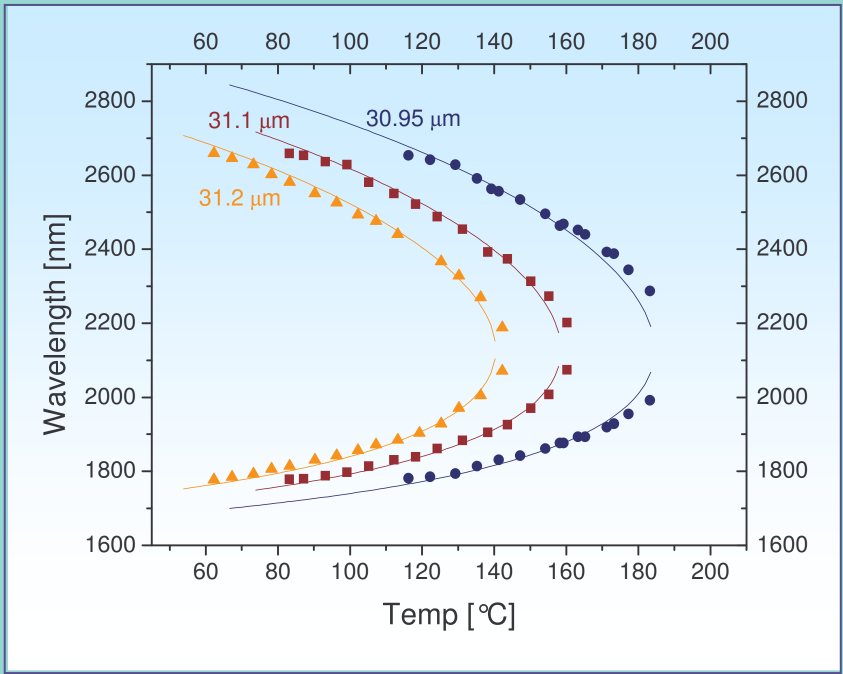
OPO Design	Singly Resonant (PPLN)
Wavelength Coverage	1.5-5 μm
Photon Energy	0.82-0.25 eV
Pulse Energy	>50 mJ
Pulse Duration	10-50 ns
Repetition Rate	1 Hz-100 Hz
Spatial Quality	$M^2 \sim 1$
Spatial Profile	Gaussian (TEM_{00})
Polarization	>99% Linear
Footprint	30x40 cm

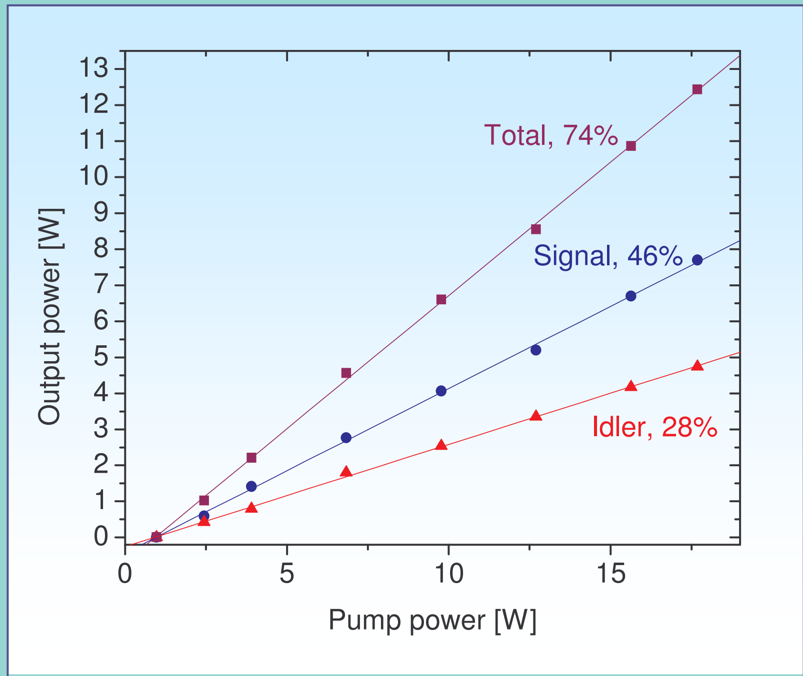
Pump Laser	Nd:YAG (Q-switched)
Wavelength	1.064 μm
Pulse Energy	500-1000 mJ
Pulse Duration	10-50 ns
Repetition Rate	1Hz-100 Hz

Picosecond OPO: High-Power Generation



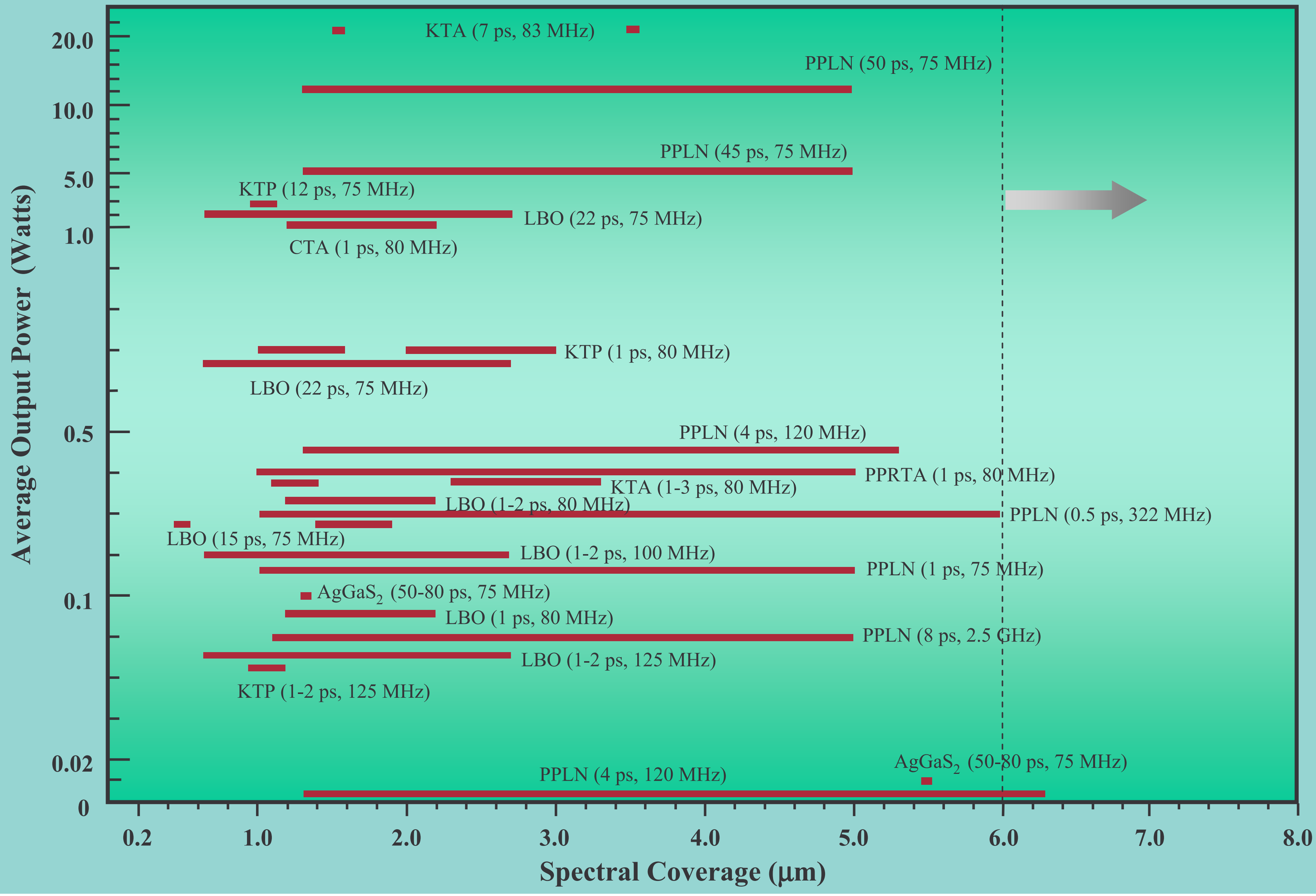
- 8 W signal (1.85µm) for 17.7 W pump
- Total 12.4 W signal & idler





C. Hoyt, M. Sheik-Bahae, and M. Ebrahimzadeh, *Opt. Lett.* 27, 1543-1545 (2002).

Picosecond OPOs



Femtosecond OPOs

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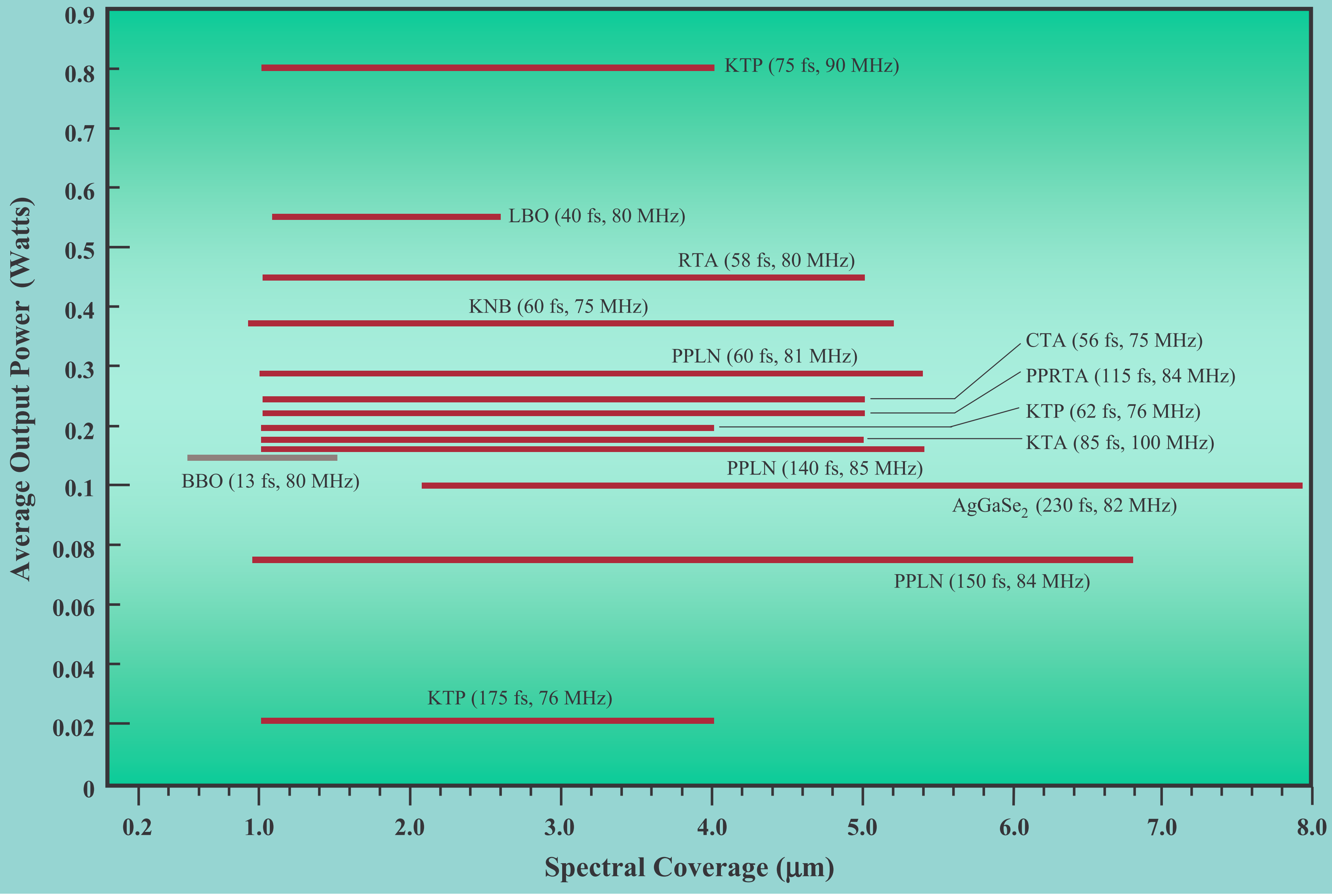
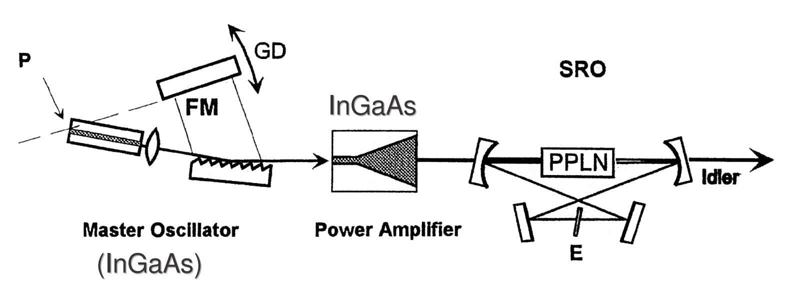


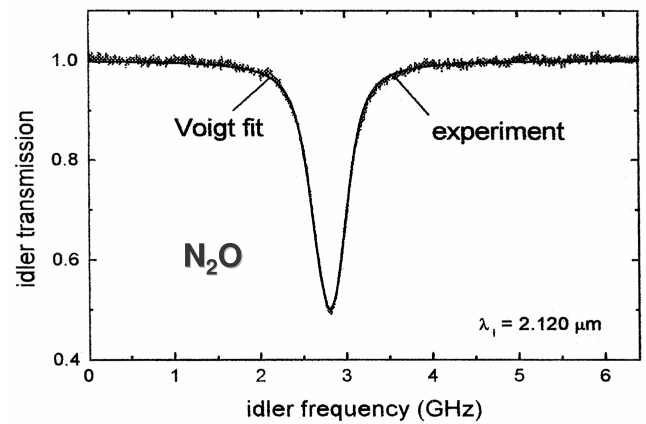
Some Applications!

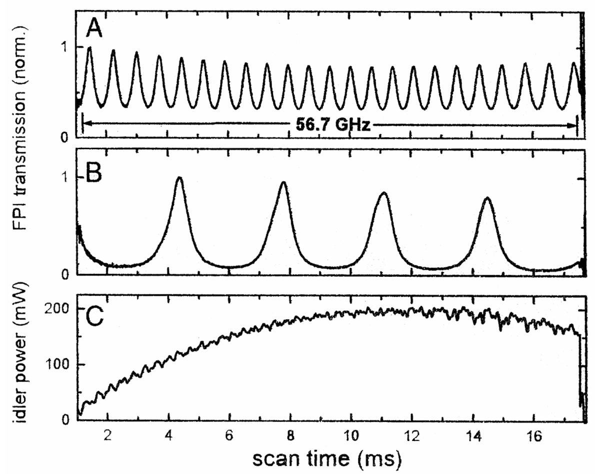
Direct-Diode-Pumped CW SRO

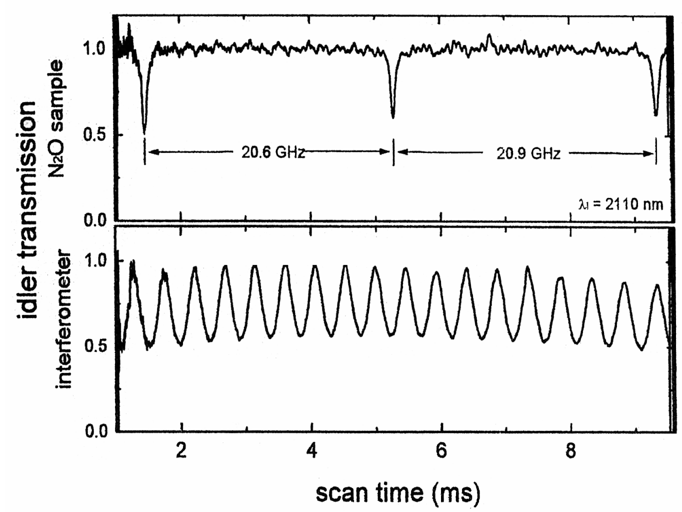
- 2.5 W @ 925 nm
- Δν ~ 4 MHz
- 60 GHz continuous tuning



- 200 mW idler output
- 2.01-2.19 μm idler tuning
- 56 GHz continuous tuning

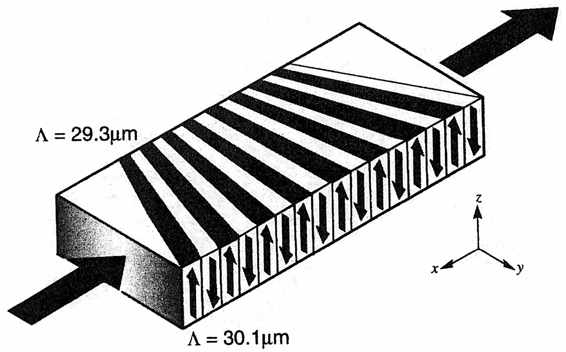


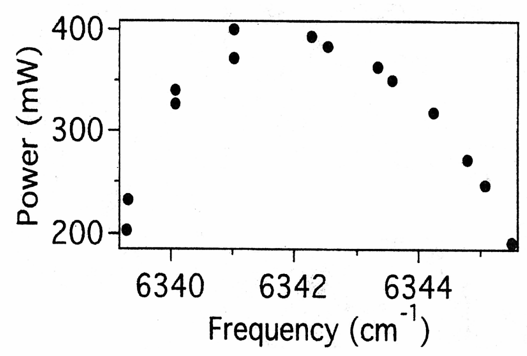


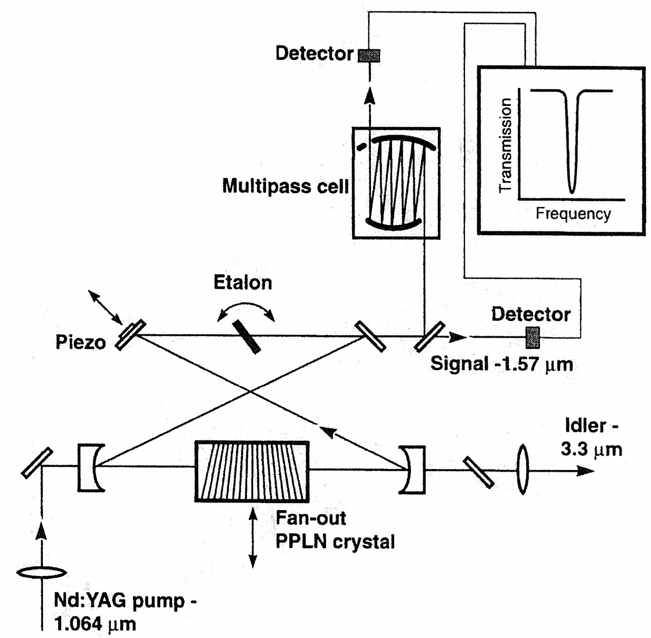


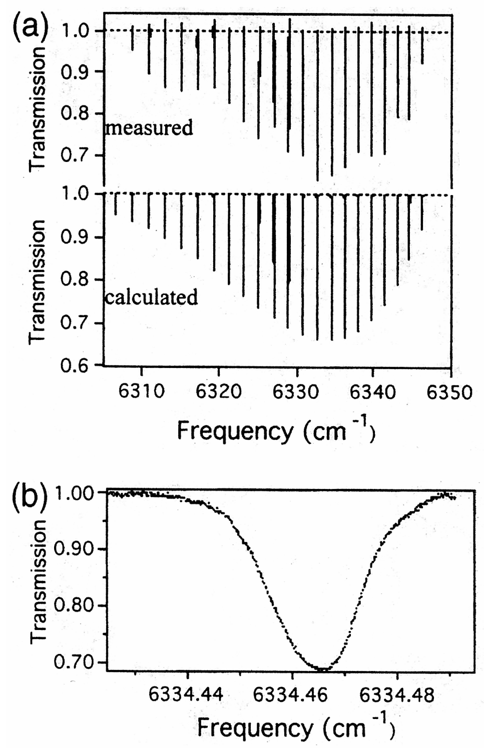
M. E. Klein, C. K. Laue, D.-H. Lee, K.-J. Boller, and R. Wallenstein, *Opt. Lett.* 25, 490-492 (2000).

PPLN CW SRO



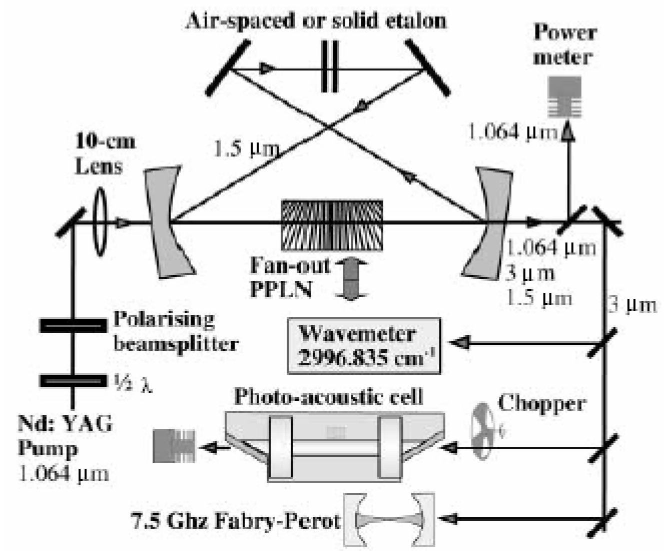


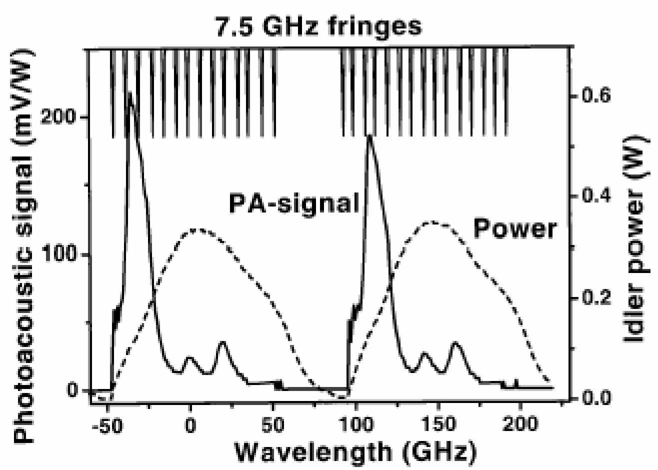




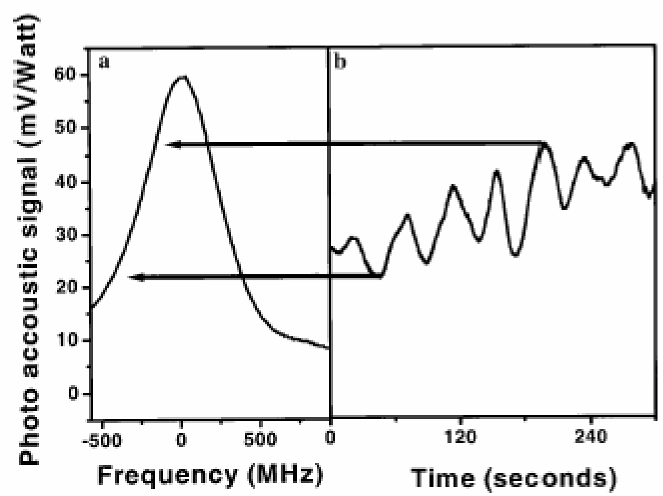
P. E. Powers, T. J. Kulp, and . E. Bisson, *Opt. Lett.* 23, 159-161 (1998).

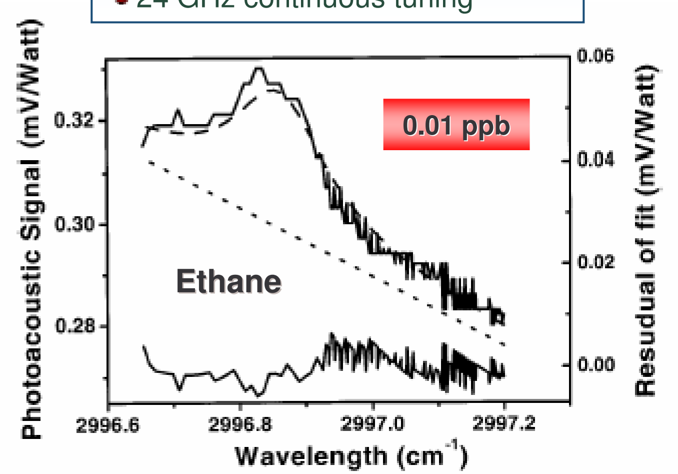
CW SRO: Photoacoustic Spectroscopy





- 1.5 W idler output (10 W pump)
- 3.0-3.8 µm idler tuning
- 100 GHz mode-hop-tuning
- 24 GHz continuous tuning



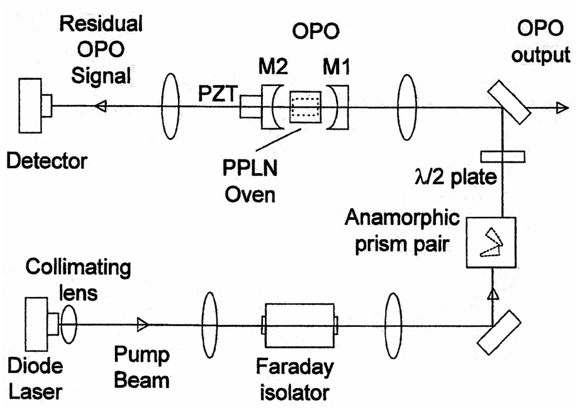


$\Delta\nu_{drift}$ < 200 MHz over 300 s
(< 3 MHz over 1 s)

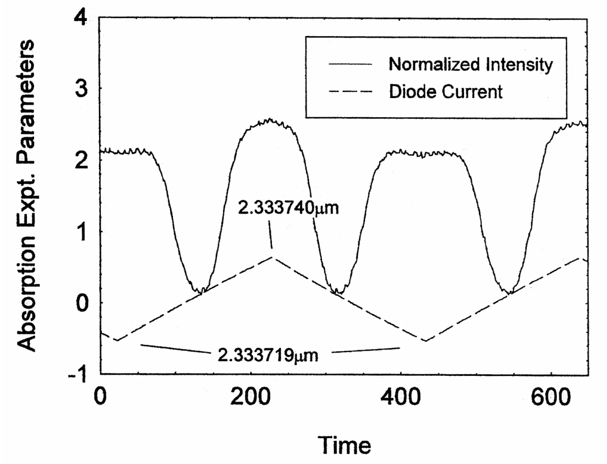
M. M. J. W. Van Herpen, S. Lee, S. E. Bisson, S. te Lintel Hekkert, F. J. M. Harren, *App. Phys. B* (2002).

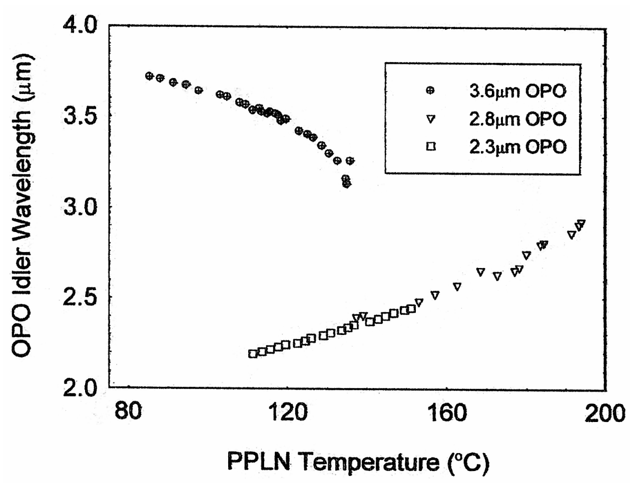
Diode-Pumped CW DRO: Spectroscopy

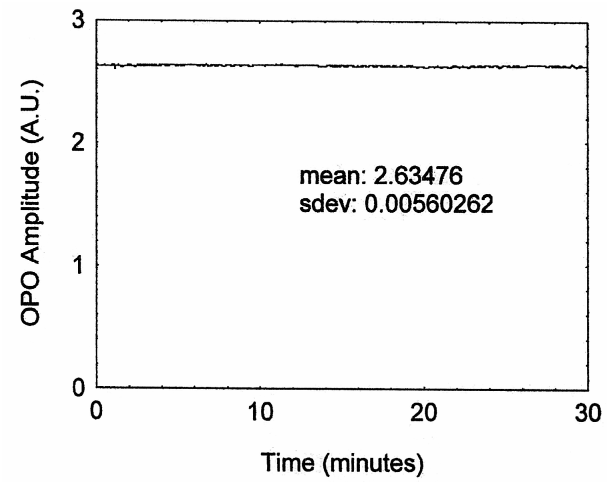
- 18 mW idler output
- 2.2-3.7 μm idler tuning
- 40 GHz continuous tuning
- 20 MHz linewidth



Continuous Tuning through diode laser pump tuning

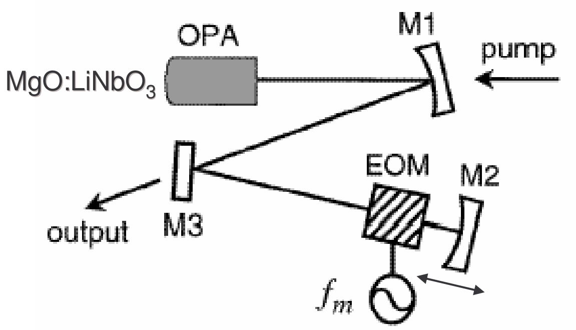


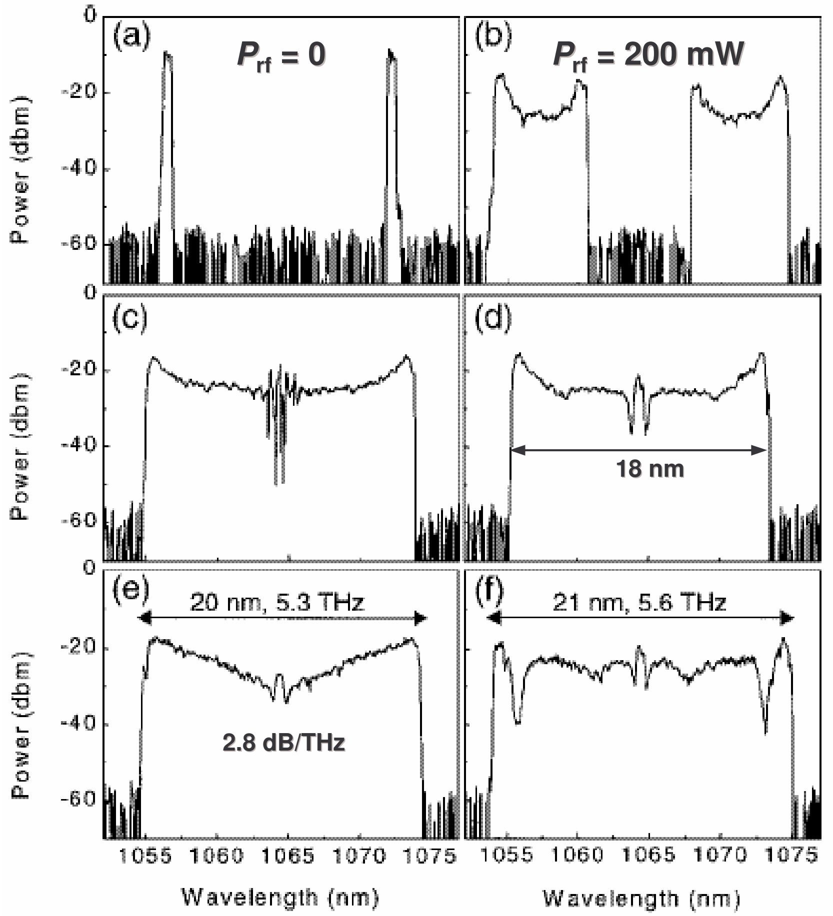


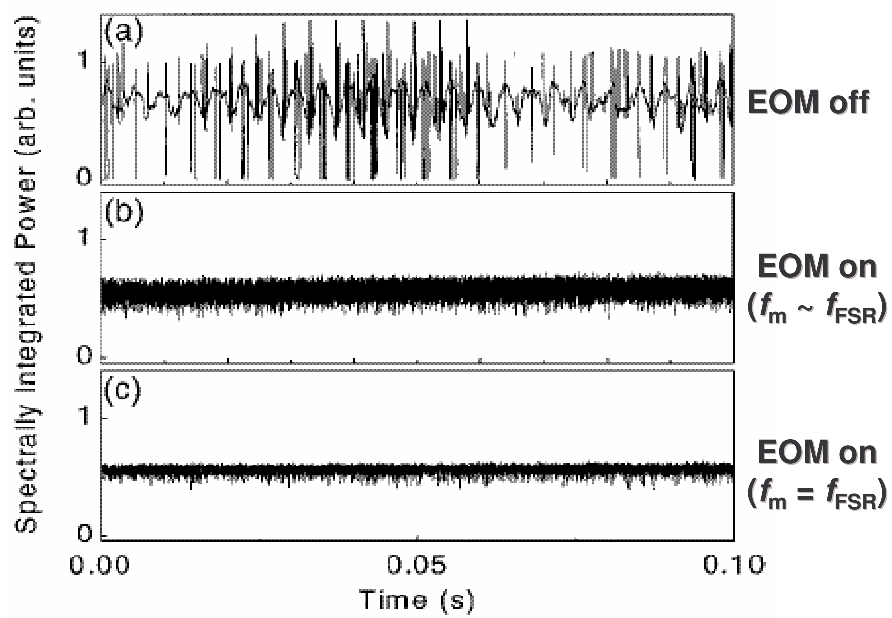


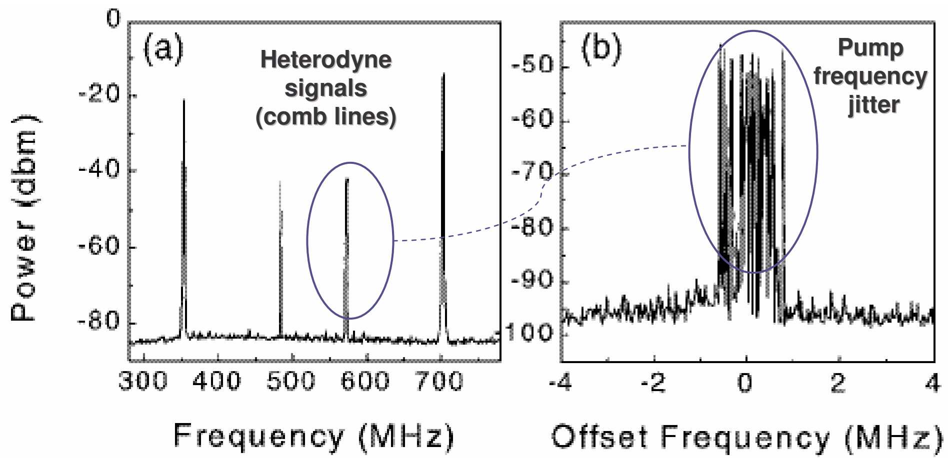
A. J. Henderson, P. M. Roper, L. A. Borschowa, and R. D. Mead, *Opt. Lett.* 25, 1264 (2000).

CW DRO: Frequency Comb Generation









S. A. Diddams, L-S Ma, J. Ye, and J. L. Hall, *Opt. Lett.* 24, 1747 (1999).

Nanosecond SRO: Cavity Ring-down Spectroscopy

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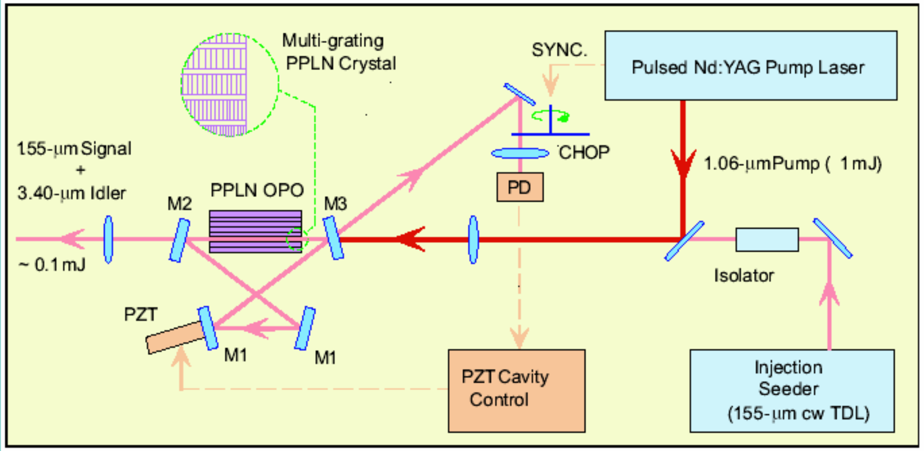
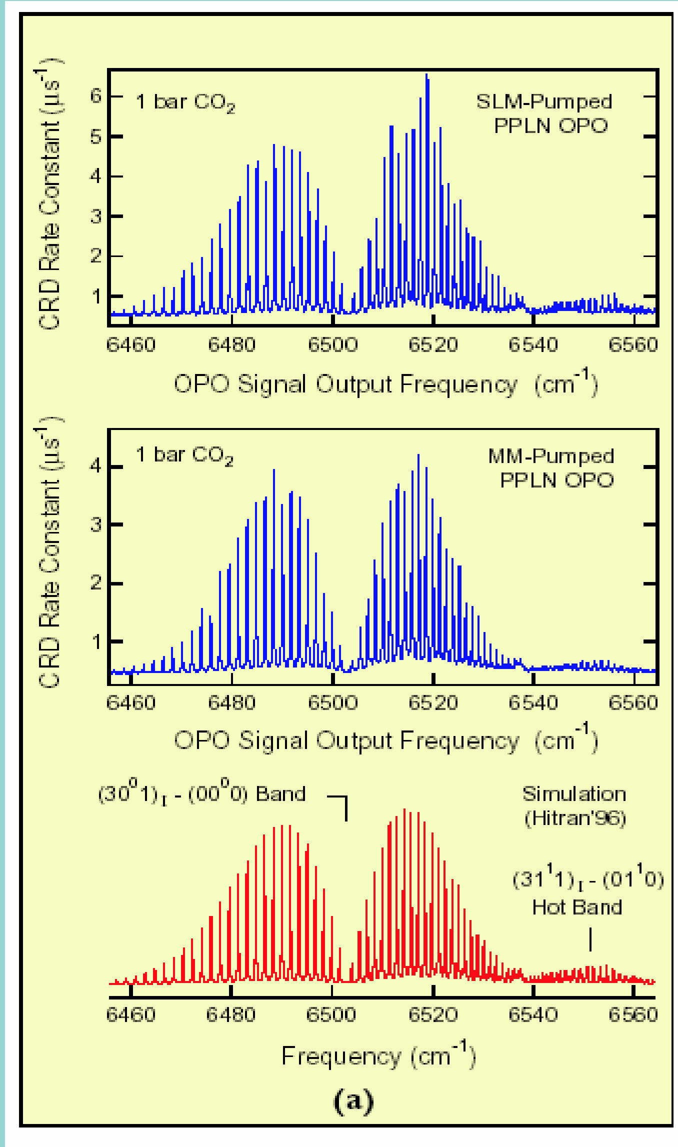
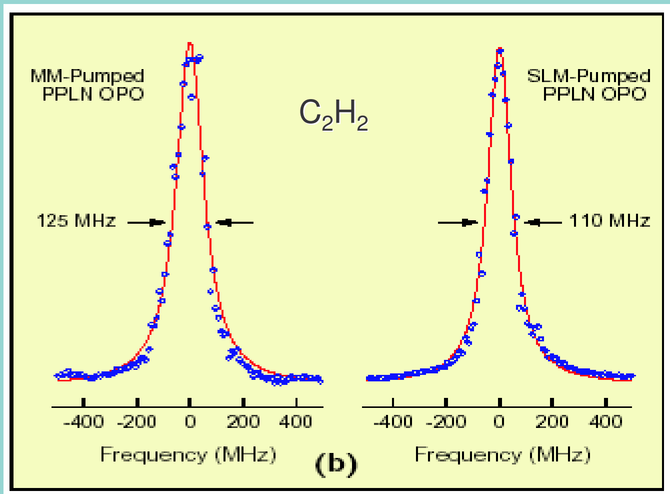




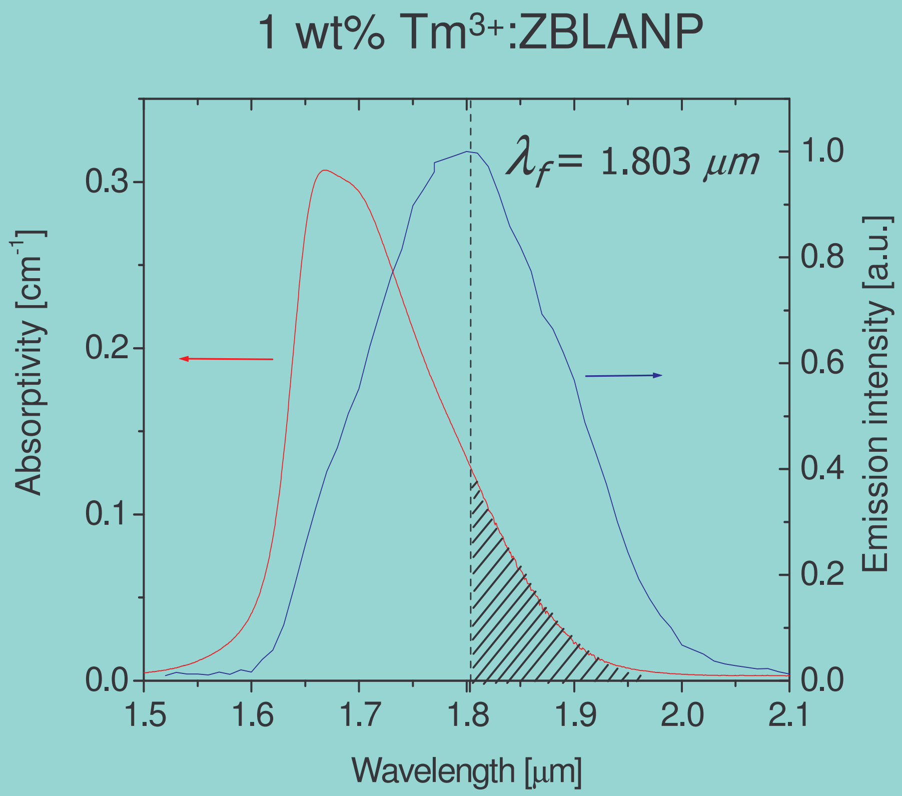
- 0.1 mJ signal pulse energy
- 1.5, 3.5 µm (signal, idler)
- 250 cm^{-1} continuous tuning
- <120 MHz linewidth (8 ns pulses)



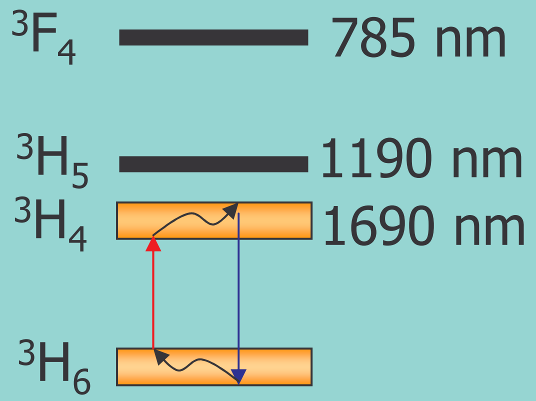
Y. He, P. Wang, R. T. White, and B. J. Orr, *Optics & Photonics News* (May 2002).

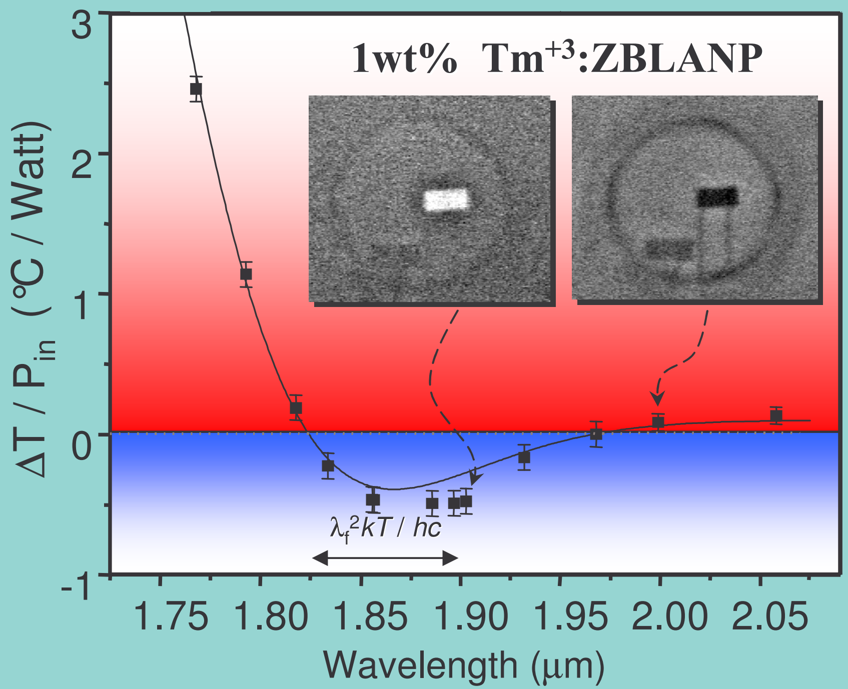
High-Power ps OPO - Application

Optical Refrigeration in Solids



$$\frac{P_{cool}}{P_{absorbed}} = \frac{\lambda - \lambda_f}{\lambda_f}$$





C. W. Hoyt, M. Sheik-Bahae, R. I. Epstein, *et al.*, *Phys. Rev. Lett.* 85, 3600 (2000).

Atomic mercury flux monitoring using an optical parametric oscillator based lidar system

Mikael Sjöholm, Petter Weibring, Hans Edner and Sune Svanberg

Atomic Physics Division, Lund Institute of Technology, P.O. Box 118, 221 00 Lund, Sweden

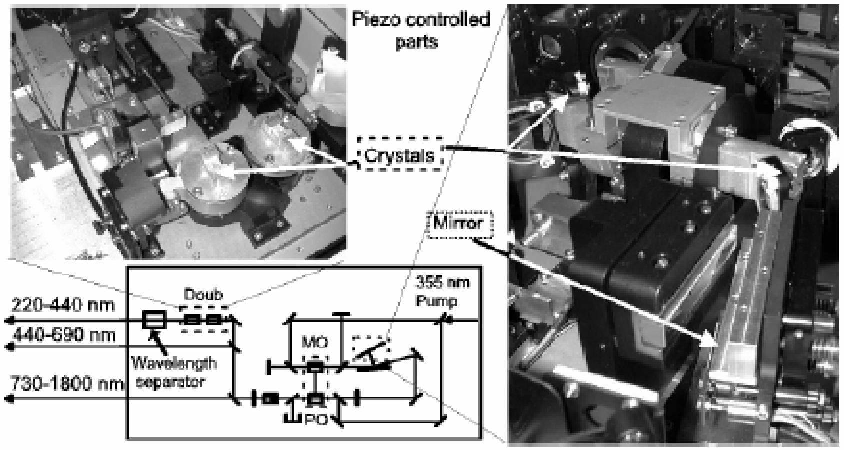


Fig. 2. Schematic overview of the master oscillator (MO) and power oscillator (PO) transmitter.

Fig. 1. The mobile lidar system in a field campaign in Rosignano Solvay, Italy.

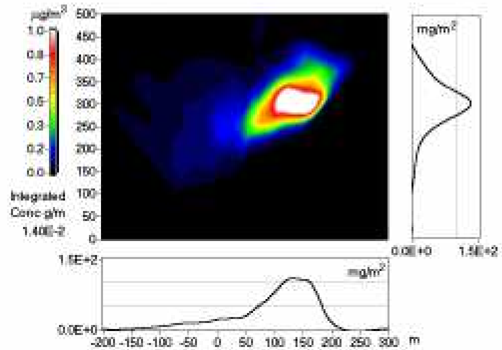
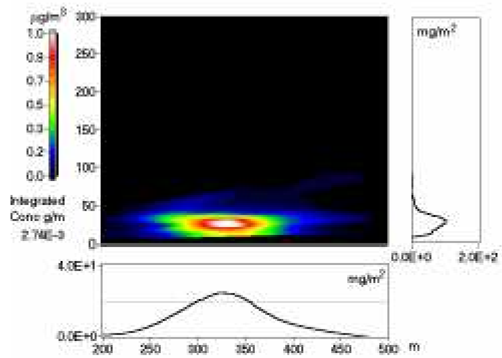


Fig. 3. (417 KB) Movie of horizontal concentration maps from the MCCA plant in Rosignano Solvay 2002-02-03, 12:11-12:38.



Summary

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Optical Parametric Oscillators

Flexible solid-state sources of light with unique spectral and temporal versatility

CW	$\longrightarrow$	13 fs
1 Hz	$\longrightarrow$	30 GHz
1 mW	$\longrightarrow$	30 W
1 μJ	$\longrightarrow$	200 mJ
400 nm	$\longrightarrow$	12 μm

New Challenges

- ***Wavelength barrier > 5 μm (cw/ps/fs OPOs):***

  Alternative QPM (e.g. GaAs) and BPM Materials (e.g. $ZnGeP_2$, $LiInS_2$, etc.)

  Novel Device Architectures (e.g. cascade, intracavity, etc.)

- ***Wavelength barrier < 1 μm (cw OPOs):***

  Novel visible laser pump sources (e.g. GaN diodes)

- ***Power barrier > few Watts (cw/fs OPOs):***

  High-power pump sources (e.g. fiber, crystalline, etc.)

- ***Novel Devices:***

  Integrated Microstructures, waveguides (GaAs, PPLN)

- ***New Application Areas:***

  Biophotonics, IR Imaging, Frequeny Metrology, etc.

Many New Challenges / Opportunities Remain:

Devices

Applications

Materials