Raman Laser

H. J. Eichler, T. Riesbeck and H. Rhee

- → Concepts
- → Raman-Laser for H_2O-Lidar at 935 and 942 nm
- → Outlook:

  Raman-Laser for CO_2- detection at 1570 to 1610 nm

One-day meeting ESA-DLR on Technology Activities for Spaceborne DIAL Instruments

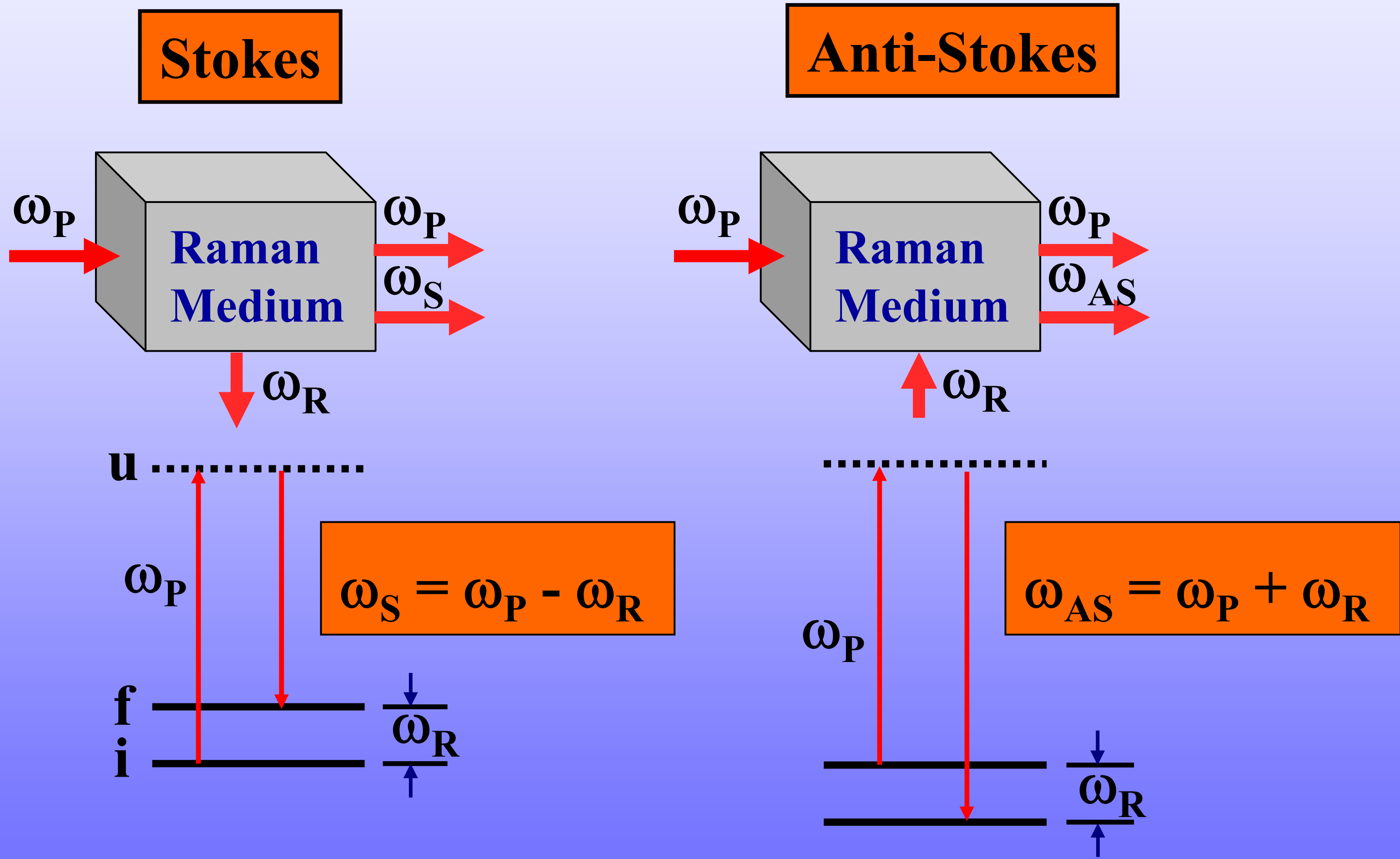
18.Nov.2005

Requirements for WALES-Laser-Transmitter

last update 2004

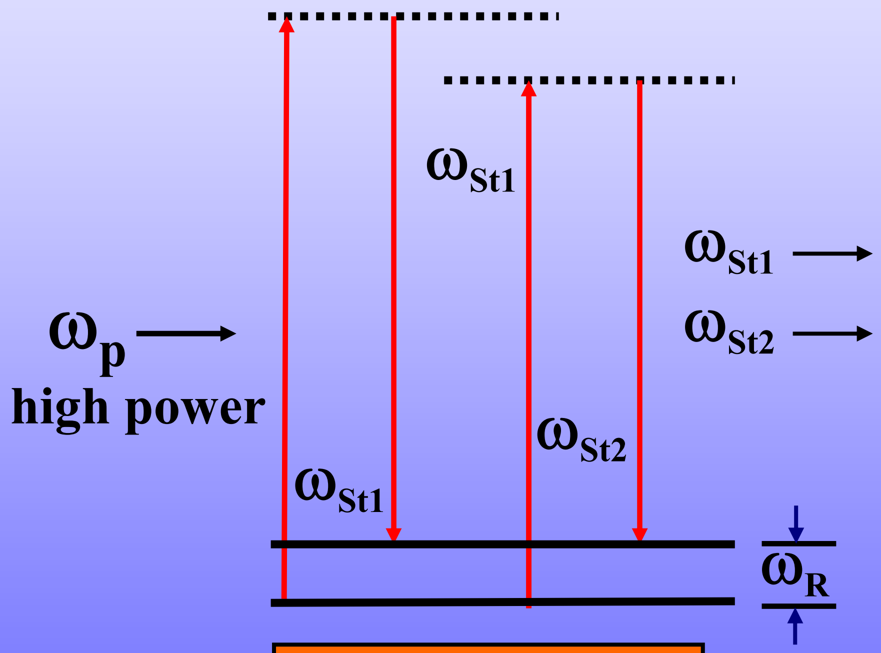
Wavelengths [nm]	I. **935.906** / **935.561** / **935.684** / **935.840** II. 943.284 / 943.442 / 943.083 / 942.650
Pulse energy [mJ]	**75**
Pulse duration [ns]	< 200
Repetition rate [Hz]	> **50**
Pulse-to-pulse interval [ms]	**10**
Linewidth [MHz]	< 160
Beam quality [M^2]	< 2
Polarization (linear) [%]	> 99
Tuning range [GHz]	+/- 10

Spontaneous Raman-Scattering



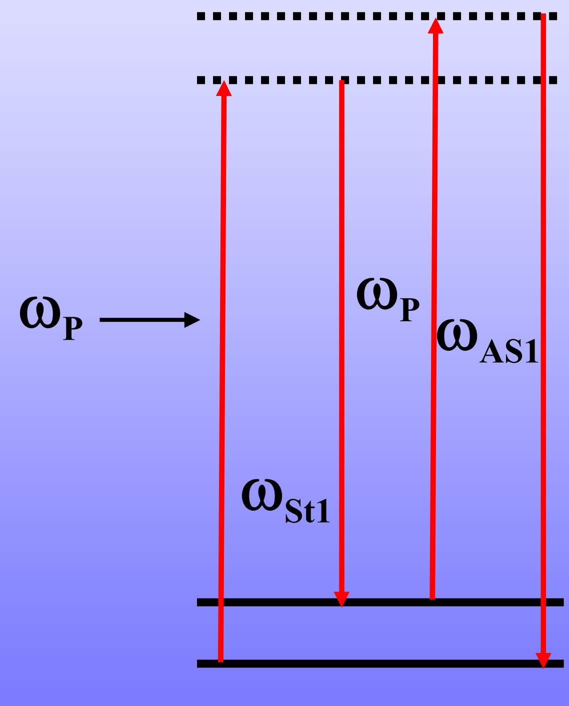
Stimulated Raman-Scattering

Stokes radiation of first and higher orders



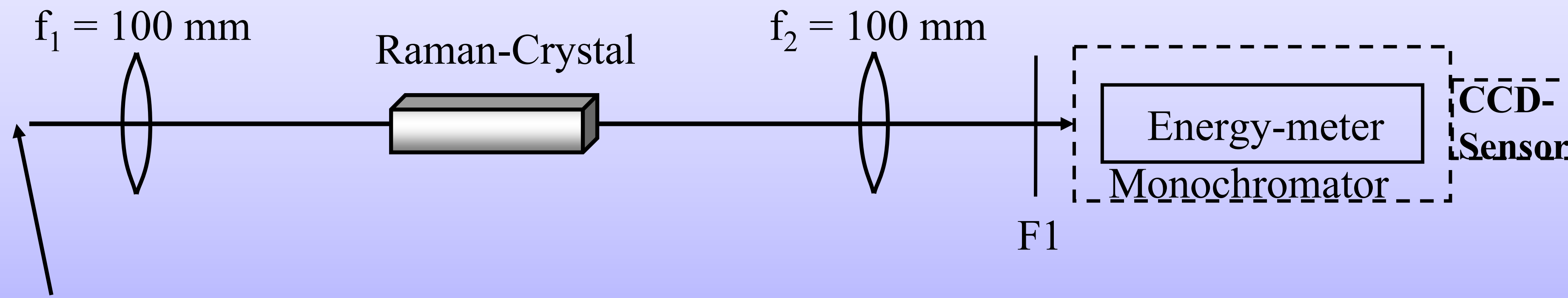
$$\omega_{Stn} = \omega_P - n\omega_R$$

Combined Stokes und anti-Stokes Generation



$$2\omega_P \longrightarrow \omega_{St} + \omega_{ASt}$$

Stimulated Raman-Scattering



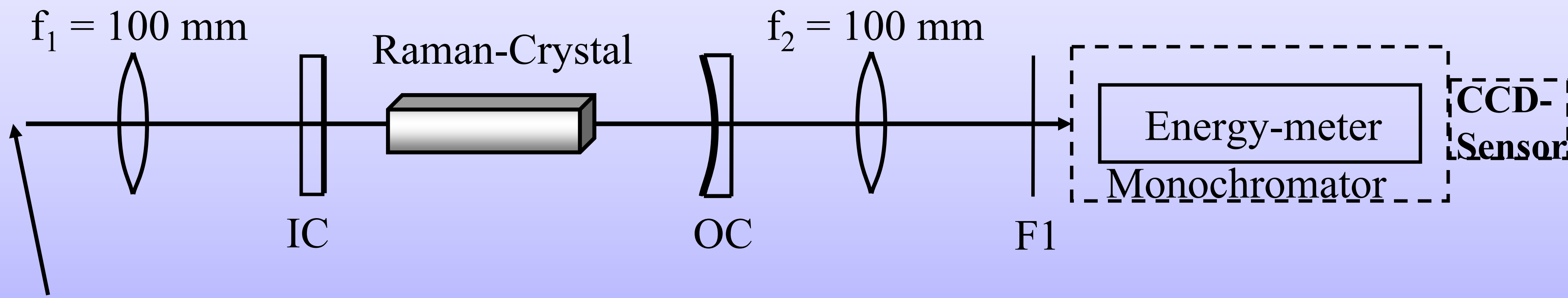
ps-Nd^{3+}:YAG-Pump laser:

λ_P = 1064 nm / 532 nm

E_p = 10 mJ / 4 mJ

τ_p = 110 ps / 80 ps

Raman-Laser



ns-Nd^{3+}:YAG-Pump laser:

$\lambda_p = 1064$ nm

$E_p = 275$ mJ

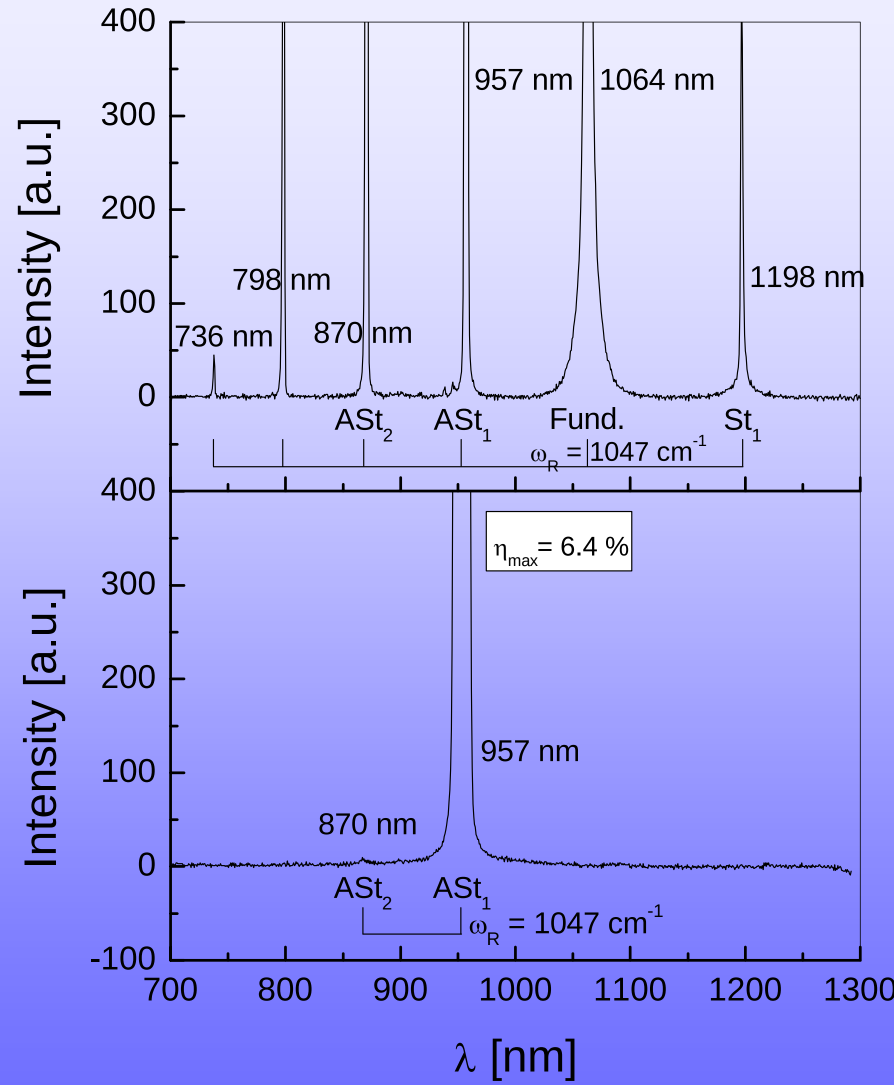
$\tau_p = 8 - 12$ ns

Raman-Laser

Generated spectrum without resonator:

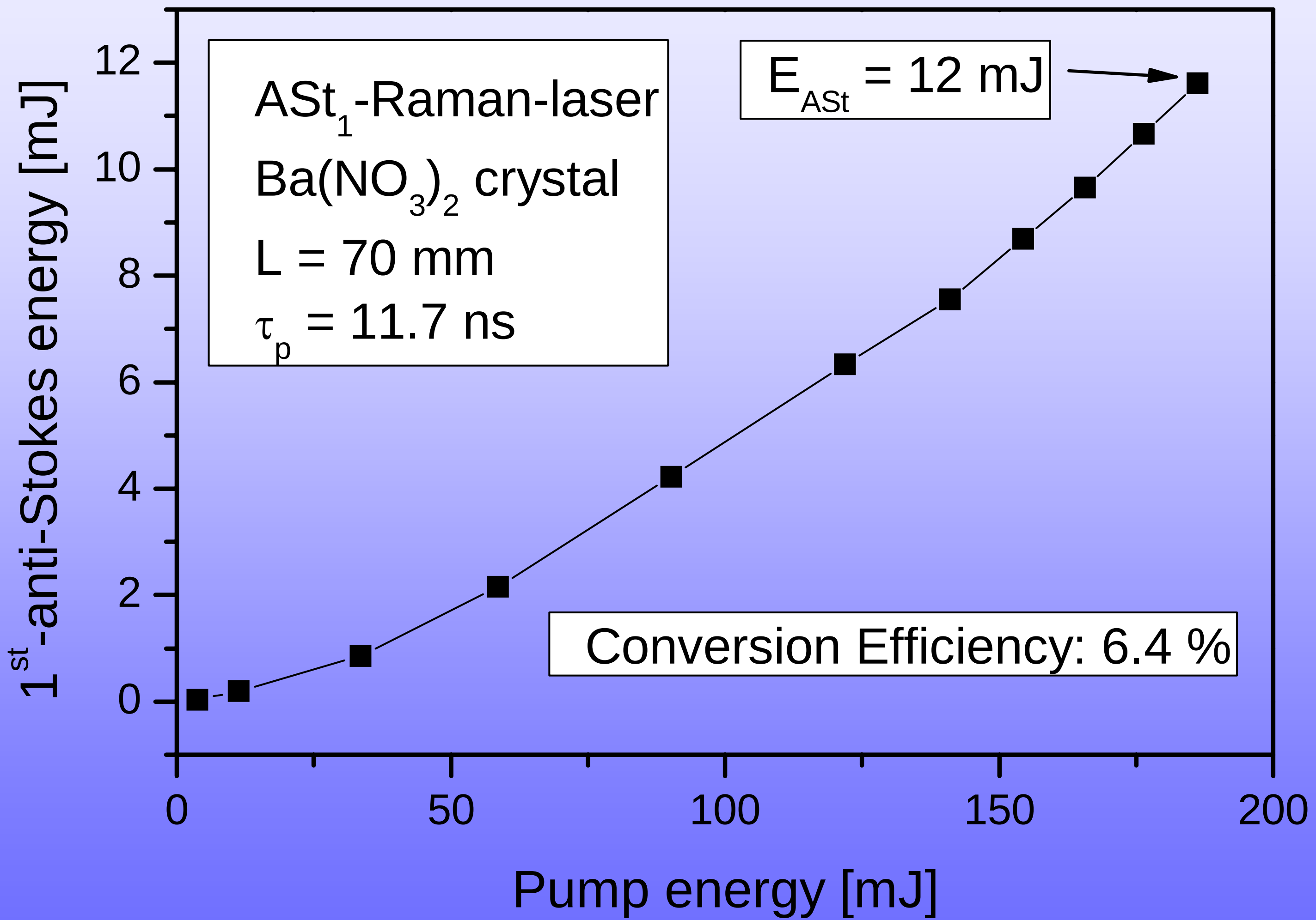
Generated spectrum with resonator:

Anti-Stokes-Raman-Laser!



Raman-Laser

Output energy



Anti-Stokes-Raman-crystals for water vapour detection with Nd:YAG pump laser

Wanted wavelength [nm]	Nd:YAG pump wavelength & linewidth [nm]	Possible material	Raman-line attributes
943,284	1052.1 ± 0.5	BiB_3O_6	ASt_2
943,442			
943,083			
942,650			
935,561		AANP or β-BaB_2O_4	ASt_1 or ASt_2
935,684			
935,906	1064.1 ± 0.5	AANP	ASt_1
935,561			
935,684			
935,840			
943,284		BiB_3O_6	ASt_2
943,442			
943,083			
942,650			
935,906	1064.6 ± 0.5	AANP	ASt_1
935,840			
943,284		BiB_3O_6	ASt_2
943,442			
943,083			
942,650			

Raman-crystals for anti-Stokes-generation with Yb:YAG pump laser

Wanted wavelength [nm]	Pump laser wavelength [nm]	Raman wavelength [nm]	Line attribution	Raman crystals
935.561 . . . 943.442	Yb:YAG (1020 – 1050)	921.58 . . . 960.08	ASt_1	$Ba(NO_3)_2$ Na_2SO_4 $KAl(SO_4)_2$ $PbWO_4$ $KGd(WO_4)_2$ $NaY(WO_4)_2$ $Ca_3(NbGa_2)\cdot Ga_3O_{12}$ $ZnWO_4$ YVO_4

Yb:YAG + barium nitrate or lead tungstate

barium nitrate $Ba(NO_3)_2$:

$g_R = 10$ cm/GW

1037,3 nm —— Raman shift: 1047 cm^{-1} ——→ 935,7 nm

$\Delta\nu = 0,42\ cm^{-1}$

lead tungstate ($PbWO_4$) :

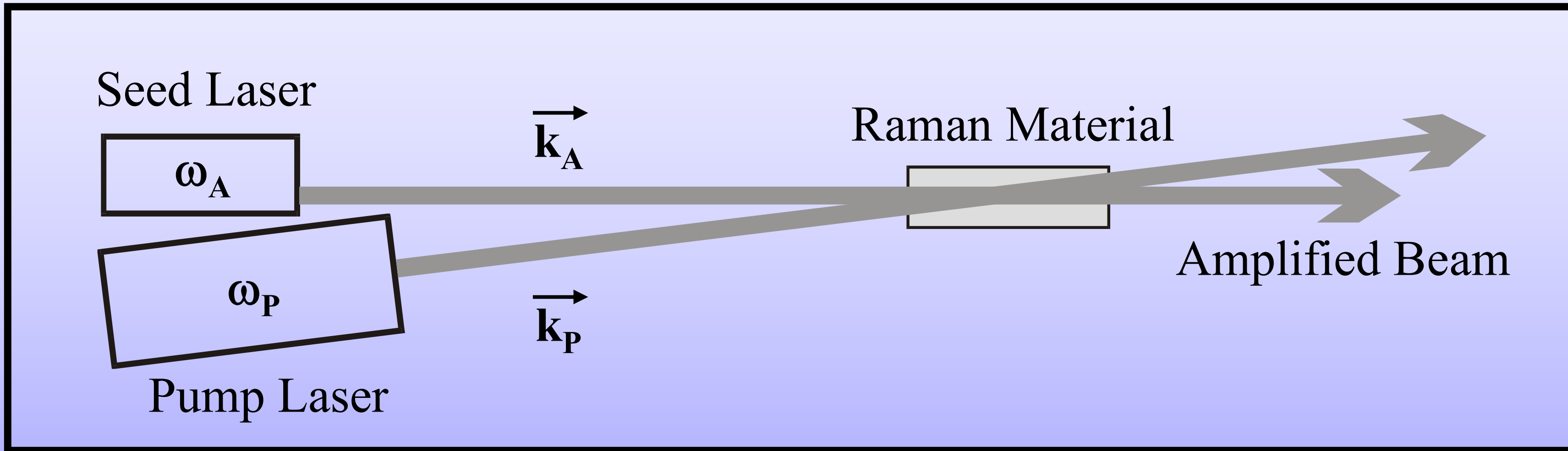
$g_R = 3.1$ cm/GW

1021,8 nm —— Raman shift: 901 cm^{-1} ——→ 935,7 nm

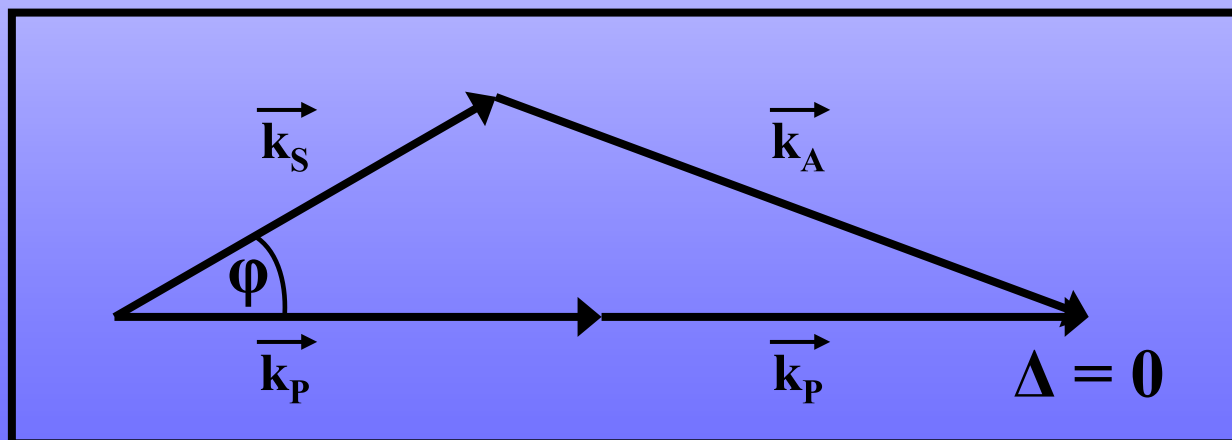
$\Delta\nu = 4,3\ cm^{-1}$

($\Delta\lambda \sim 0.4$ nm)

Schematic Setup for Seeder Amplification



momentum conservation (phase matching)



Stokes-Raman Crystals for CO_2-detection with Nd and Yb pump laser

Wanted wavelength [nm]	Pump wavelength & linewidth [nm]	Raman-crystal	Raman-shift & linewidth of material [cm^{-1}]	Generated wavelength [nm] and attribution
1570 - 1610	1052.1 ± 0.5	$C_{16}H_{15}N_3O_4$	1588 ± 1.5	S_2: 1580.1 ± 1.1
	1064.6 ± 0.5	α-$C_{14}H_{12}O$	3065 ± 9	S_1: 1580.2 ± 1.1
		$Ba(NO_3)_2$	1047 ± 0.4	S_3: 1599.4 ± 1.2
	1073.8 ± 0.5	$C_{13}H_{10}O$	3070 ± 6.5	S_1: 1601.9 ± 1.1
		α-$C_{14}H_{12}O$	3065 ± 9	S_1: 1600.6 ± 1.1
	1318 ± 0.5	$Y(HCOO)_3 \cdot 2H_2O$	1377 ± 5.4	S_1: 1610.2 ± 0.8
		$LiHCOO \cdot H_2O$	~ 1377	S_1: ~ 1610.2 ± 0.8
		$Ca(HCOO)_2$	~ 1377	S_1: ~ 1610.2 ± 0.8
	1357.2 ± 0.5	α-$XAl(SO_4)_2$ X: K, NH_4, Rb, Tl	990 - 992 ± 4.1 - 5.3	S_1: 1567.9 - 1568.4 ± 0.7
	1035 ± 15	$C_{13}H_{10}O$	1650 ± 4.5	S_2: 1571.9 ± 35

Stokes-Raman-conversion efficiency

- First-Stokes-efficiency up to 70 %:

  P. G. Zverev, T. T. Basiev, A. M. Prokhorov, „Stimulated Raman scattering of laser radiation in Raman crystals“, *Opt. Mater*. **11**, 335 – 352 (1999)

- Second-Stokes-efficiency > 30 %:

  G. M. A. Gad, H. J. Eichler, A. A. Kaminskii, "Highly efficient 1.3-µm second-Stokes $PbWO_4$ Raman laser", *Optics Letters*, **28**, Nr. 6, 426 - 428 (2003)

Advantages and Drawbacks

Optical Parametric Oscillator OPO

\+ broad tuning range
→ universal materials for many wavelengths

− frequency selection required

− only negative frequency shifts

− optical resonator required for high conversion efficiency

Stimulated Raman Shifter SRS

○ tuning range:
1nm for crystals, 20nm for glass
→ special material for each wavelength

\+ direct injection seeding

\+ positive and negative frequency shifts

\+ high gain
→ single pass amplification of seed

− needs further engineering

Summary

- Anti-Stokes-Raman-shifting to water absorption lines at 935 and 942 nm is possible with: Nd:YAG-pump laser (3 crystals)
  Yb:YAG-pump laser (10 crystals)
- Anti-Stokes Raman-laser with 12 mJ output energy and 6.4 % efficiency has been demonstrated with $Ba(NO_3)_2$.
- Calculations show that Raman-amplification of 100 mW seed beam to 30 mJ in 10 ns is possible with 100 mJ pump beam.
- Stokes-Raman-shifting to CO_2-absorption lines at 1570 to 1610 nm is possible with: Nd:YAG-pump laser (11 crystals)
  Yb:YAG-pump laser (1 crystal)
- First-Stokes efficiency up to 80 %

References

[1] A. A. Kaminskii, S. N. Bagaev, D. Grebe, H. J. Eichler, A. A. Pavlyuk, R. Macdonald, "Efficient multiwave Stokes and anti-Stokes operation of a Raman parametric laser based on a tetragonal $NaLa(MoO_4)_2$ crystal", *Quant. Electron.*, **26**, Nr. 3, 193 - 195 (1996)

[2] A. A. Kaminskii, H. Eichler, J. Findeisen, Ch. Barta, "Room-Temperature High-Order Stimulated Raman Scattering and Stimulated Emission in Ultra-Low-Phonon Energy Orthorhombic $PbCl_2{:}Nd^{3+}$ Crystal", *phys. stat. sol. (b)*, **206**, R3 (1998)

[3] A. A. Kaminskii, H. J. Eichler, D. Grebe, R. Macdonald, J. Findeisen, S. N. Bagaev, A. V. Butashin, A. F. Konstantinova, H. Manaa, R. Moncorge, F. Bourgeois, G. Boulon, "Orthorhombic ($LiNbGeO_5$): efficient stimulated Raman scattering and tunable near-infrared laser emission from chromium doping", *Opt. Materials*, **10**, 269 - 284 (1998)

[4] A. A. Kaminskii, N. V. Klassen, B. S. Redkin, H. J. Eichler, J. Findeisen, "Tetragonal tungstates $NaY(WO_4)_2$ and $NaY(WO_4)_2{:}Nd^{3+}$-novel $\chi^{(3)}$-nonlinear-and laser-active crystals: multicomponent and Raman-parametric generation and low-threshold stimulated emission of Nd^{3+} ions by two intermultiplet IR transitions $^4F_{3/2}$ to $^4I_{11/2}$ and $^4F_{3/2}$ to $^4I_{13/2}$", *Dokl. Akad. Nauk.*, **363**, Nr. 1, 34 - 38 (1998)

References

[5] A. A. Kaminskii, H. J. Eichler, K. Ueda, N. V. Klassen, B. S. Redkin, L. E. Li, J. Findeisen, D. Jaque, J. Garcia-Sole, J. Fernández and R. Balda, "Properties of Nd^{3+}-doped and undoped tetragonal $PbWO_4$, $NaY(WO_4)_2$, $CaWO_4$, and undoped monoclinic $ZnWO_4$ and $CdWO_4$ as laser-active and stimulated Raman scattering-active crystals", *Appl. Opt.*, **38**, Nr. 21, 4533 - 4547 (1999)

[6] A. A. Kaminskii, S. N. Bagaev, A. M. Jurkin, A. E. Koch, H. J. Eichler, J. Findeisen, "New nonlinear-laser effects in a β-BaB_2O_4 $\chi^{(2)}$- and $\chi^{(3)}$-active crystal", *Dokl. Akad. Nauk.*, **367**, Nr. 4, 468 - 474 (1999)

[7] A. A. Kaminskii, S. N. Bagaev, N. V. Kravtsov, S. N. Chekina, Ya. V. Vasiliev, N. I. Ivannikova, K. Ueda, J. Lu, H. J. Eichler, G. M. A. Gad, J. Hanuza, J. Fernandez, P. Reiche, "Spectroscopy and cw laser action, magnetooptics and nonlinear optical frequency conversion in Ln^{3+} doped and undoped $Bi_4Ge_3O_{12}$ and $Bi_4Si_3O_{12}$ crystals", *Laser Physics*, **11**, Nr. 8, 897 - 918 (2001)

[8] A. A. Kaminskii, P. Becker, L. Bohatý, K. Ueda, K. Takichi, J. Hanuza, M. Moczka, H. J. Eichler, G. M. A. Gad, "Monoclinic bismuth triborate BiB_3O_6 – a new efficient $\chi^{(2)} + \chi^{(3)}$ – nonlinear crystal: multiple stimulated Raman scattering and self-sum-frequency lasing effects", *Opt. Comm.*, **206**, 179 - 191 (2002)

References

[9] A. A. Kaminskii, H. Klapper, J. Hulliger, H. J. Eichler, J. Hanuza, K. Ueda, K. Takichi, C. Wickleder, G. M. A. Gad, M. Maczka, "High-order many-phonon stimulated Raman scattering in orthorhombic benzophenone ($C_{13}H_{10}O$) and monoclinic α-4-methylbenzophenone (α-$C_{14}H_{12}O$) crystals", *Laser Phys.*, **12**, 1041 - 1053 (2002)

[10] A. A. Kaminskii, T. Kaino, T. Taima, A. Yokoo, K. Ueda, K. Takichi, J. Hulliger, H. J. Eichler, J. Hanuza, J. Fernandez, R. Balada, M. Moczka, G. M. A. Gad, "Monocrystalline 2-Adamantylamino-5-Nitropyridine (AANP) - a novel organic material for laser Raman converters in the visible and near-IR", *Jpn. J. Appl. Phys.*, **41**, 1041 - 1053 (2002)

[11] H. J. Eichler, G. M. A. Gad, A. A. Kaminskii, H. Rhee, "Raman crystal lasers in the visible and near-infrared", *J. of Zhejiang Univ. SCIENCE*, **4**, Nr. 3, 241 - 253 (2003)

[12] G. M. A. Gad, H. J. Eichler, A. A. Kaminskii, "Highly efficient 1.3-µm second-Stokes $PbWO_4$ Raman laser", *Optics Letters*, **28**, Nr. 6, 426 - 428 (2003)

[13] J. Findeisen, "Sichtbare und infrarote Festkörperlaser mit nichtlinearer Frequenzumsetzung sowie Anregung über resonante Zwischenniveaus", Dissertation (1999)

[14] P. G. Zverev, T. T. Basiev, A. M. Prokhorov, „Stimulated Raman scattering of laser radiation in Raman crystals“, *Opt. Mater*. **11**, 335 – 352 (1999)