TUNABLE LASERS

LA3NET Workshop at Fraunhofer ILT

Aachen, Nov. 5th 2013

Bernd Jungbluth

OUTLINE

- Tunable Coherent Light Sources – *Introduction and Overview*

- Tunable Lasers – *Design Basics and Challenges*
- Design Examples I – *Tunable Lasers*

- Nonlinear Frequency Mixing – *Extending the Tuning Range*
- Design Examples II – *Frequency Converters and Parametric Devices*

- Summary – *Lessons Learned*

Fraunhofer ILT

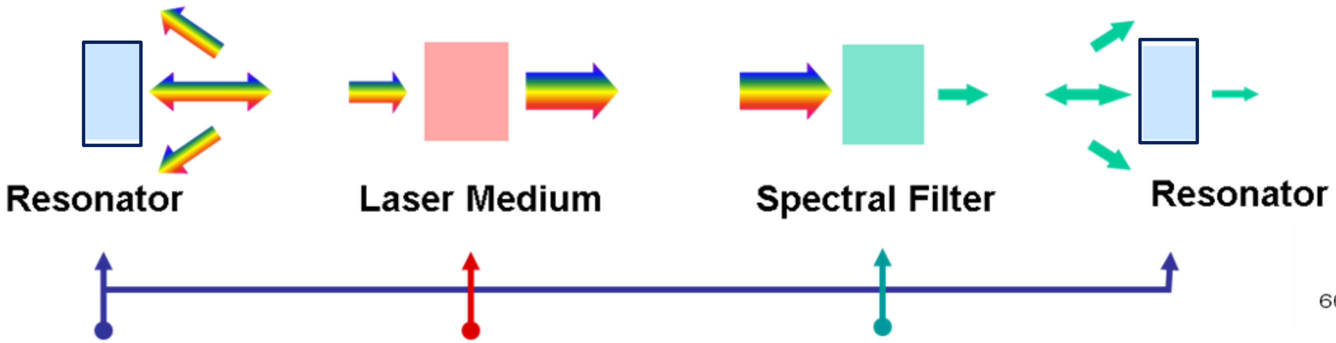
Tunable Coherent Light Sources

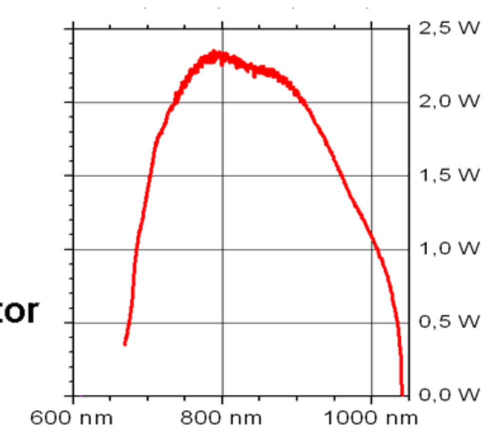
– Introduction & Overview

Fraunhofer
ILT

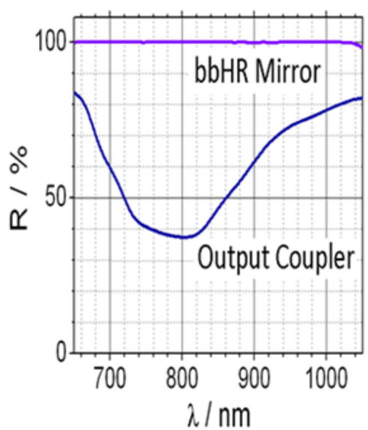
Tunable Lasers

Working Principle

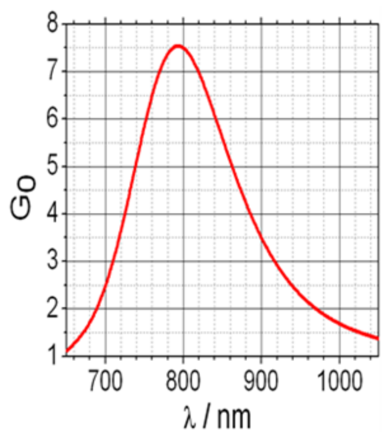




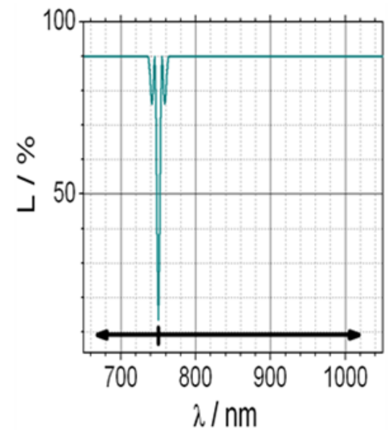
Broadband Tunable Laser Output



Broadband Optical Resonator



Broadband Gain Laser Medium



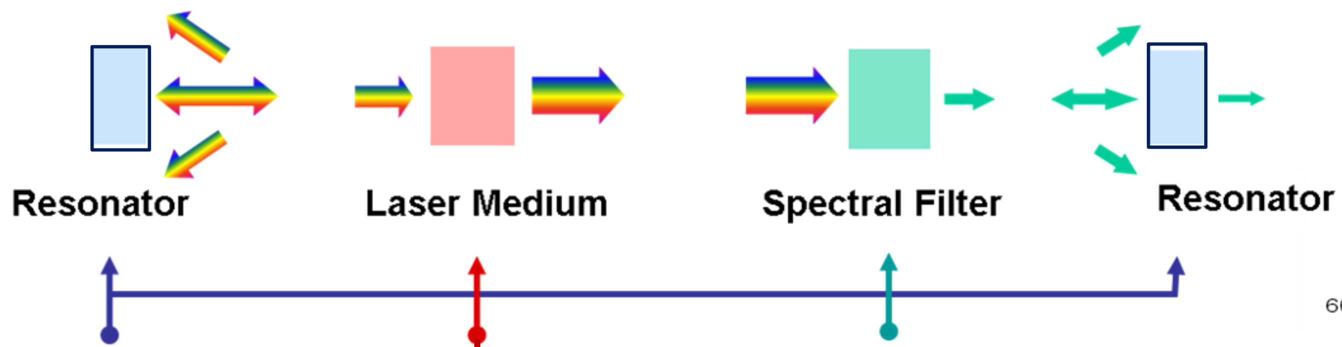
Broadband Tunable Spectral Filter

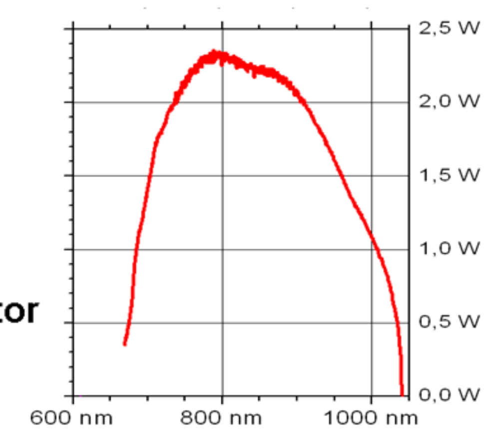
Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

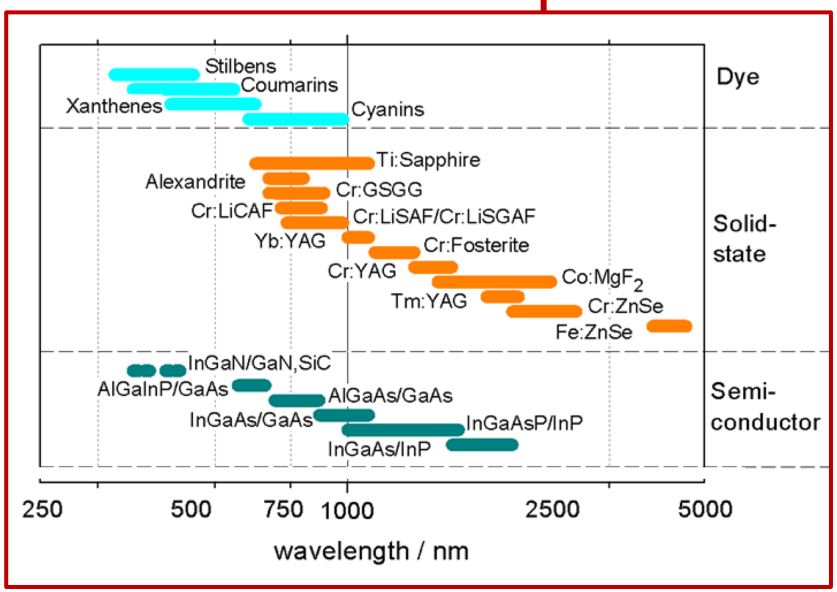
Fraunhofer ILT

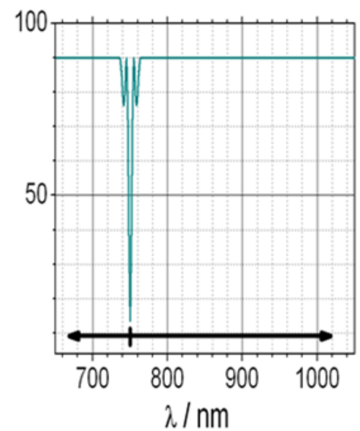
Tunable Lasers

Working Principle









Broadband Tunable Spectral Filter

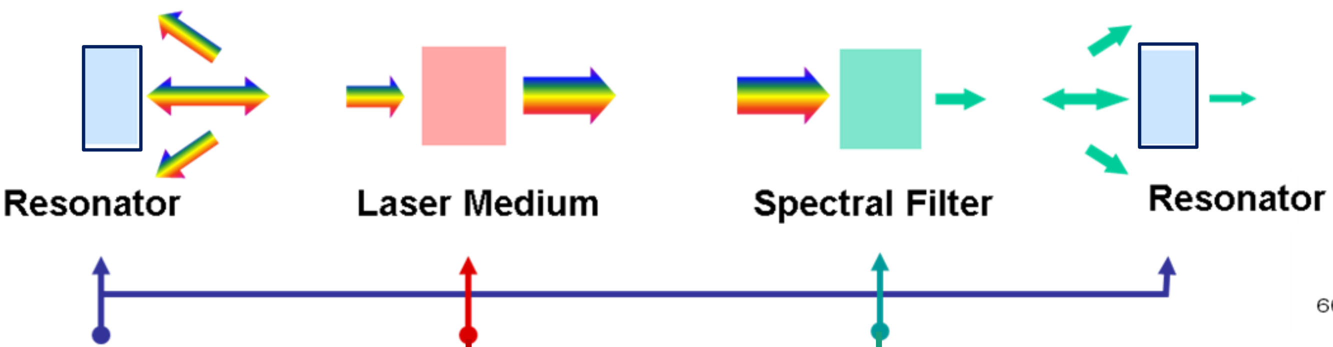
Broadband Tunable Laser Output

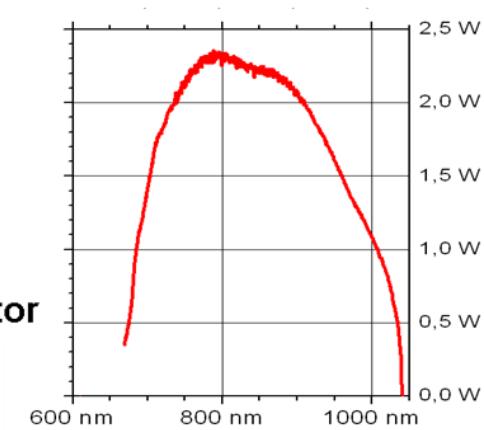
Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Fraunhofer ILT

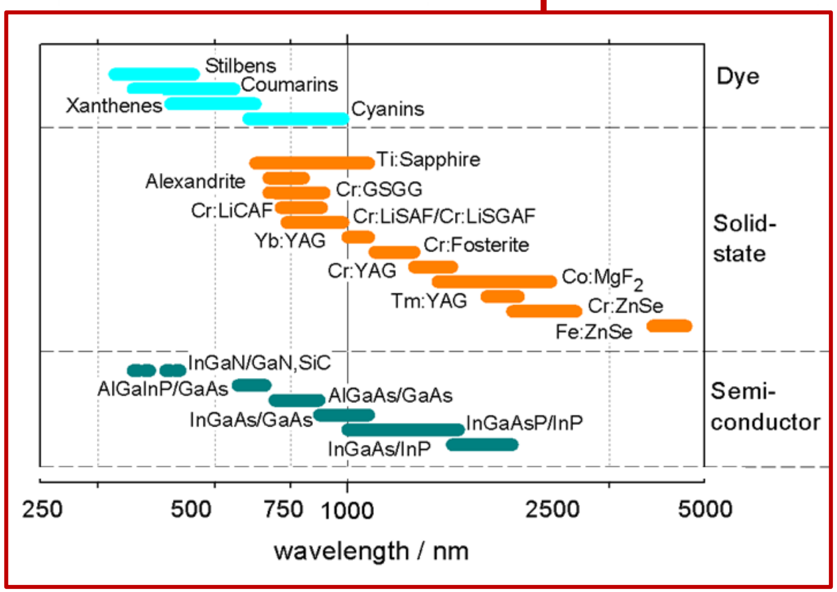
Tunable Lasers

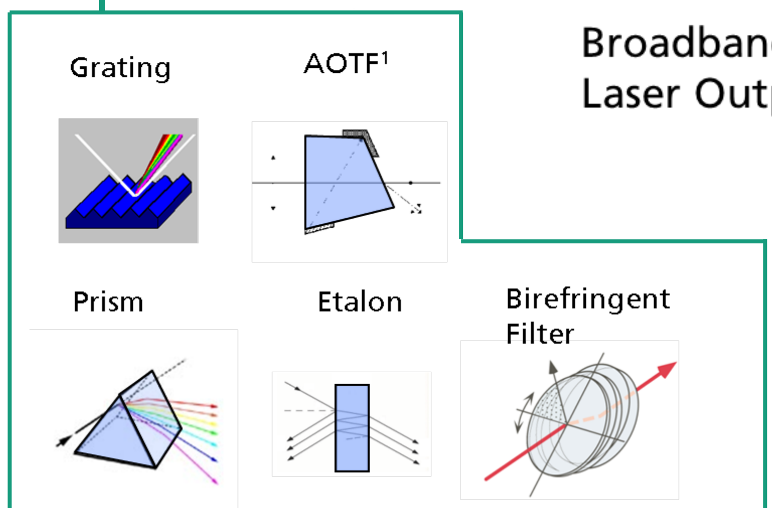
Working Principle





Broadband Tunable Laser Output





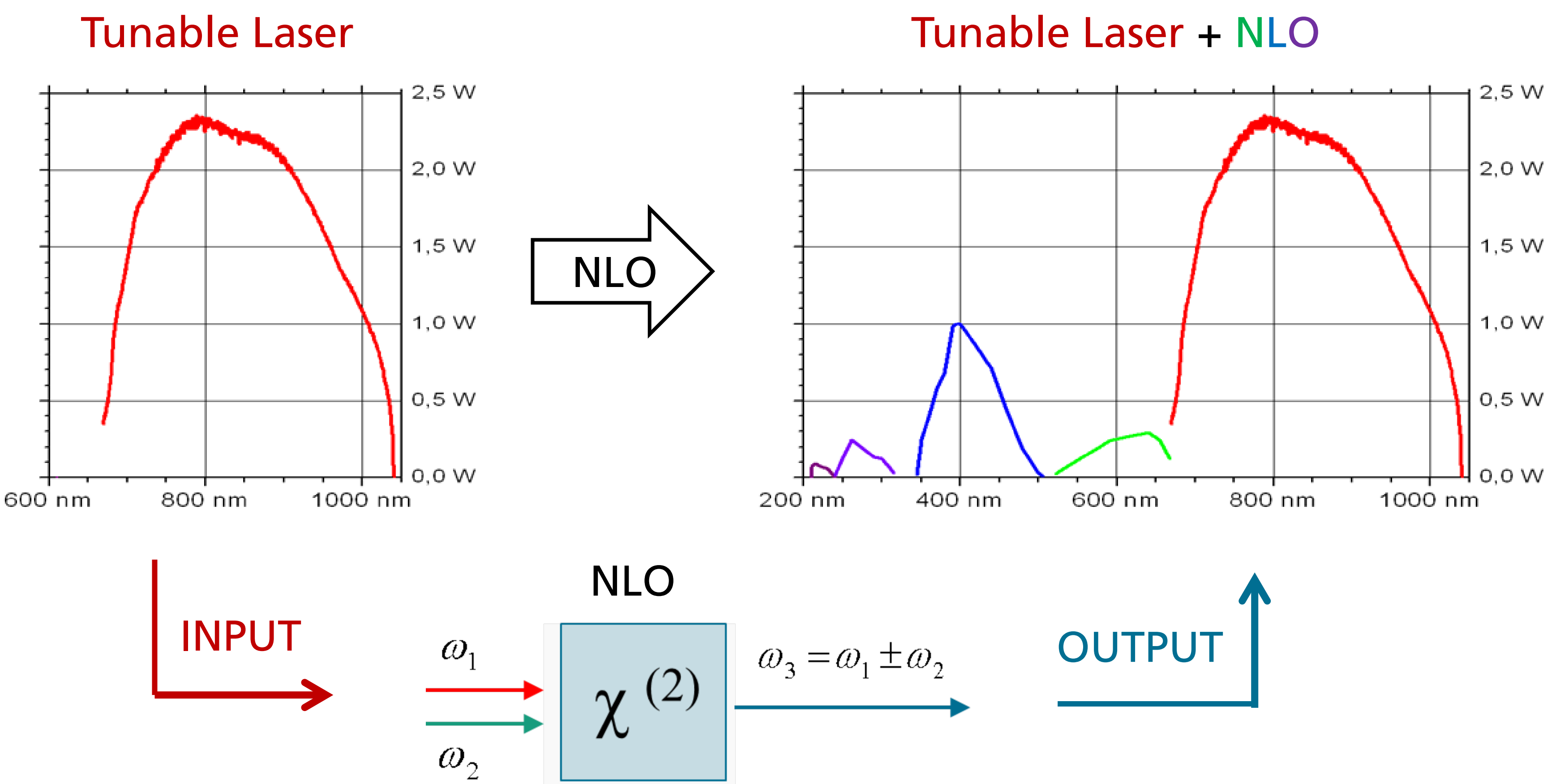
[1] AOTF = acousto optical tuning filter.

from: Meschede, „Optik, Licht, Laser“

Fraunhofer ILT

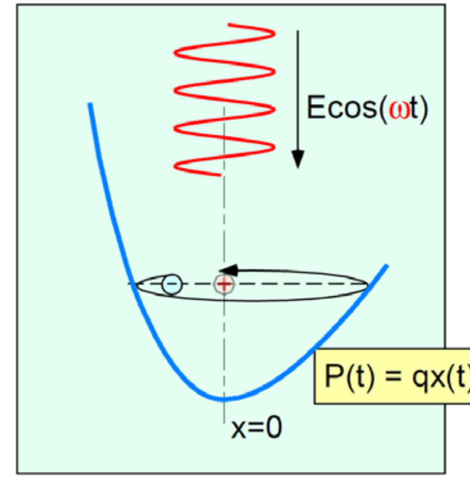
Nonlinear Optical Three-Wave-Mixing

→ Extending the Tuning Range



Nonlinear Optical Three-Wave-Mixing

→ Extending the Tuning Range



Anharmonic Field (from: Meschede, „Optik, Licht, Laser“)

Polarisation of dielectric media

$\vec{P} = \chi \vec{E}$ (for low intensity) Linear Optics

$\vec{P} = \sum_{i=0}^{\infty} \chi^{(i)} \vec{E}^{i}$ (general) Nonlinear Optics (NLO)

$$= \underbrace{\chi^{(1)} \vec{E}}_{= \vec{P}_L} + \underbrace{\chi^{(2)} \vec{E}^{2} + \cancel{\chi^{(3)} \vec{E}^{3}} + \ldots}_{= \vec{P}_{NL}}$$

Nonlinear Three-Wave-Mixing

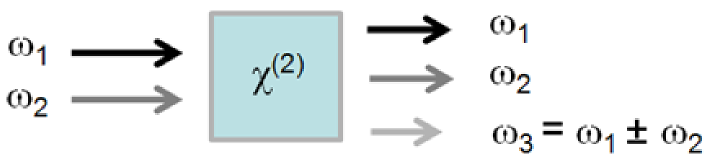
$$\Rightarrow P_{NL}(t) = \chi^{(2)} \left(E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c. \right)^2 \longrightarrow \begin{cases} 2\omega_1 \, , 2\omega_2 & \text{(SHG)} \\ \omega_1 - \omega_2 & \text{(DFG)} \\ \omega_1 + \omega_2 & \text{(SFG)} \\ \omega_1 - \omega_1 \, , \omega_2 - \omega_2 & \text{(OR)} \end{cases}$$

with $E(t) = E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c.$

Nonlinear Optical Three-Wave-Mixing

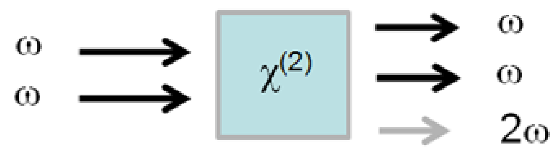
→ Extending the Tuning Range

Single Step Processes



SFG, DFG

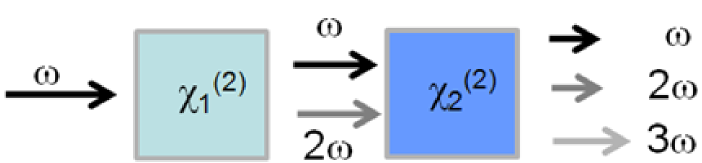
(Sum / Difference Frequency Generation)



SHG

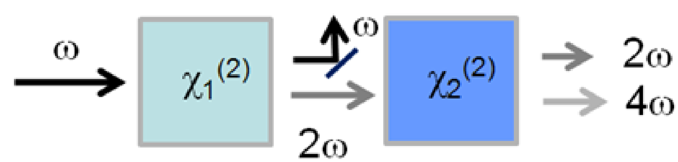
(Second Harmonic Generation)

Two Step Processes:



THG

(Third Harmonic Generation)

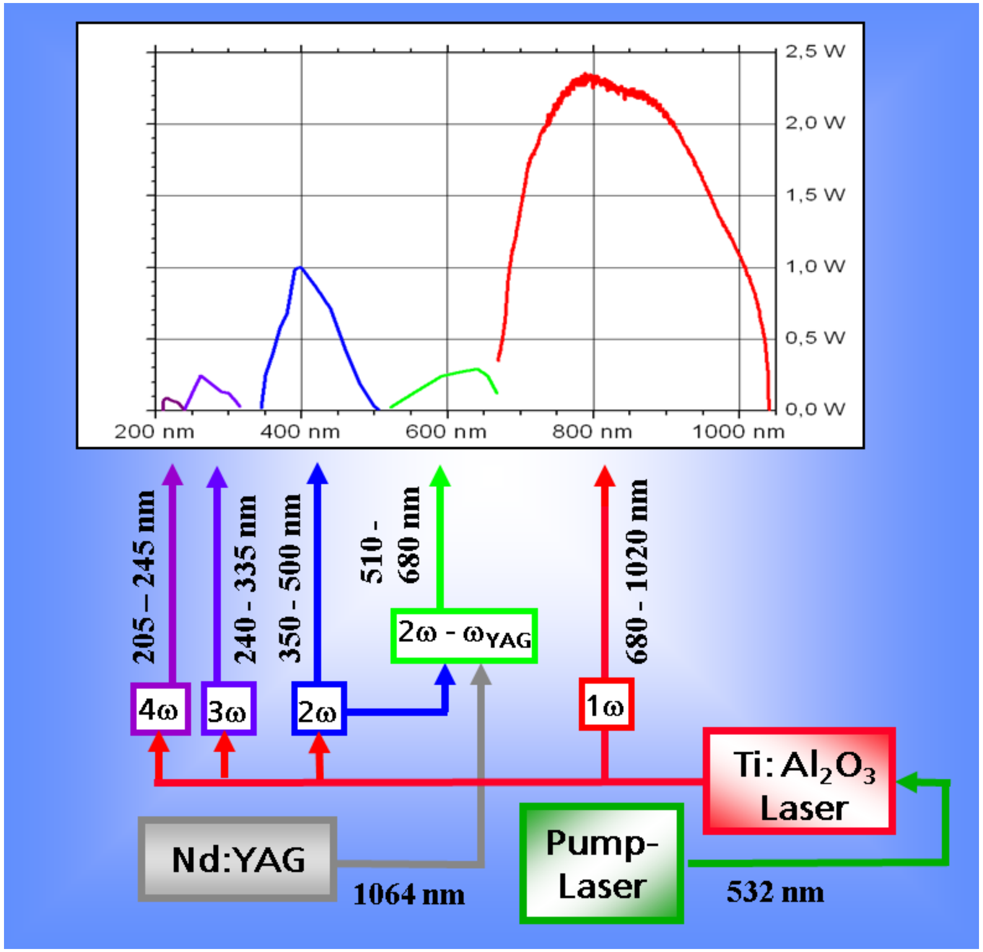


FHG

(Fourth Harmonic Generation)

Nonlinear Optical Three-Wave-Mixing

→ Extending the Tuning Range



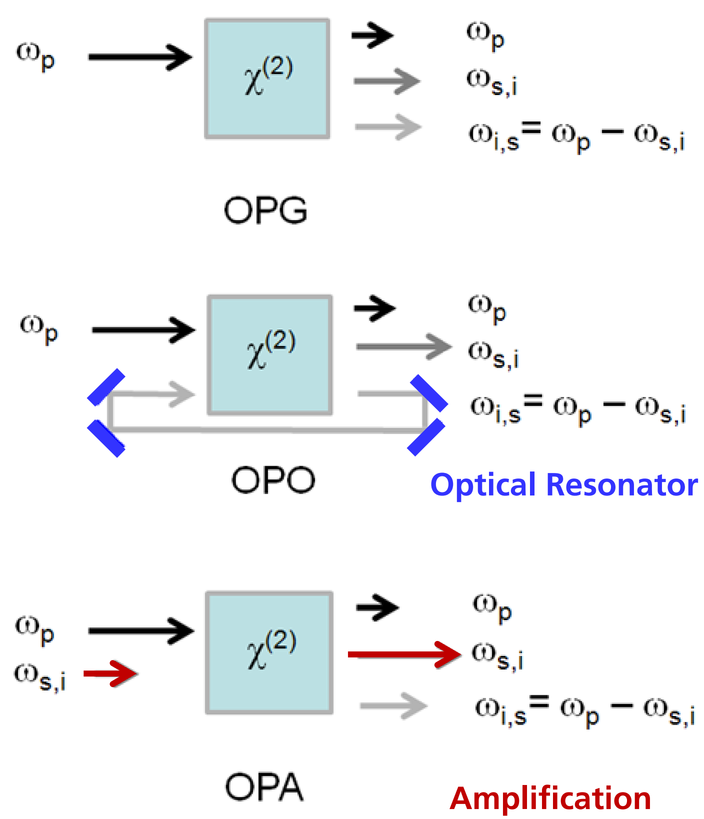
Fraunhofer ILT

Nonlinear Optical Three-Wave-Mixing II

→ Parametric Frequency Conversion

- Generation of two photons with longer wavelength (s = signal, i = idler) out of one photon with shorter wavelength (p = pump)
  - **OPG = optical parametric generator**
  - **OPO = … oscillator**
  - **OPA = … amplifier**

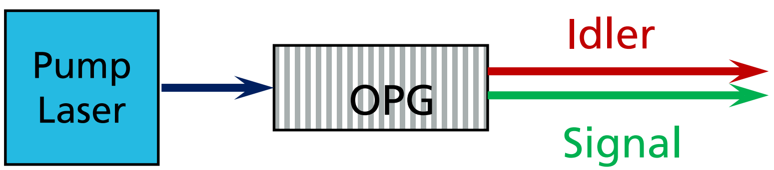
→ **Tunable laser output based on nonlinear optical three-wave-mixing**

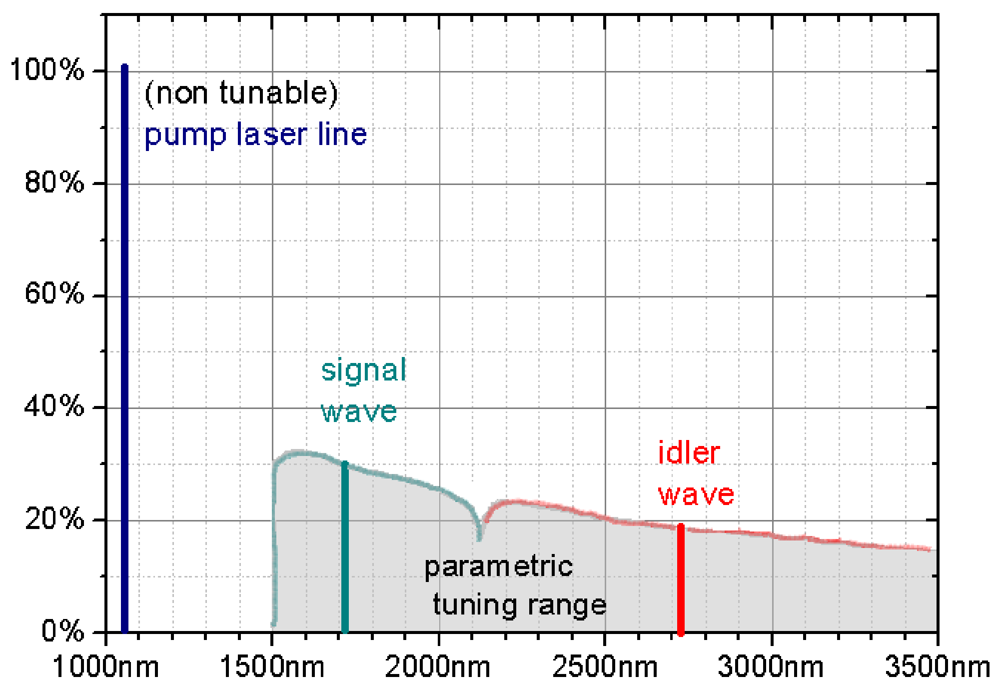


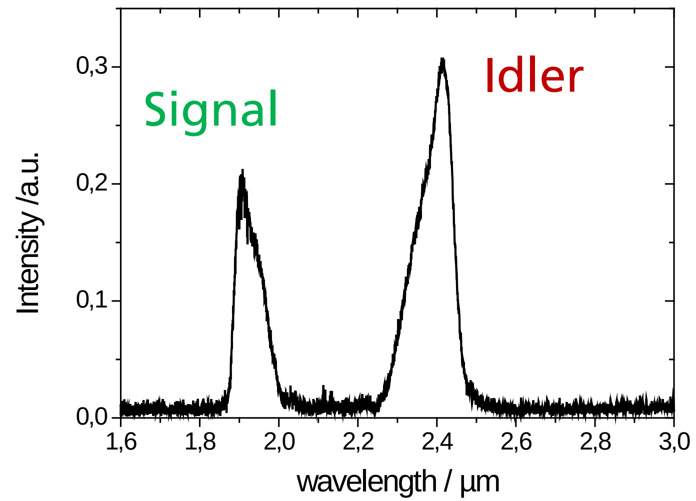
Fraunhofer ILT

Nonlinear Optical Three-Wave-Mixing II

→ Parametric Frequency Conversion



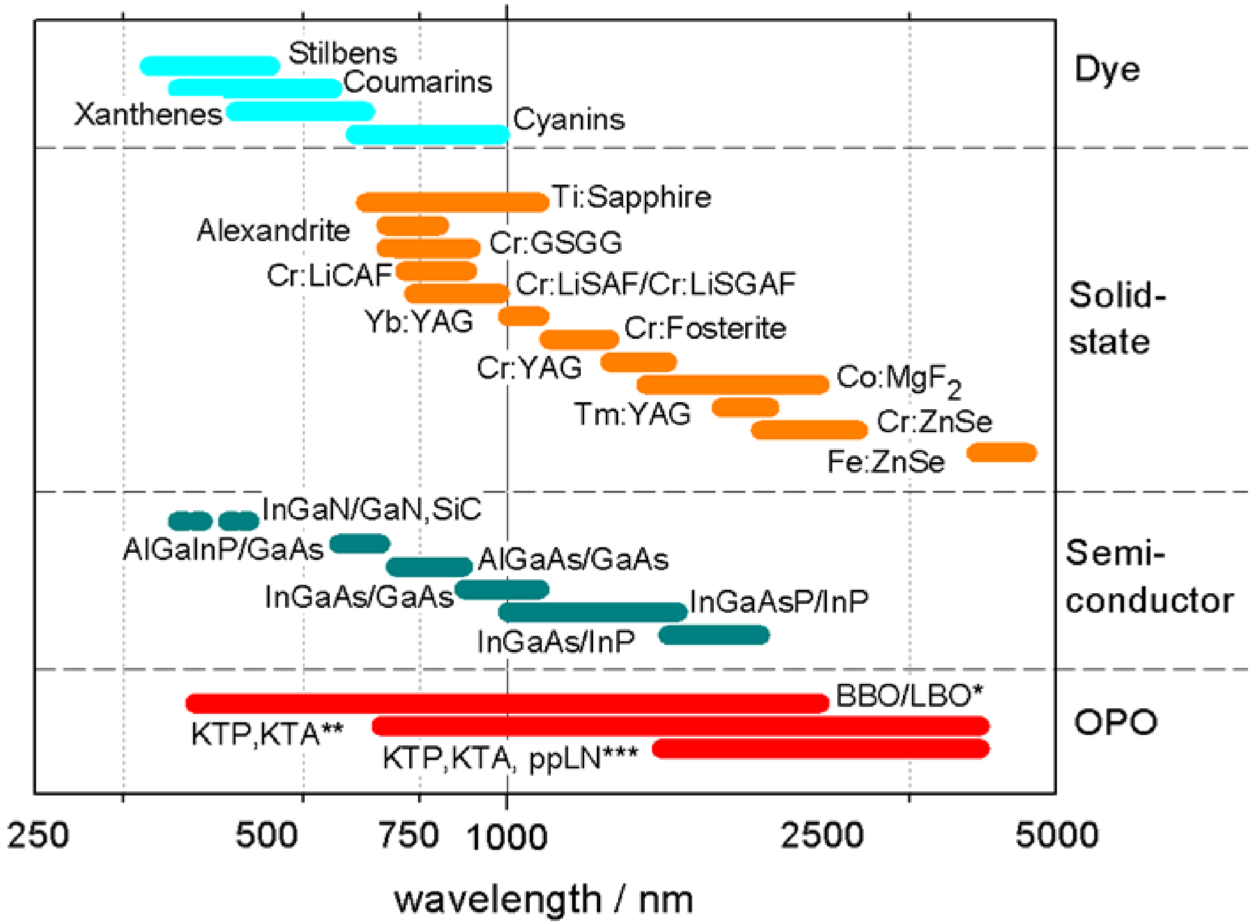




Tunable OPG (1064nm pump)

Overview

→ Tunable Laser Concepts

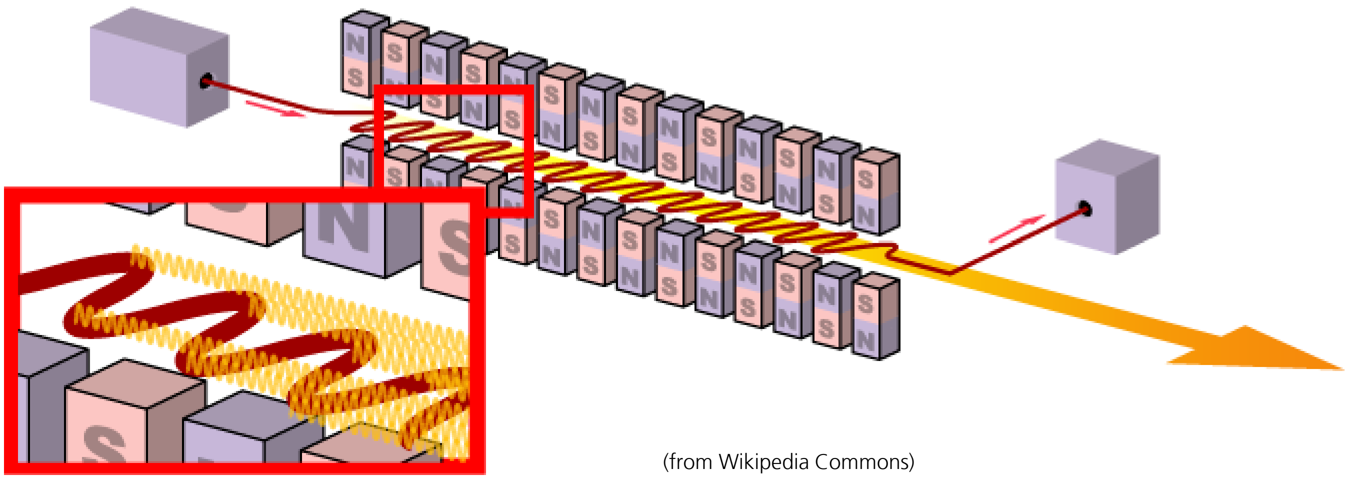


Fraunhofer ILT

Alternative Approaches

→ Here: Free Electron Laser

FEL



(from Wikipedia Commons)

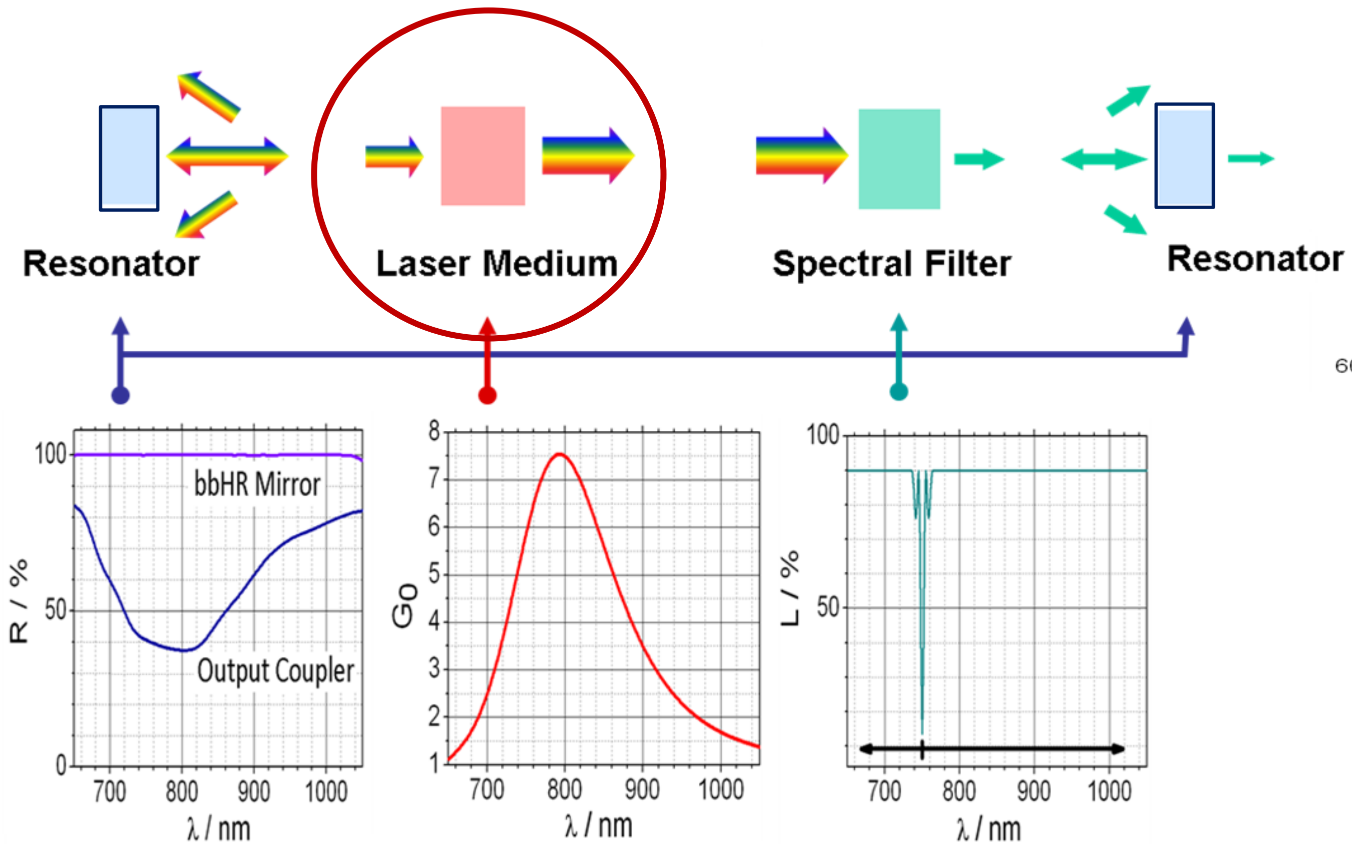
Not included in this presentation!

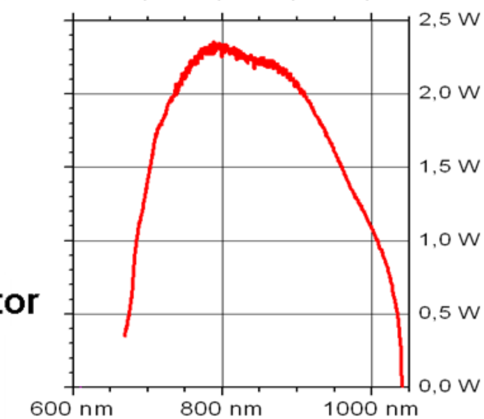
Tunable Lasers

– Design Basics and Challenges

Tunable Lasers

Working Principle





Broadband Optical Resonator

Broadband Gain Laser Medium

Broadband Tunable Spectral Filter

Broadband Tunable Laser Output

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

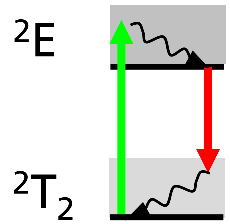
Fraunhofer ILT

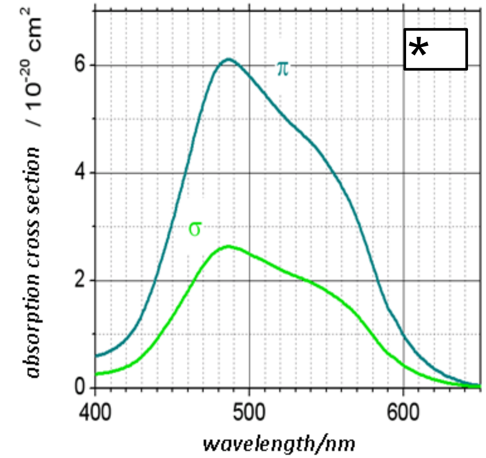
Broadband Gain Laser Media

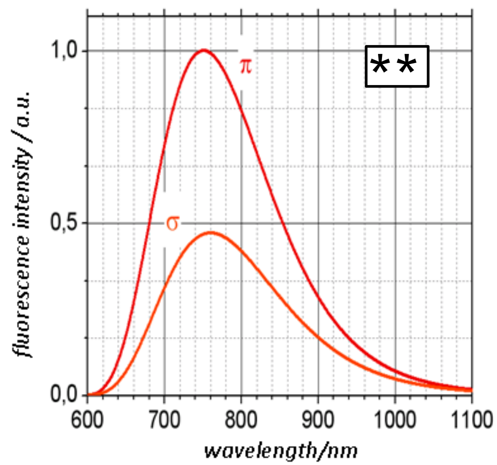
Example: Ti:Sapphire

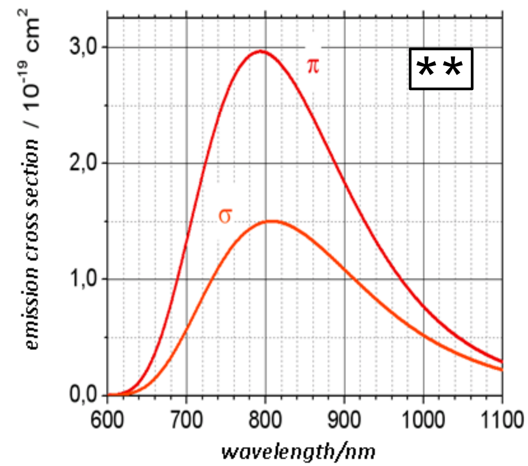
stoichiometric:	$Ti^{3+}:Al_2O_3$
Crystal structure:	hexagonal
Level structure:	4-level, vibronic
$\sigma_{\pi,max}$	$3\text{-}4 \cdot 10^{-19}\ cm^2$
E_{sat}	$0{,}9\ J/cm^2$
τ	$3{,}2\ \mu s$ (@ 300 K)
η_Q	$\cong 0{,}82$ (@ 300K)
dn_e/dT	$14{,}7 \cdot 10^{-19}\ cm^2$
κ	42 W/m/ K

Spectroscopy







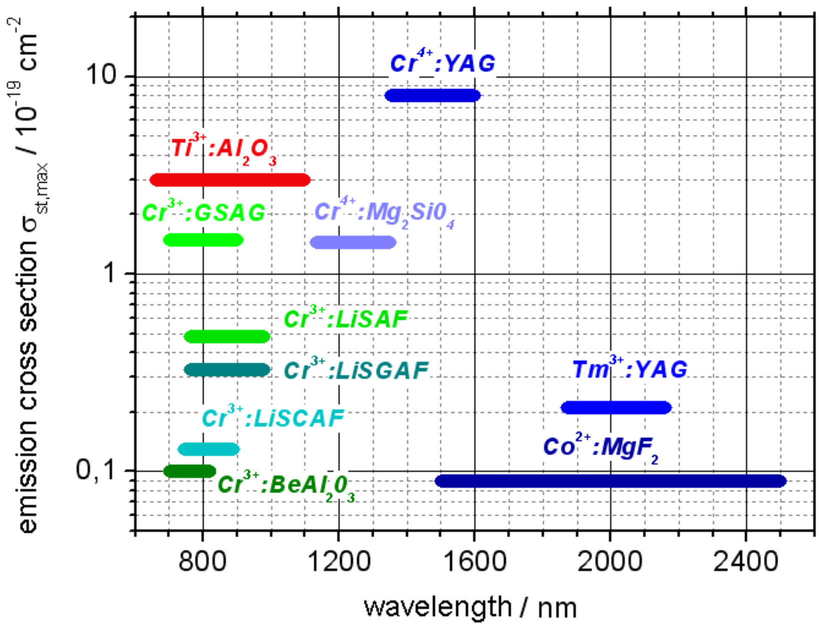


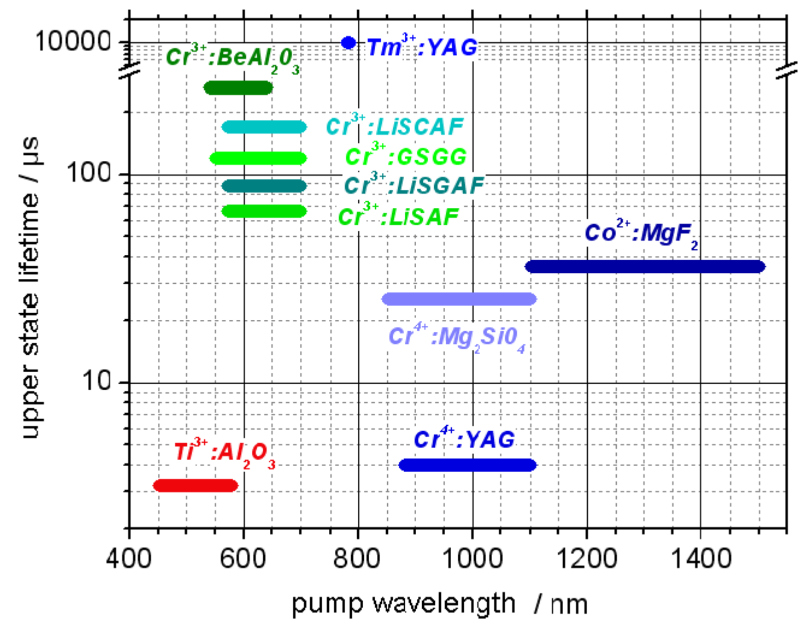
* Moulton, P. F.: Spectroscopic and laser characteristics of $Ti:Al_2O_3$. Journal of the Optical Society of America. B, **3**, 125-133 (1986)

** Egglestone, J.M.; DeShazer, L.G.; Kangas, K. W.: Characteristics and Kinetics of Laser-Pumped Ti:Sapphire Oscillators. IEEE Journal of Quantum Electronics **24**-6, 1009-1015, 1988

Broadband Gain Laser Media

Solid-state Laser Media with Broadband Emission in VIS and NIR





McCumber:

$$\Delta\lambda \times \sigma \cdot \tau_f = \frac{\lambda_0}{4\pi c n^2}\sqrt{\frac{\ln 2}{\pi}}$$

σ emission cross section

$\Delta\lambda$ gain bandwidth

τ_f upper state lifetime

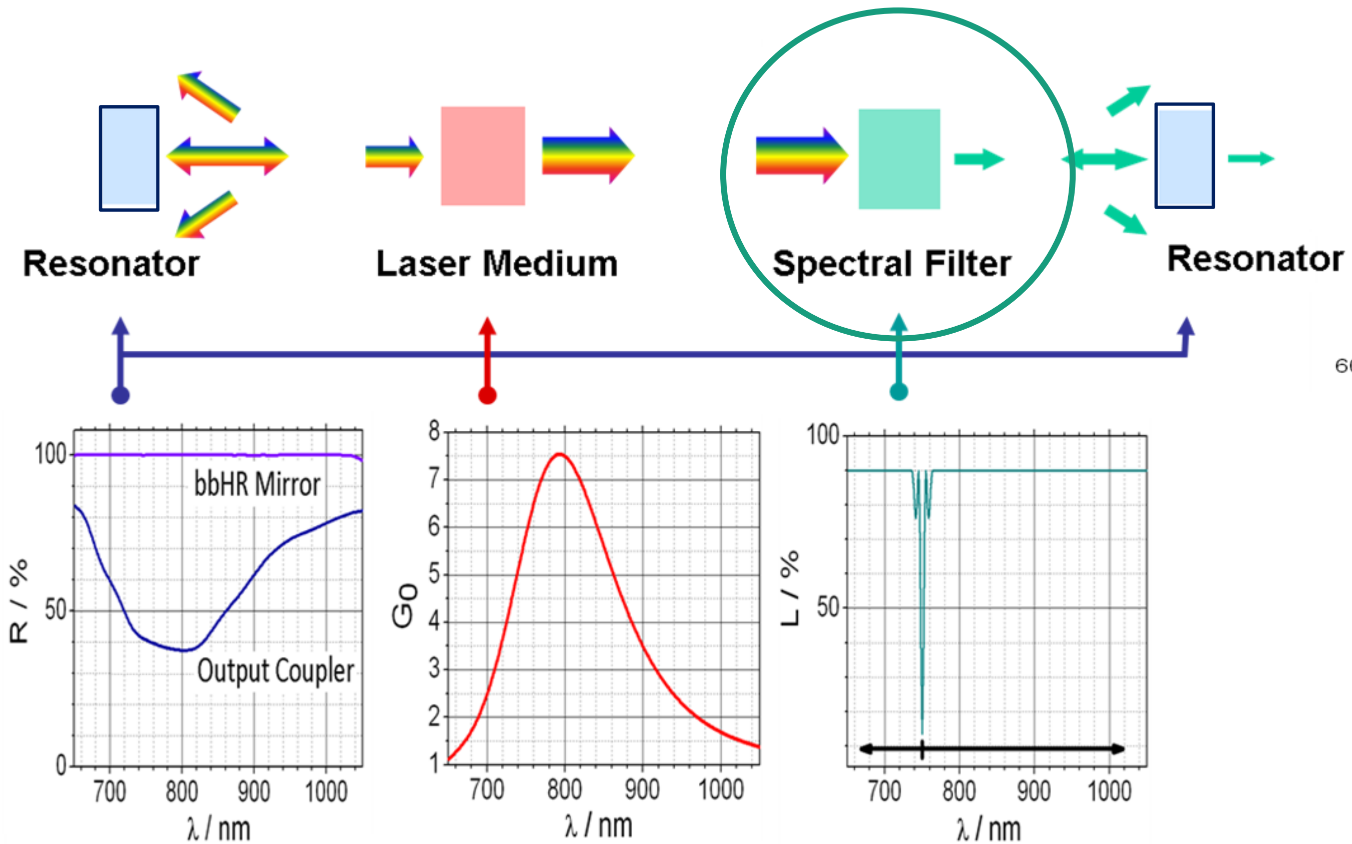
→ For laser media with large gain bandwidth $\Delta\lambda$ the product $\sigma\cdot\tau_f$ is small

→ High brightness pump sources & high fluence on resonator optics

from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Tunable Lasers

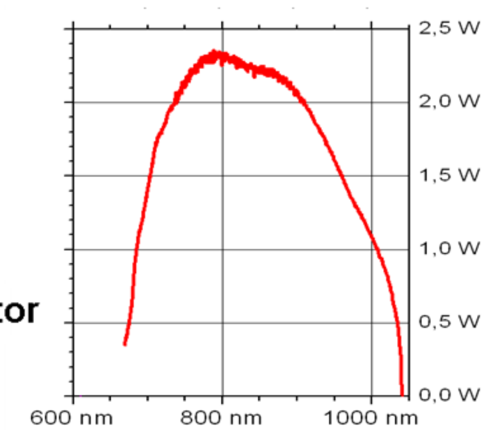
Working Principle



Broadband
Optical Resonator

Broadband Gain
Laser Medium

Broadband Tunable
Spectral Filter



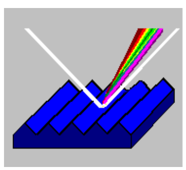
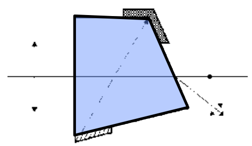
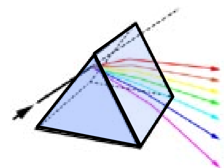
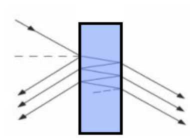
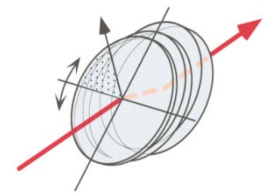
Broadband Tunable
Laser Output

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Fraunhofer
ILT

Tunable Spectral Filters

wavelength dependent…

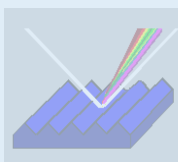
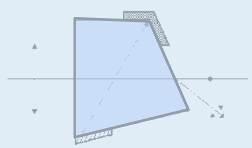
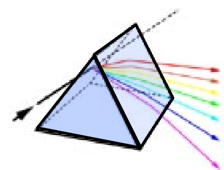
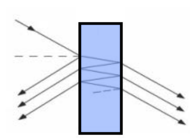
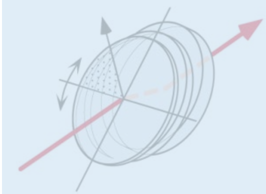
… angular deflection			… transmission	
Grating	AOTF[1]	Prism	Etalon	Lyot-Filter*
				
Tuning mechanism				
diffraction		refraction	multiple-beam interference	birefringence/ retardation
+ high resolution **- losses**	**+ robust** **- losses**	**+ contrast ratio** **- low resolution**	**+ resolution** **- thermal instability**	**+ efficiency** **- contrast ratio**

(*from: Meschede, „Optik, Licht, Laser“)

[1] AOTF = acousto optical tuning filter.

Tunable Spectral Filters

wavelength dependent…

… angular deflection			… transmission	
Grating	AOTF[1]	Prism	Etalon	Lyot-Filter*
				
Tuning mechanism				
diffraction		refraction	multiple-beam interference	birefringence/ retardation
+ high resolution - losses	+ robust - losses	+ contrast ratio - low resolution	+ resolution - thermal instability	+ efficiency - contrast ratio

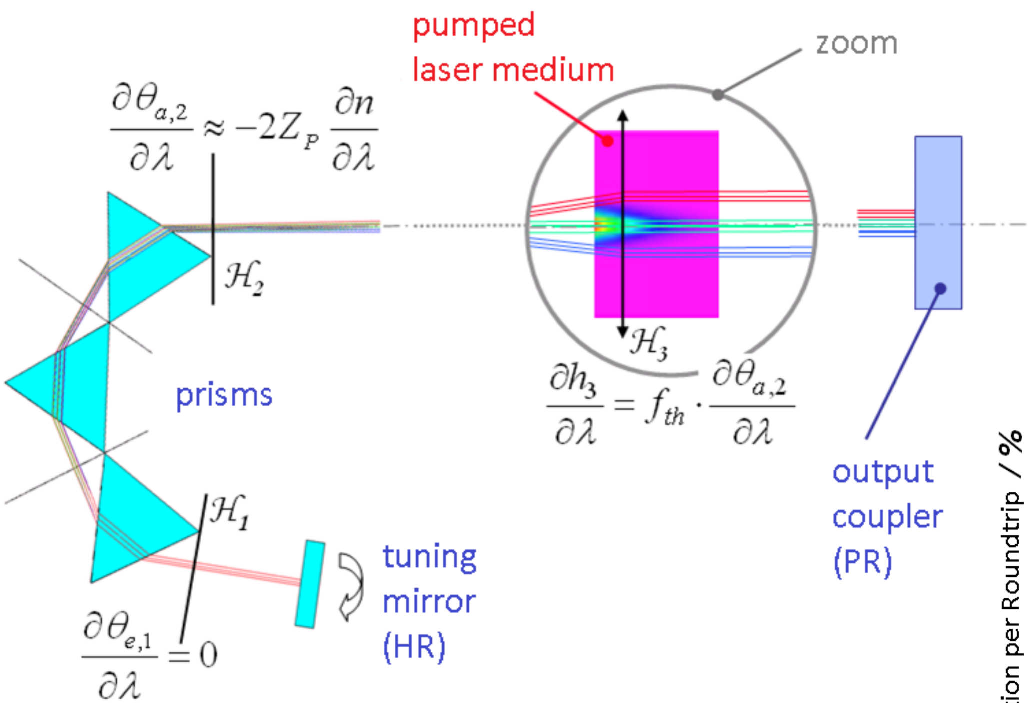
(*from: Meschede, „Optik, Licht, Laser“)

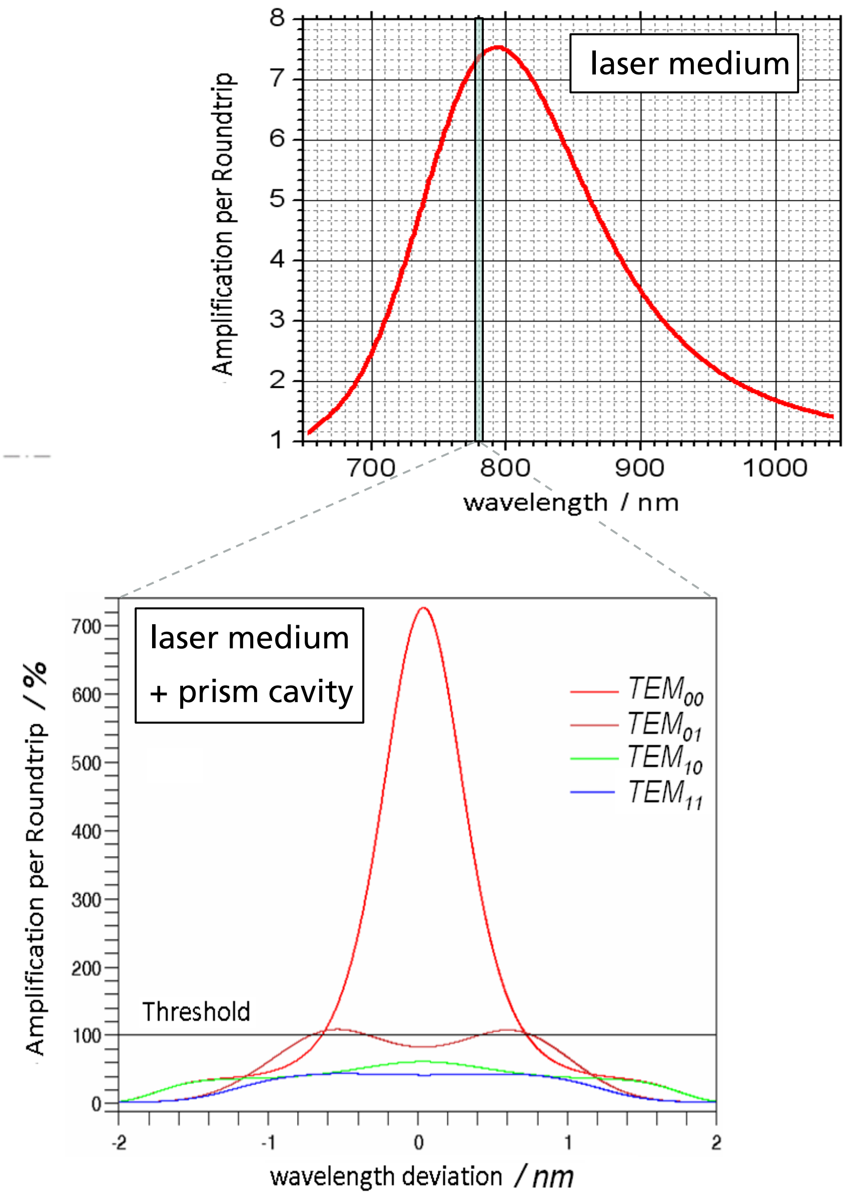
[1] AOTF = acousto optical tuning filter.

Fraunhofer ILT

Tunable Spectral Filters

Prisms





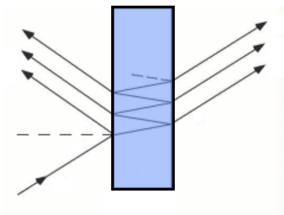
Tunable laser cavity

- Number of Brewster Prims $Z_p = 3$

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Tunable Spectral Filters

Etalon



Comb-like transmission curve from multi-beam interference:

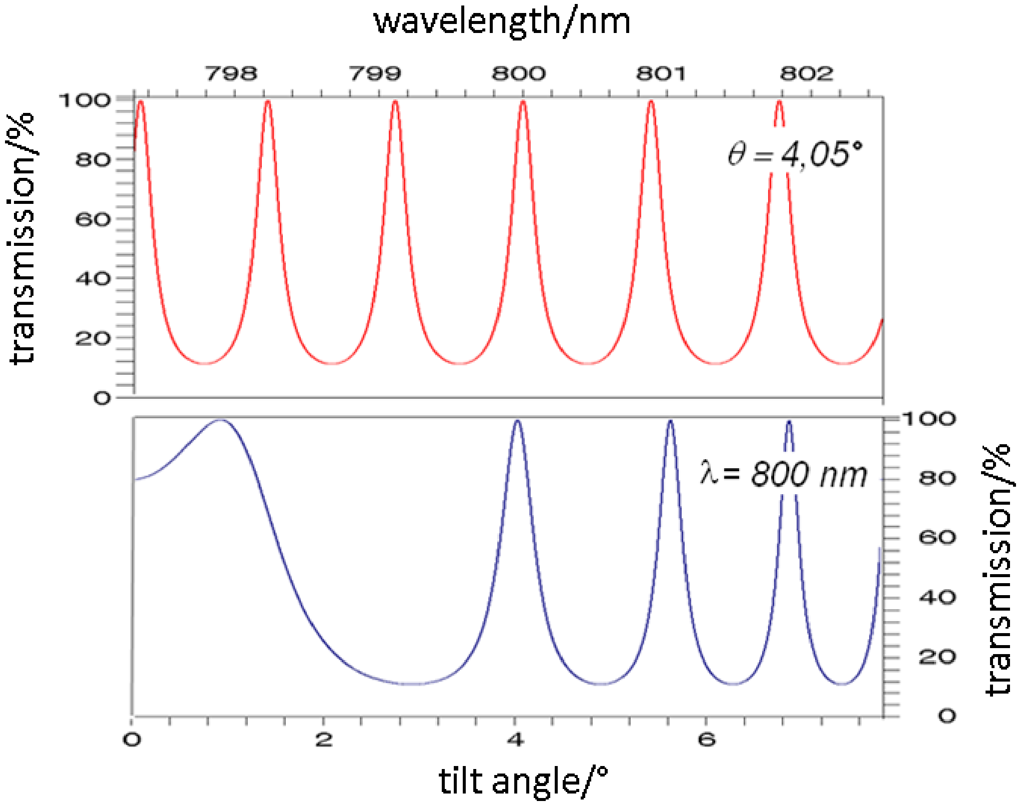
$$T_E = \frac{(1-R_E)^2}{(1-R_E)^2 + 4R_E \sin^2(\Delta\phi/2)}$$

(Airy function)

with

$$\Delta\phi = 2\pi\nu/c \cdot 2d_E \sqrt{n^2 - \sin^2\theta_i}$$

(phase difference of neighboring beams)

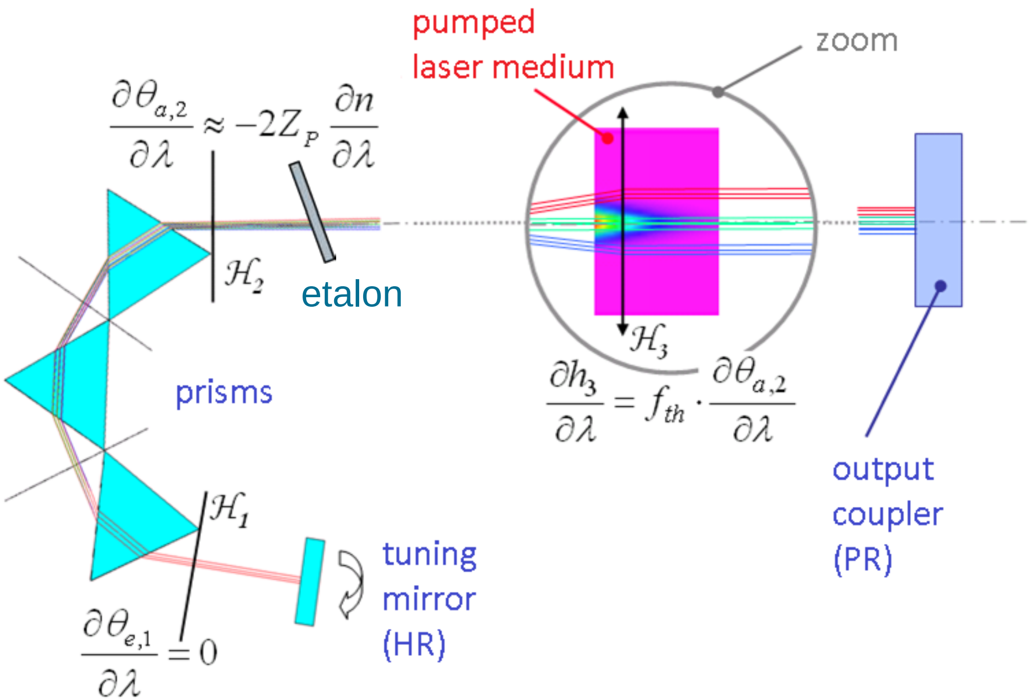


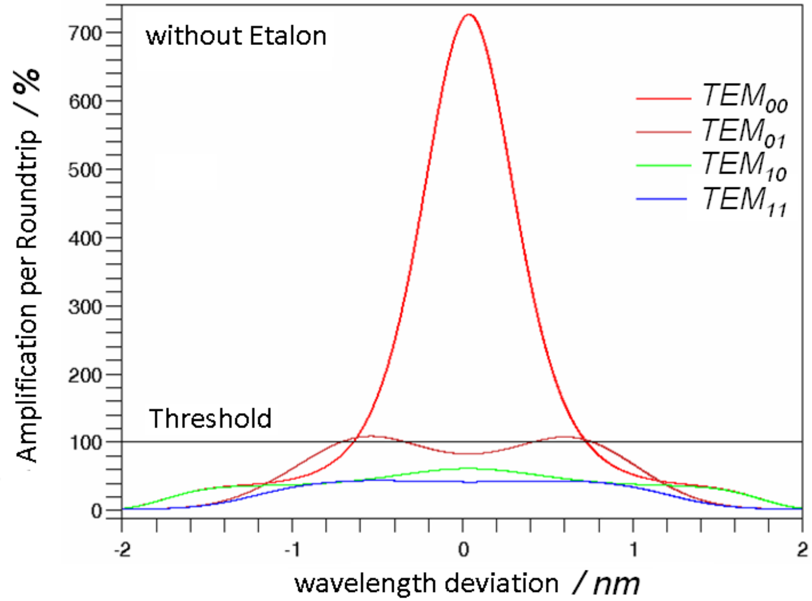
Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

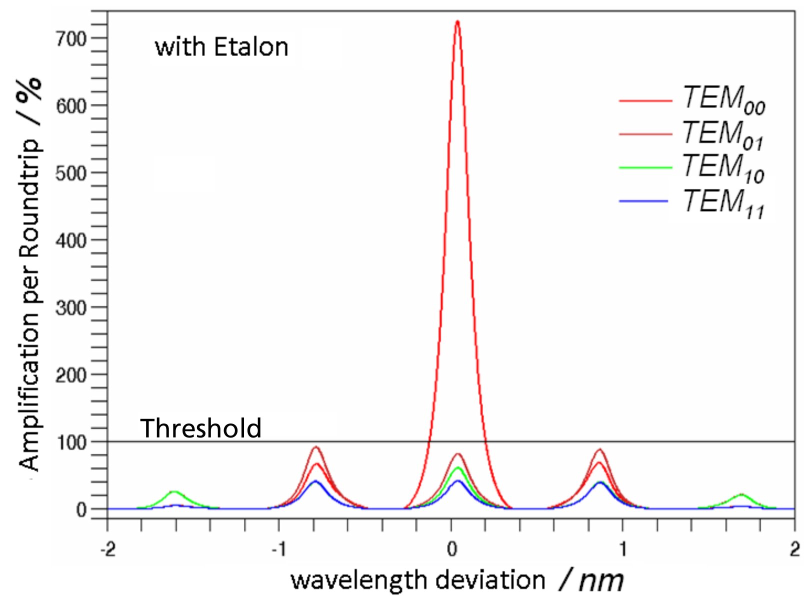
Fraunhofer ILT

Tunable Spectral Filters

Prisms, Etalon







Tunable laser cavity

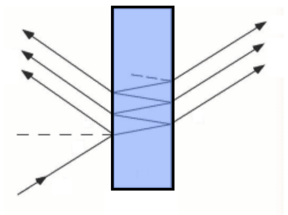
- Number of Brewster Prims $Z_p = 3$
- Solid-Etalon

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Fraunhofer ILT

Tunable Spectral Filters

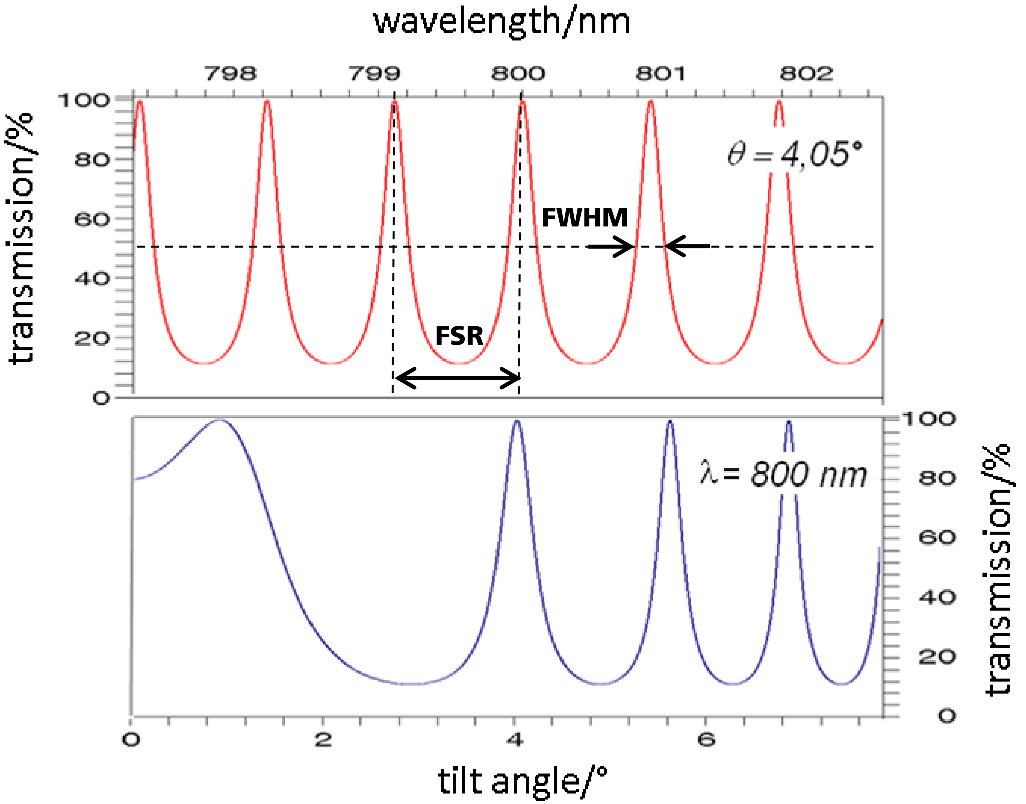
Etalon



Comb-like transmission curve from multi-beam interference:

$$T_E = \frac{(1-R_E)^2}{(1-R_E)^2 + 4R_E \sin^2(\Delta\phi/2)}$$

(Airy function)



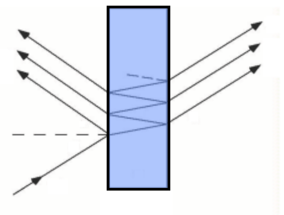
Design parameters:

FSR	$\Delta\nu_E = c \cdot \left[2d_E \cdot \sqrt{n^2 - \sin^2\theta_i} \right]^{-1}$
Finesse	$\mathcal{F} = FSR / FWHM \approx \pi \sqrt{R_E} / (1 - R_E)$

→ thickness

Tunable Spectral Filters

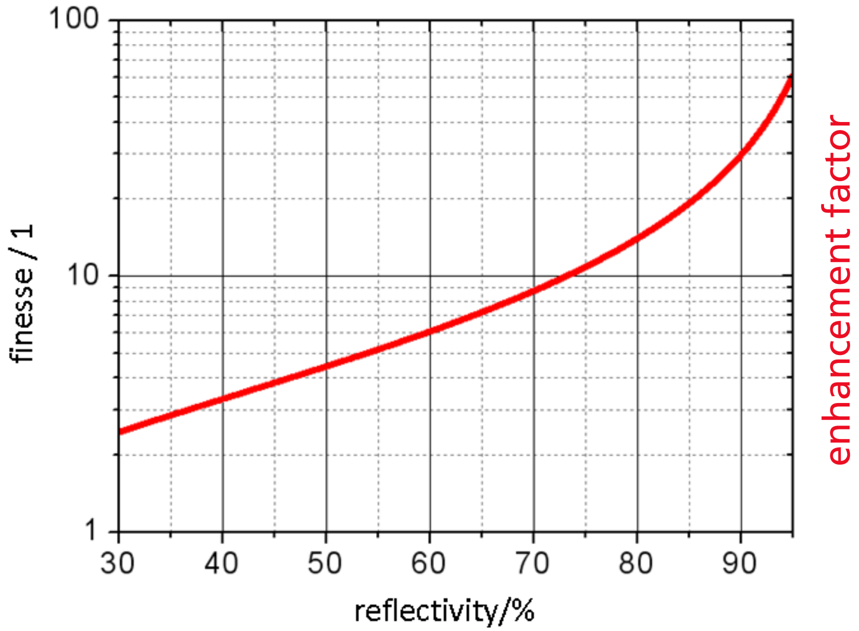
Etalon



Comb-like transmission curve from multi-beam interference:

$$T_E = \frac{(1-R_E)^2}{(1-R_E)^2 + 4R_E \sin^2(\Delta\phi/2)}$$

(Airy function)



High finesse → high intensity enhancement !!!

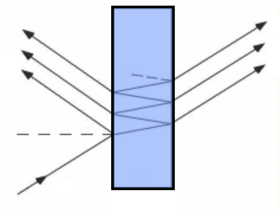
Design parameters:

FSR	$\Delta\nu_E = c \cdot \left[2d_E \cdot \sqrt{n^2 - \sin^2\theta_i} \right]^{-1}$	→	thickness
Finesse	$\mathcal{F} = FSR / FWHM \approx \pi \sqrt{R_E} / (1 - R_E)$	→	reflectivity

Fraunhofer ILT

Tunable Spectral Filters

Etalon

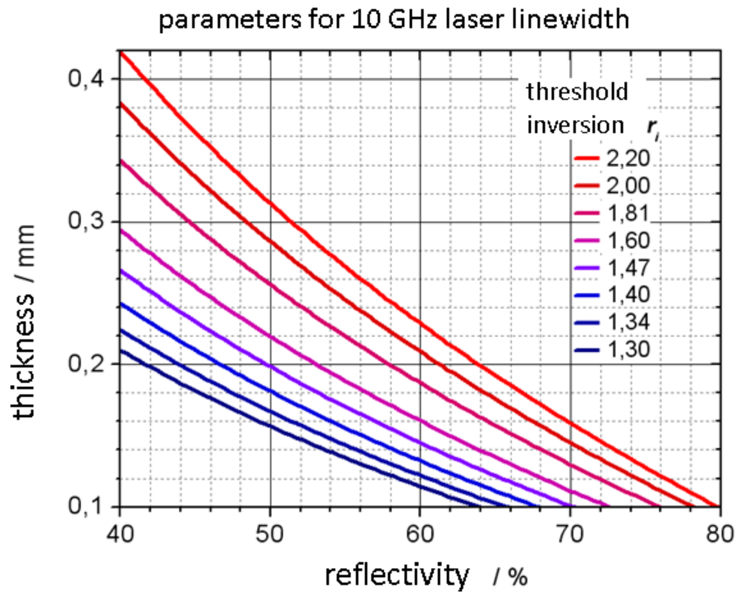


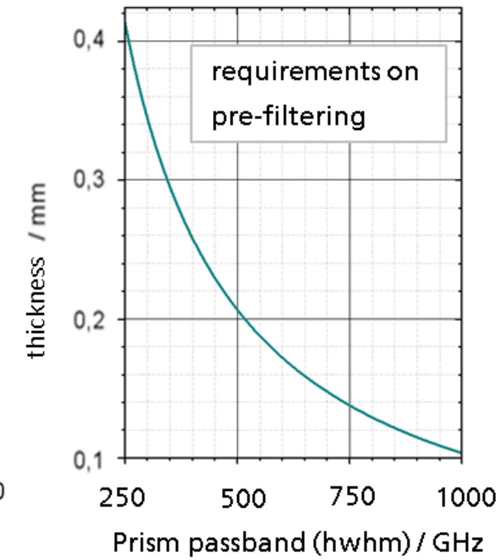
Measures for fluence reduction

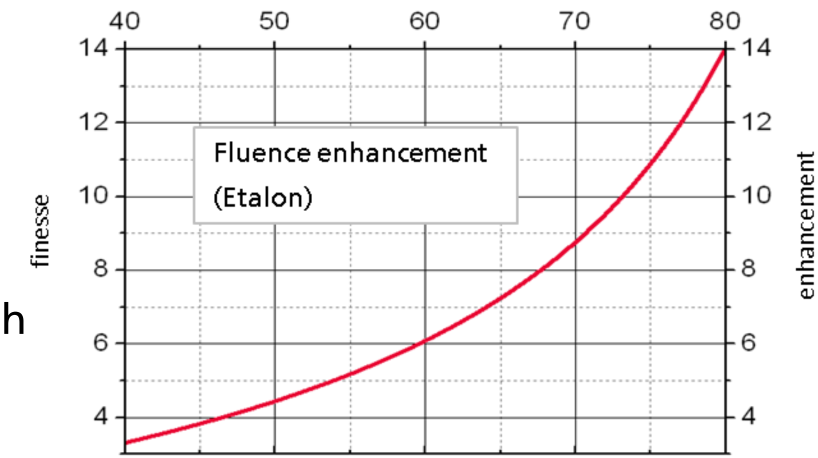
- thicker Etalons
- lower Finesse

→ smaller FSR of the etalon

→ smaller passband width of the prefiltering (prism cavity)



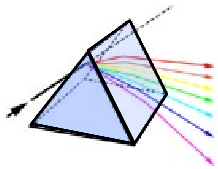




Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Tunable Spectral Filters

Prisms

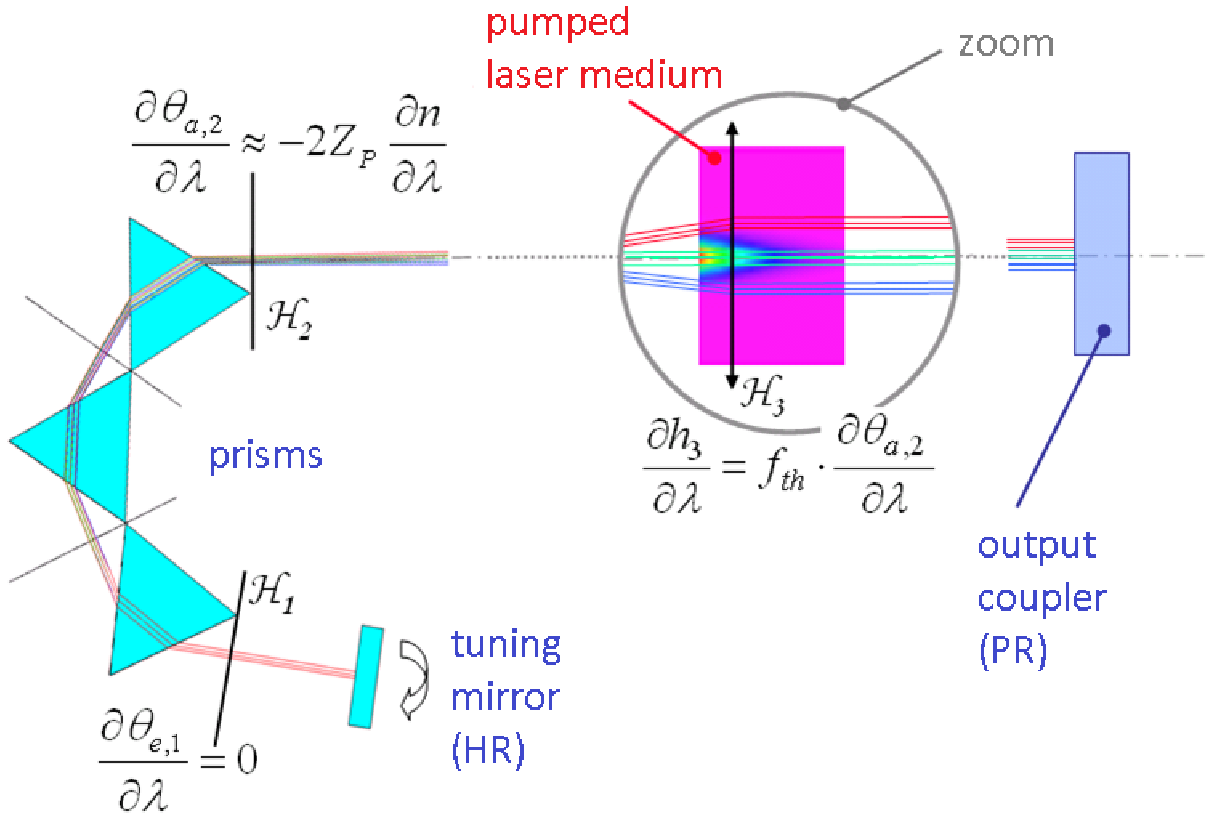


Passband width depends on:

- Dispersion of the glass
- Number Z_p of Prisms
- Optical Setup (here thermal lens)

→ Optimization measures:

- Choice of glass (e.g.. SF14, SF18…)
- Optical setup

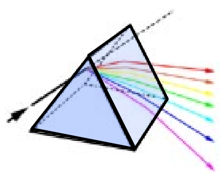


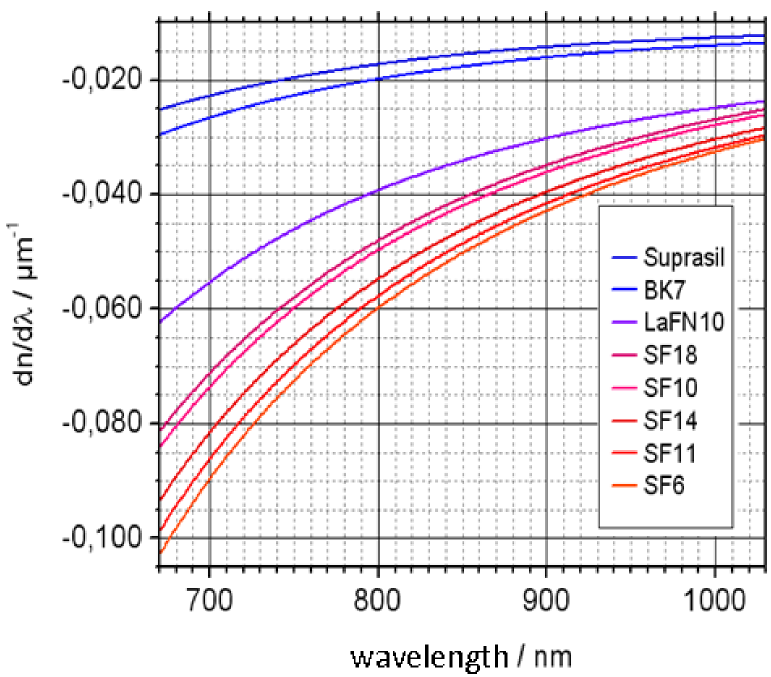
Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Tunable Spectral Filters

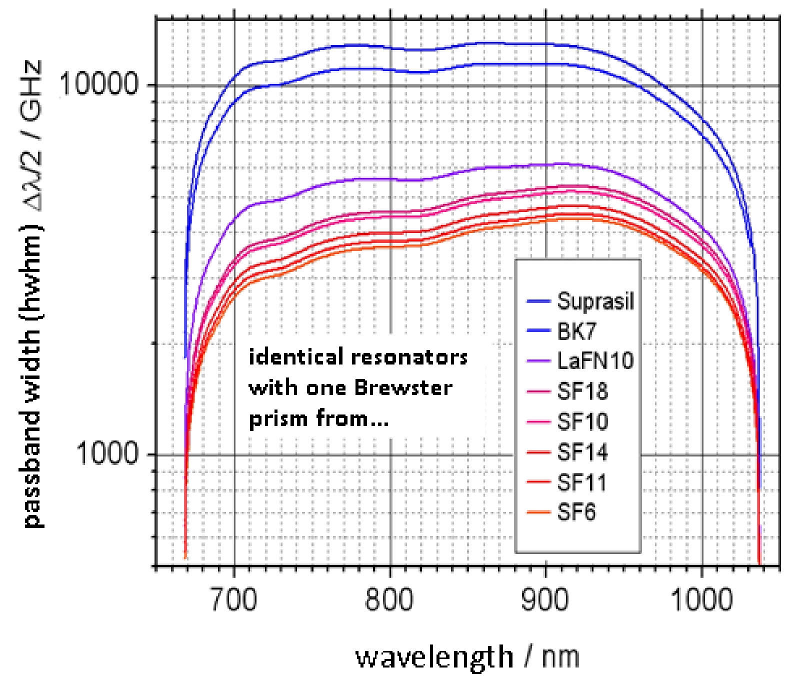
Prisms

Choice of glass





glass dispersion



calculated passband

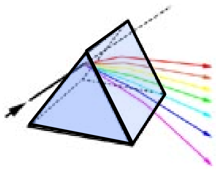
Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Fraunhofer ILT

Tunable Spectral Filters

Prisms

Choice of glass



	LIDT [J/cm^2] (0% damage after ~1800 pulses)	
	1064 nm @ 12 ns	**532 nm @ 10 ns**
N-BK7	2017	74.4
N-FK5	1574	226
F2	690	7.7
N-LASF44	720	18.5
N-LAF21	933	15.0
SF6	185	surface damage
Suprasil CG	1866	> 280

LIDT =
Laser
Induced
Damage
Threshold

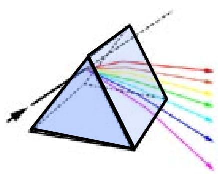
	LIDT [J/cm^2] (0% damage after ~2000 pulses)	
	1064 nm @ 74 ps	**532 nm @ 74 ps**
N-BK7	31.8	8.2
N-FK5	35.2	9.7
F2	16.7	3.5
N-LASF44	13.8	3.7
N-LAF21	12.6	4.7
SF6	6.4	surface damage
Suprasil	39.2	11

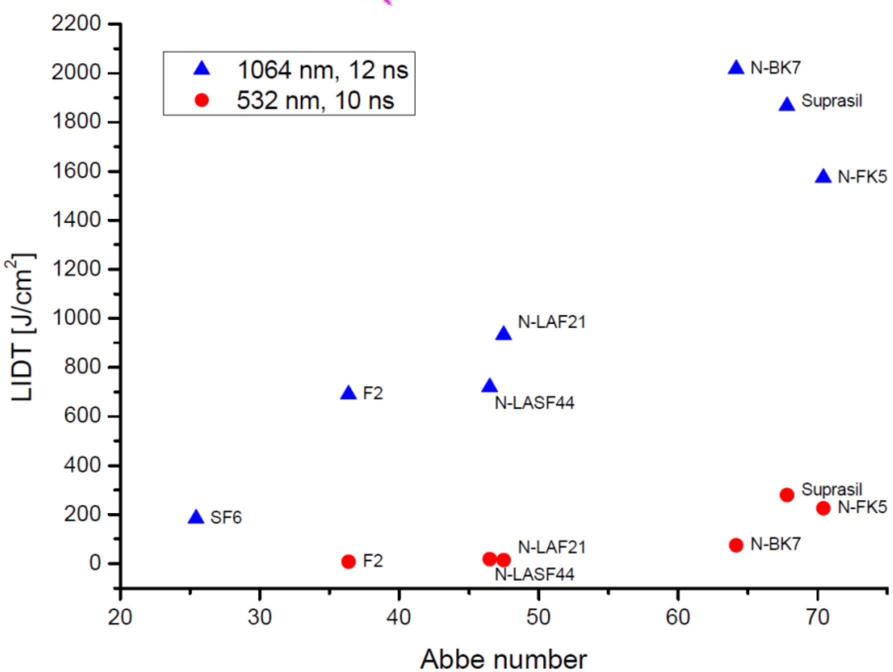
From Ralf Jedamzik et al.(Schott): „Recent Results on Bulk Laser Damage Threshold of Optical Glasses“, LASE Conference , Proc. SPIE 8603-04, 2013

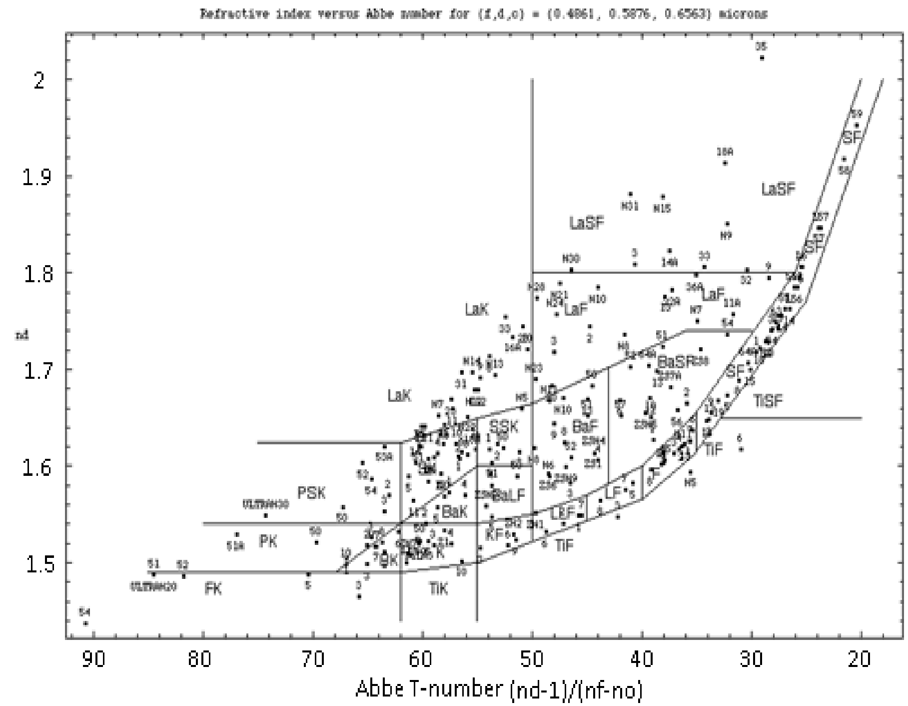
Tunable Spectral Filters

Prisms

Choice of glass







LIDT vs. Abbe number

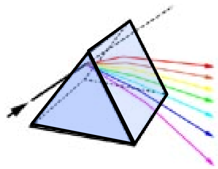
Index vs. Abbe number

From Ralf Jedamzik et al.(Schott): „Recent Results on Bulk Laser Damage Threshold of Optical Glasses“, LASE Conference , Proc. SPIE 8603-04, 2013

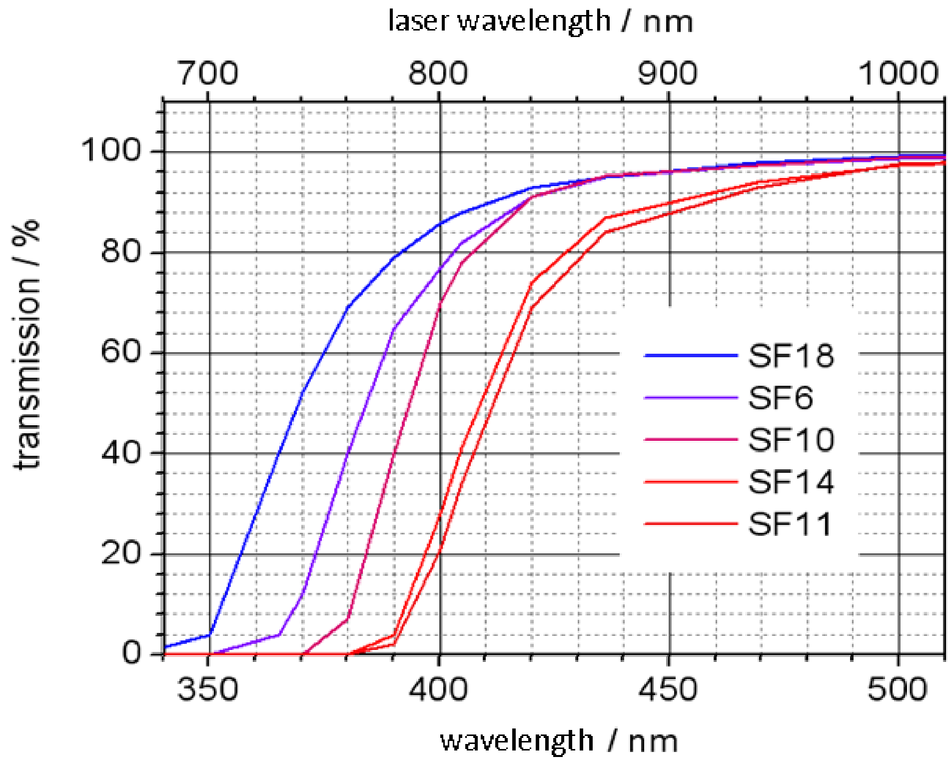
Fraunhofer ILT

Tunable Spectral Filters

Prisms



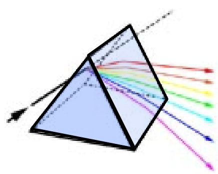
Choice of glass



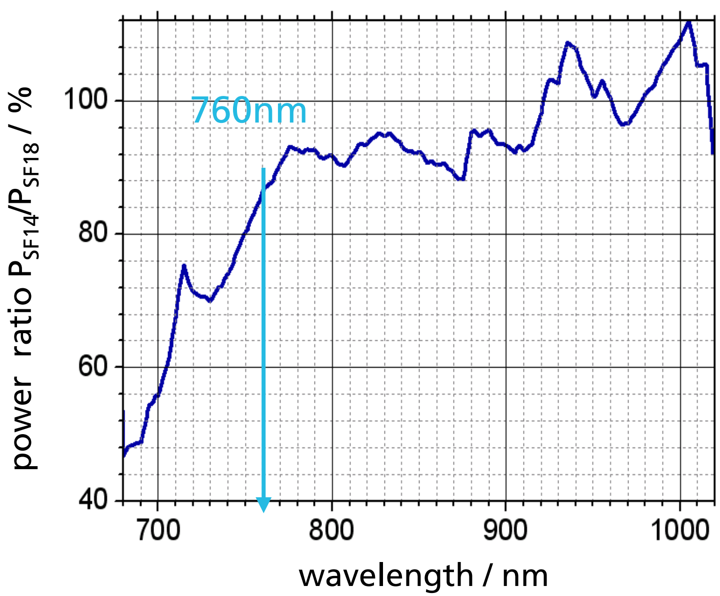
here: susceptibility to 2-Photon absorption

Tunable Spectral Filters

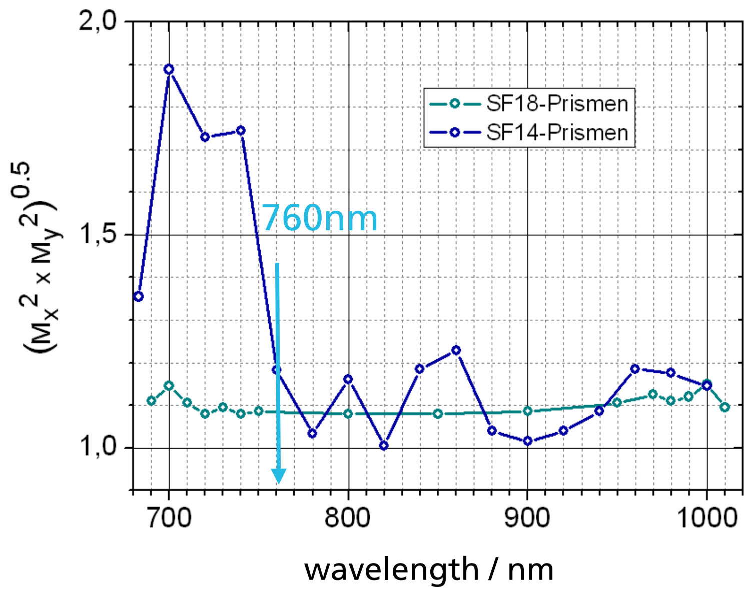
Prisms



Choice of glass



power degradation (SF14 vs. SF18)
due to 2-photon-absorption



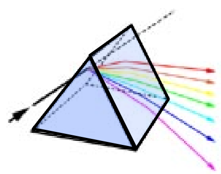
beam degradation (SF14 vs. SF18)
due to 2-photon-absorption

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Fraunhofer ILT

Tunable Spectral Filters

Prisms

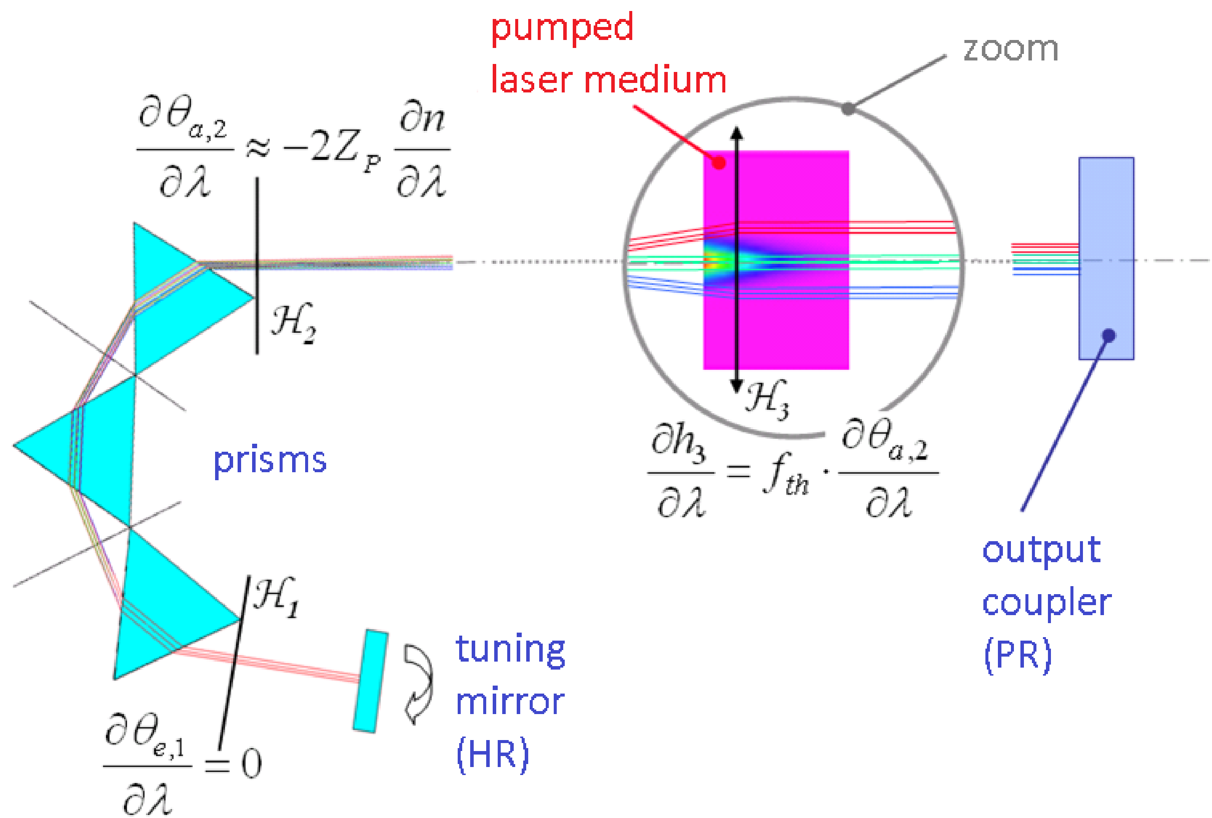


Passband width depends on:

- Dispersion of the glass
- Number Z_p of prisms
- Optical Setup (here thermal lens)

→ Optimization measures:

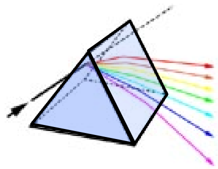
- Choice of glass (e.g.. SF14, SF18…)
- Optical setup



Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Tunable Spectral Filters

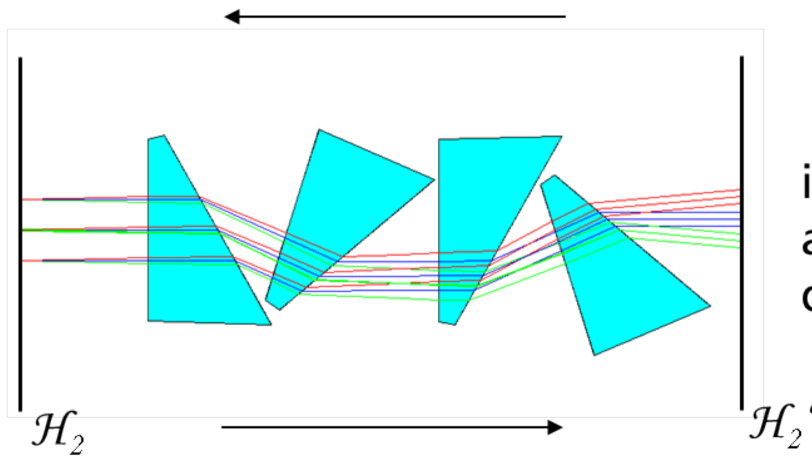
Prisms



Optical Design

transversal magnification M_T

decreased intensity



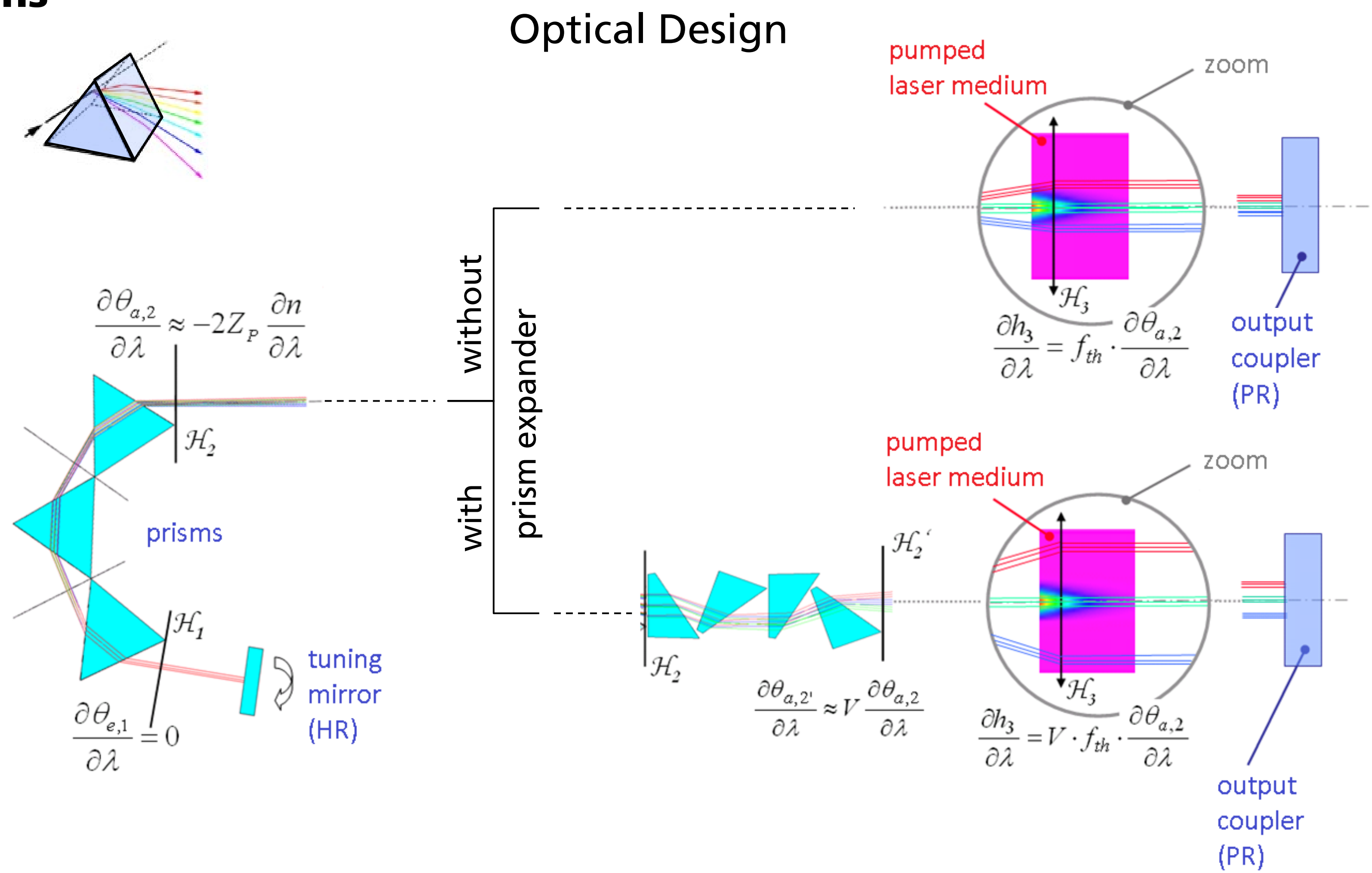
increased angular dispersion

angular magnification $M_A = M_T$

use of telescopes inside the cavity, here prism expander

Tunable Spectral Filters

Prisms

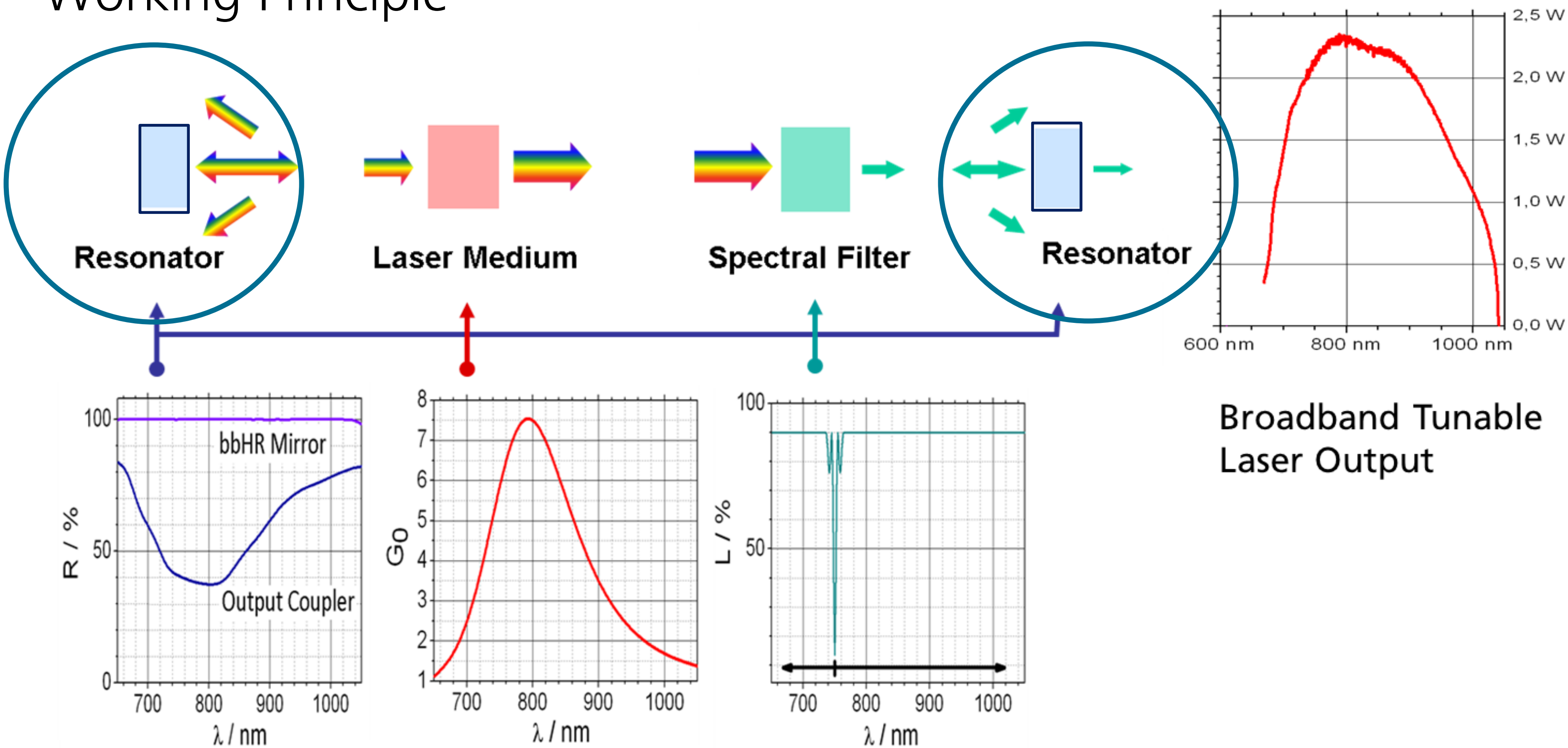


Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Fraunhofer ILT

Tunable Lasers

Working Principle



Broadband Tunable Laser Output

Broadband Optical Resonator

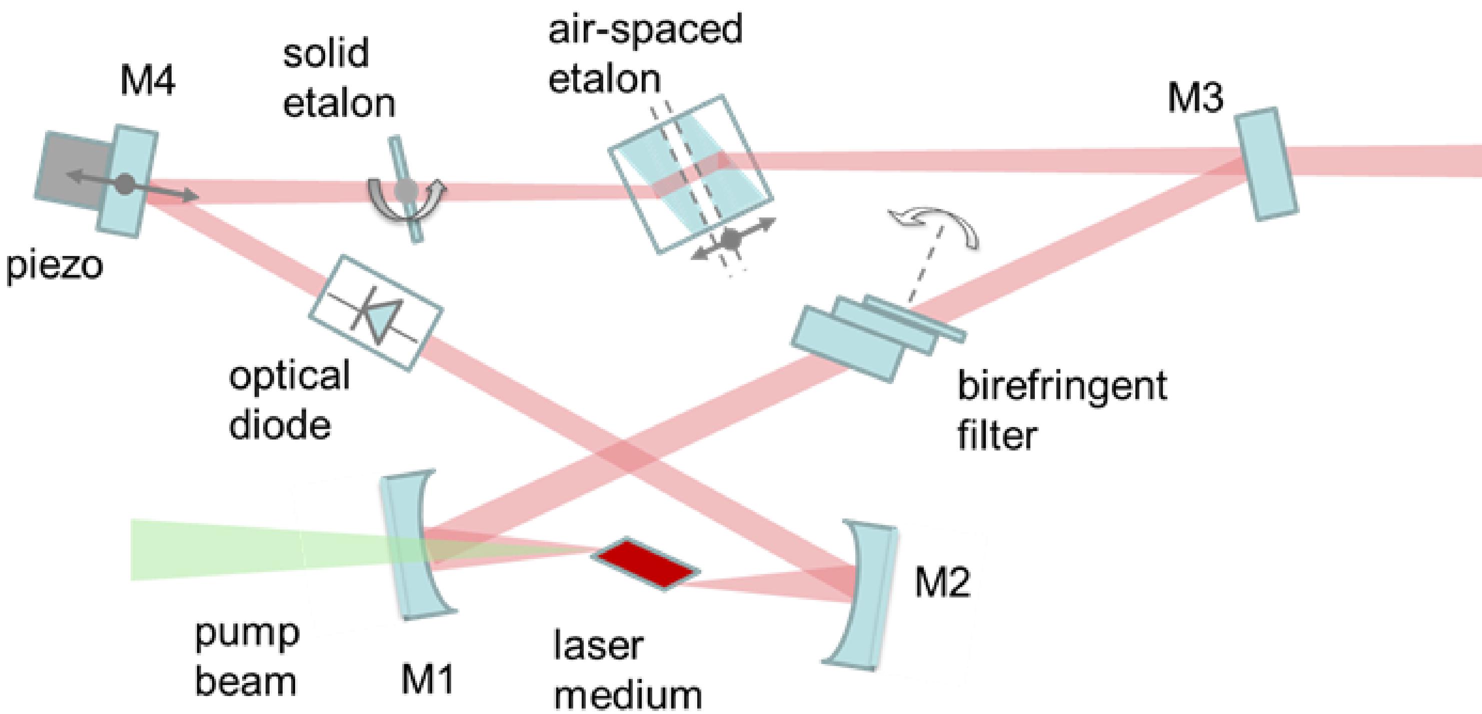
Broadband Gain Laser Medium

Broadband Tunable Spectral Filter

Pictures from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Resonator Architecture

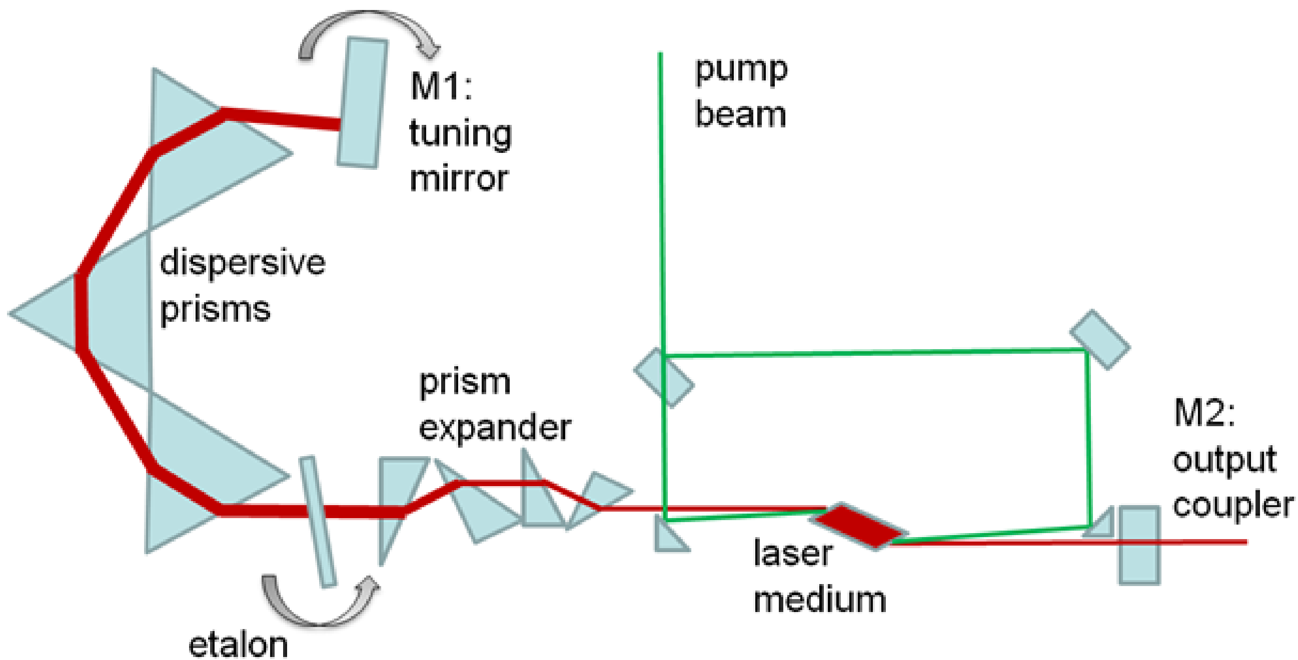
Single Frequency Laser (CW)



Fraunhofer ILT

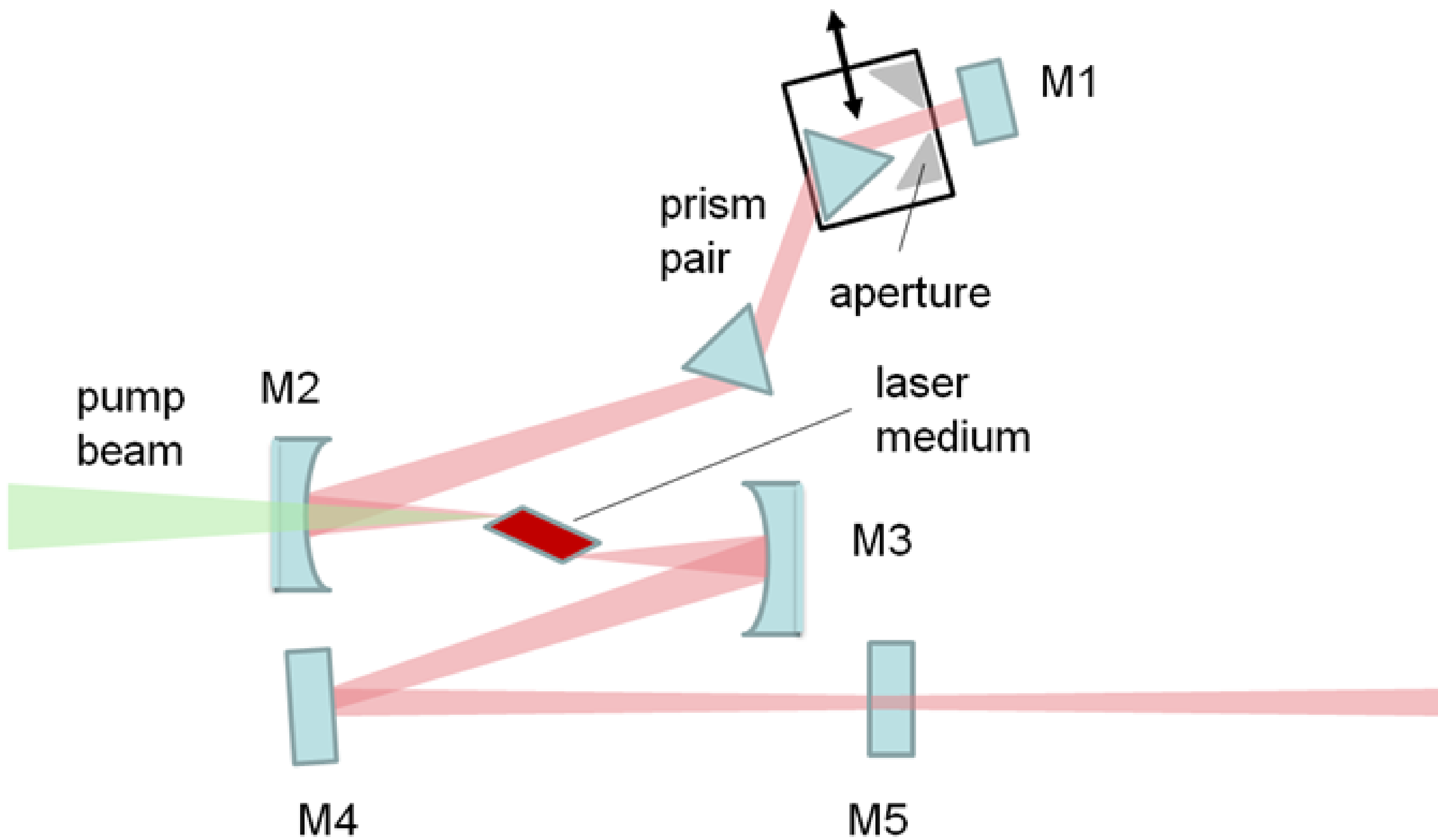
Resonator Architecture

Gain-Switched Laser (ns pulses)



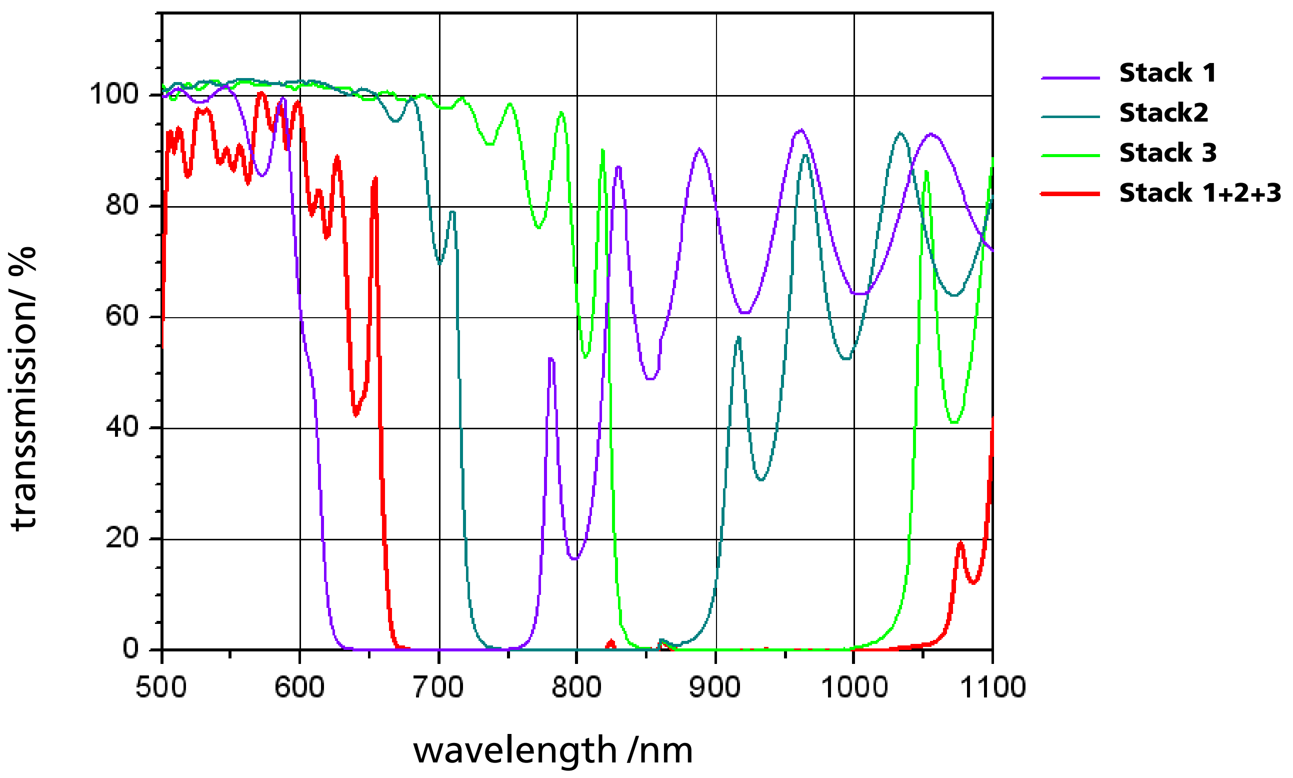
Resonator Architecture

Modelocked Laser (ps and fs pulses)



Broadband Dielectric Coatings

Analysis of performance limits



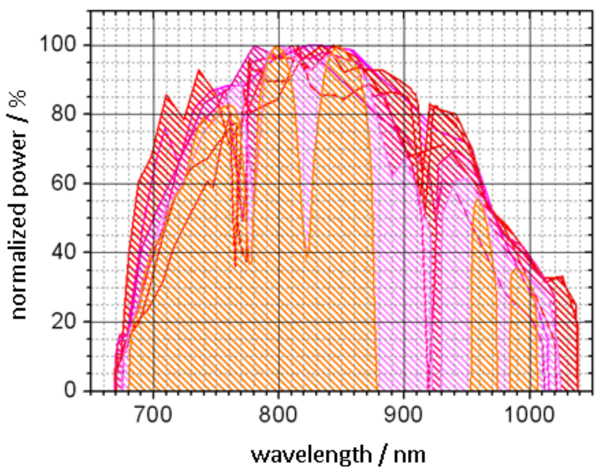
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich

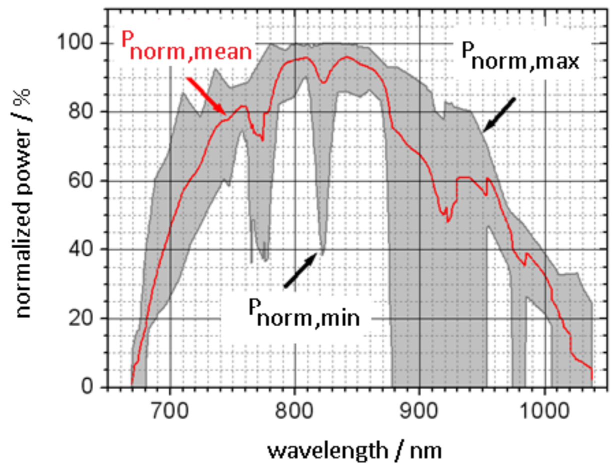
Fraunhofer
ILT

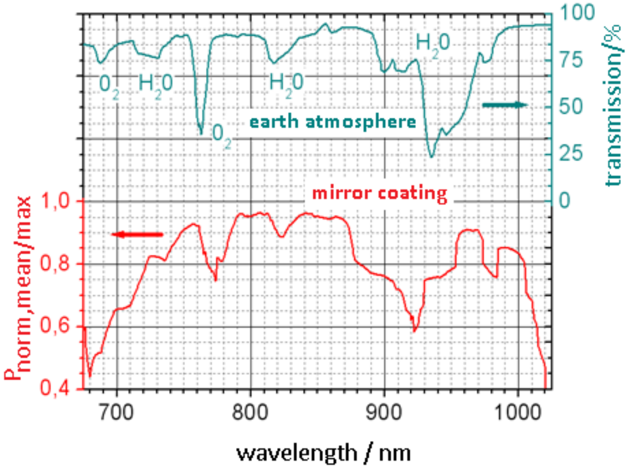
Broadband Dielectric Coatings

Air Enclosures in Dielectrical Coating Stacks

measured output power → statistics → analysis







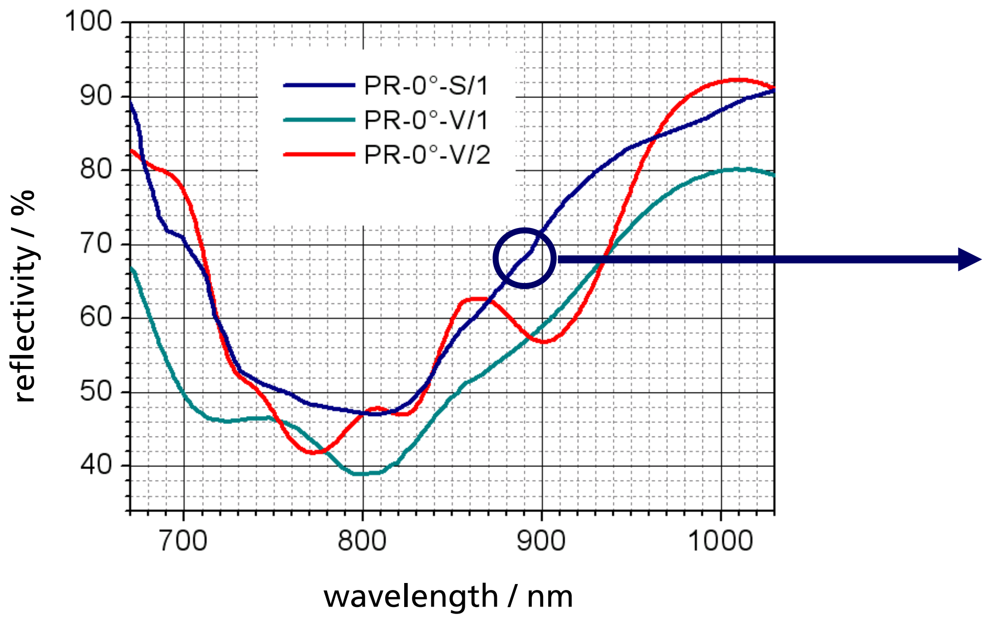
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

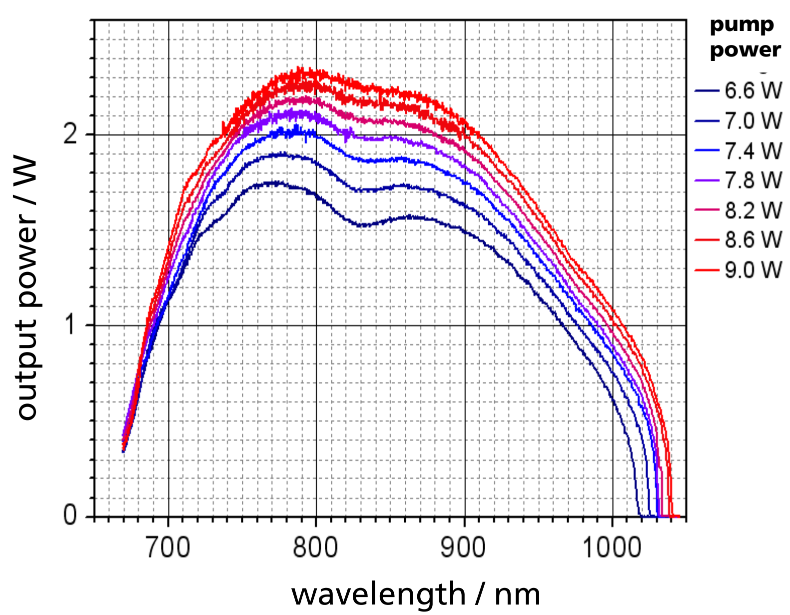
Fraunhofer ILT

Broadband Dielectric Coatings

Output coupler with customized reflectivity profile

output couplers (different lots) → laser performance (PR-0°-S/1)



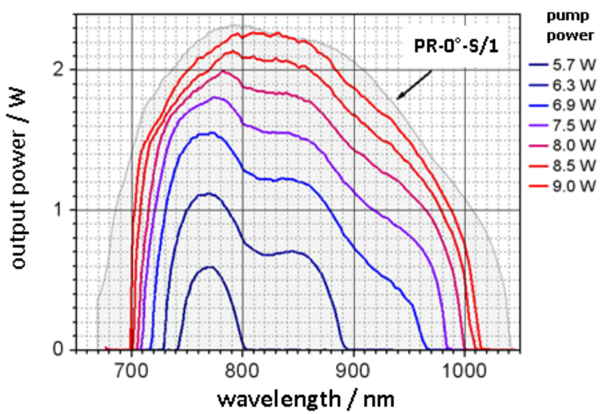


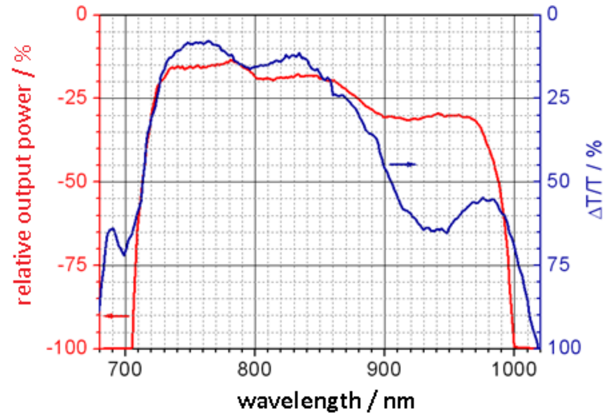
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

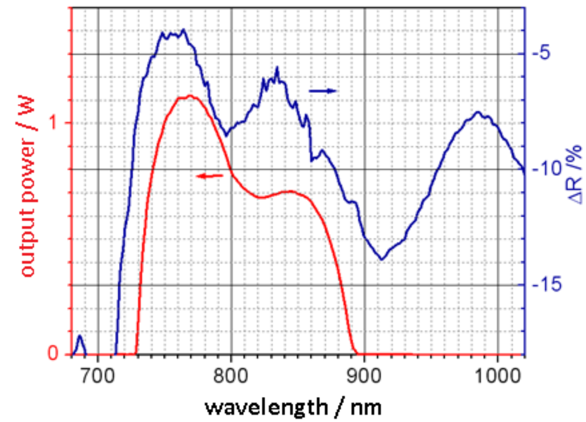
Broadband Dielectric Coatings

Output coupler with customized reflectivity profile

Charge: PR-0°-V/1:

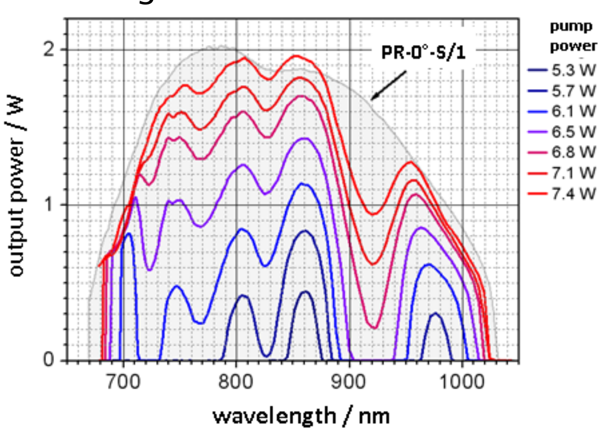


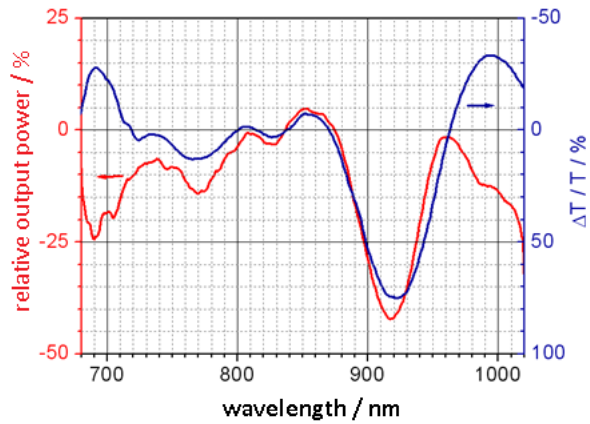


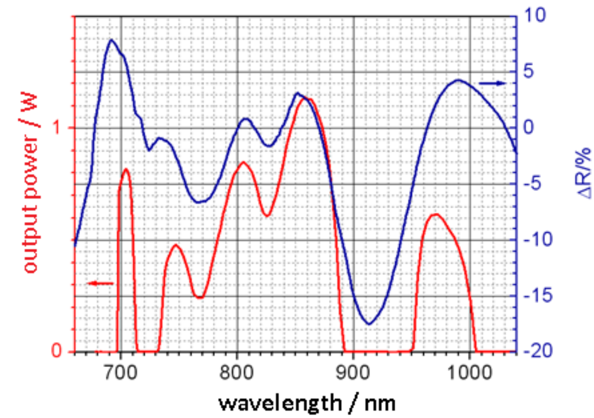


„highest power level“ „near threshold“

Charge: PR-0°-V/2:







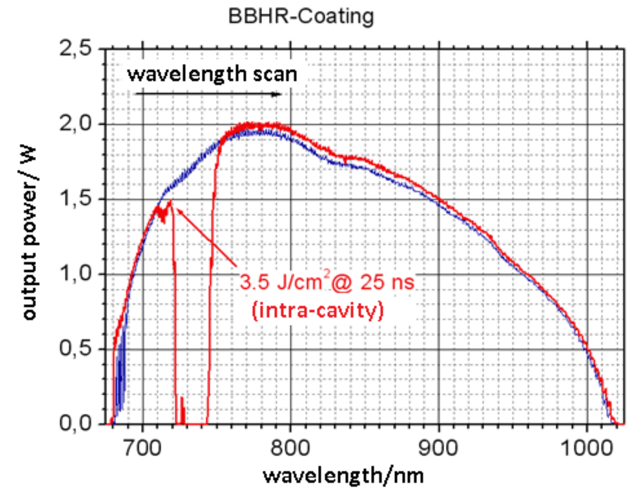
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

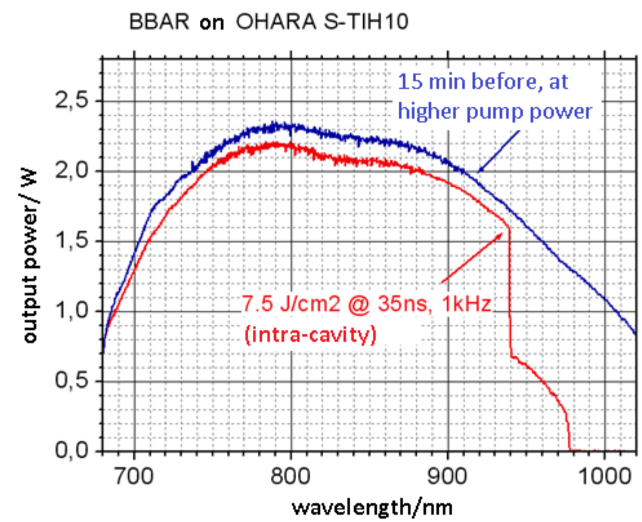
Fraunhofer ILT

Broadband Dielectric Coatings

LIDT in Laser Operation

	coating	substrate/type	fluence /(J·cm^{-2})	number of tests
			LIDT	
damage	MgF_2	SF18	2	3
damage	PR	etalon	7,5/F**	10
damage	BBHR	FS	2,5	6
damage	BBAR	SF11	5	5
damage	BBAR	OHARA S-TIH10	5	5
			acceptable load >	
no damage	PR	output coupler	10	>20
no damage	BBAR	FS	7	>10
no damage	BBAR	BK7	6	3
no damage	BBAR	LaFN21	0,75	3
no damage	BBAR	SK11	0,75	3
no damage	BBAR	NSF10	0,75	3



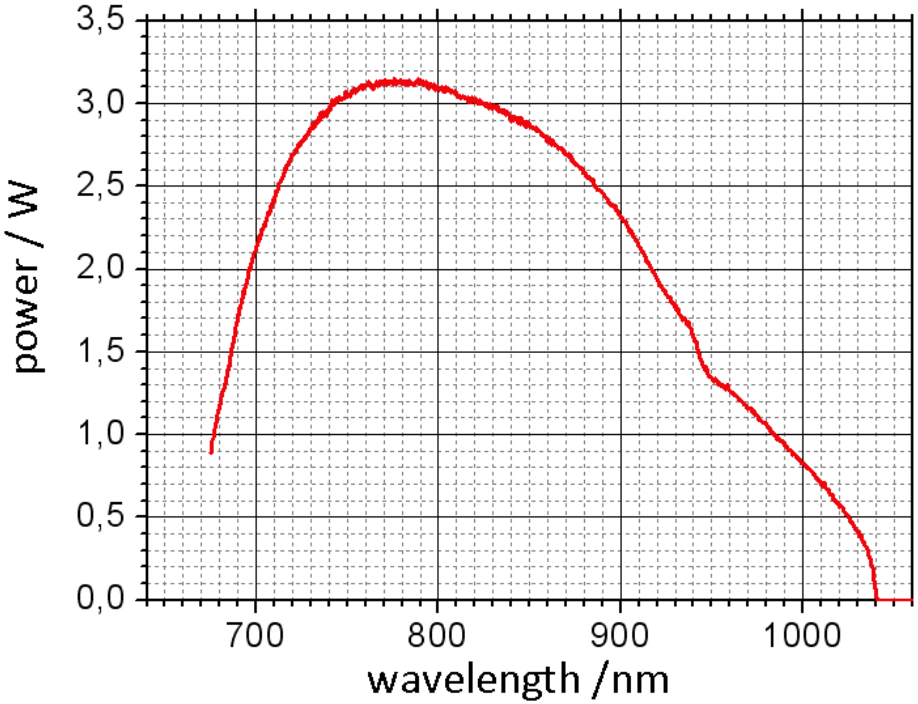


from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Design Examples I

– *Tunable Lasers*

Gain Switched Ti:Sapphire Laser



Output power curve at 10W pump power provided by an INNOSLAB MOPA (Edgewave)

Laser Prototype

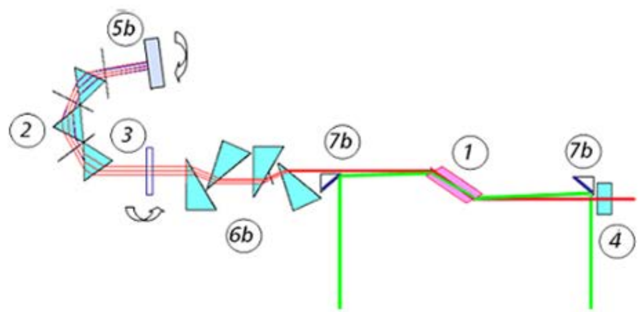
Tuning Range	680-1020 nm
Laser Linewidth	10 GHz (0,33 cm^{-1})
Pulse Energy	3 mJ
Pulse Duration	10 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	1 kHz

from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

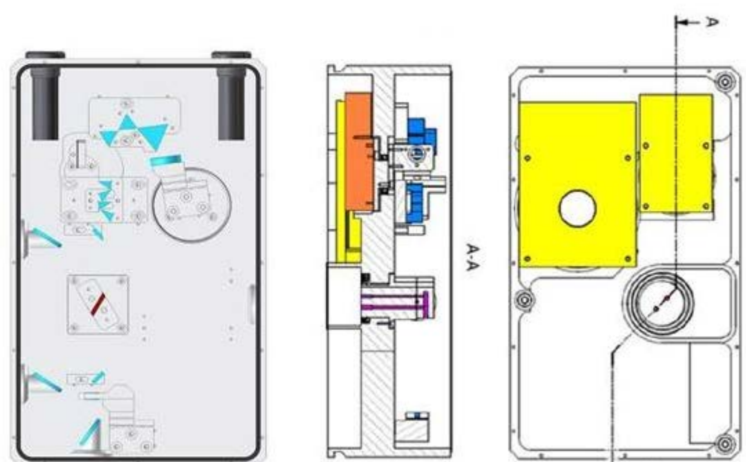
Fraunhofer ILT

Gain Switched Ti:Sapphire Laser

optical design



mechanical design



optics section

supply section

Laser Prototype

- Tuning Range 680-1020 nm
- Laser Linewidth 10 GHz (0,33 cm^{-1})
- Pulse Energy 3 mJ
- Pulse Duration 10 ns
- Beam Quality $M^2 < 1,5$
- Pulse Frequency 1 kHz

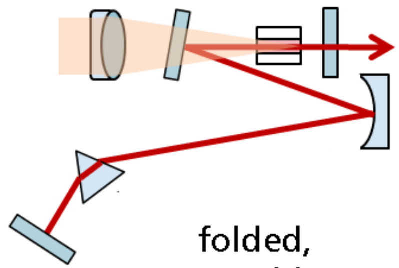
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Fraunhofer ILT

Diode Pumped, Tunable Alexandrite Laser

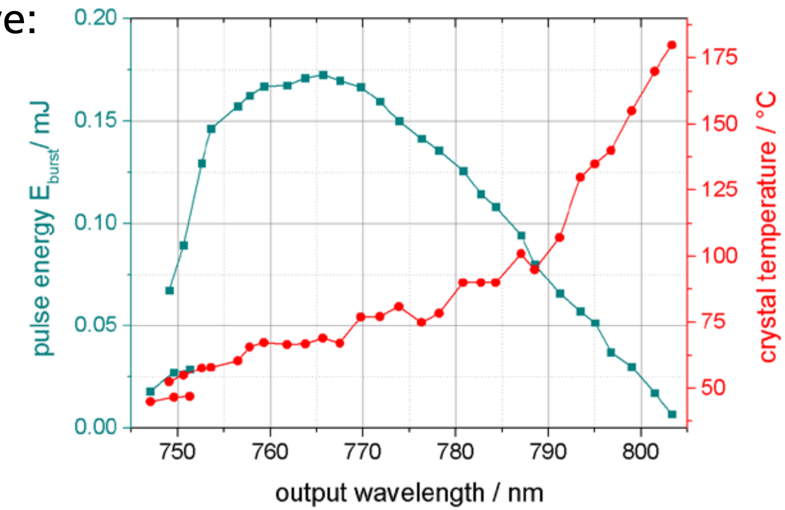
Feasibilty demonstration

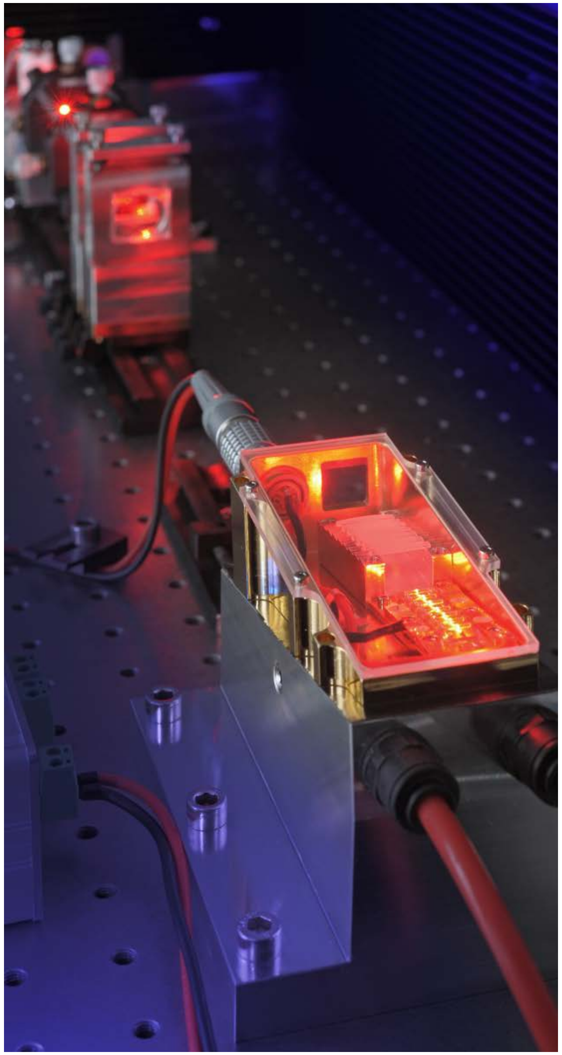
- Tunability: 745 – 805 nm
- Lab Setup:



folded,
tunable cavity

- Tuning Curve:





Fraunhofer ILT

Diode Pumped, Tunable Alexandrite Laser

Feasibilty demonstration

- Tunability: 745 – 805 nm
- QCW @ 35 Hz
- Burst energy: 620µJ @ 772 nm
- Efficiency (opt.-opt.): 20% (30% slope)
- Beam quality: $M^2 \cong 1{,}1$

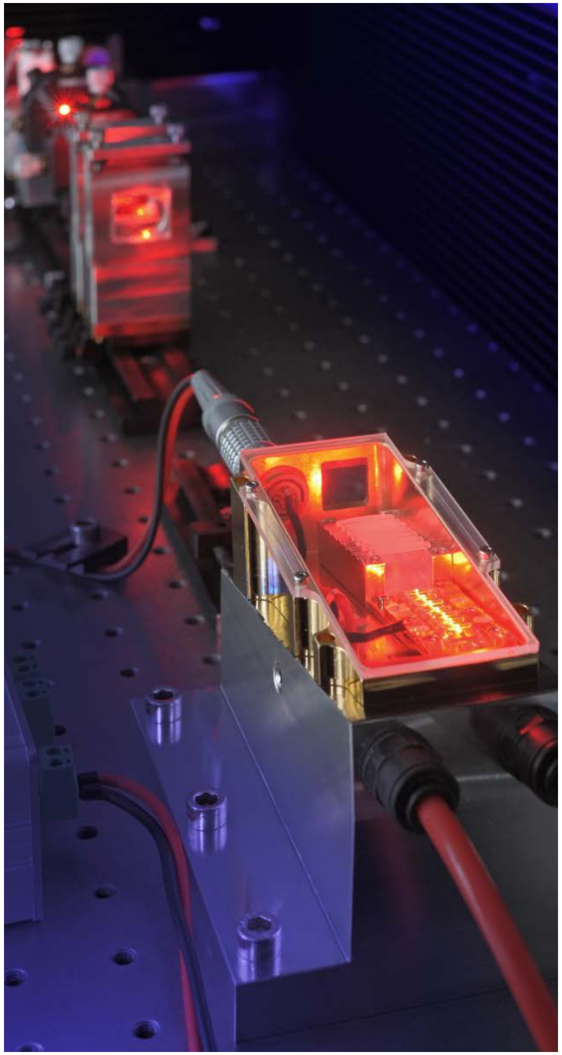
Based on a newly developed diode module

- Optical peak pulse output power > 16 W
- Spectral line width: 2.2 nm
- Beam quality: $M^2 = 25 / 41$ in the fast / slow axis
- Electro-optical efficiency > 30 %

→ Replacement of flashlamps as pump source

Target Application:

- frequency doubled, Q-switched, SF-Laser with UV output for atmospheric LIDAR measurements

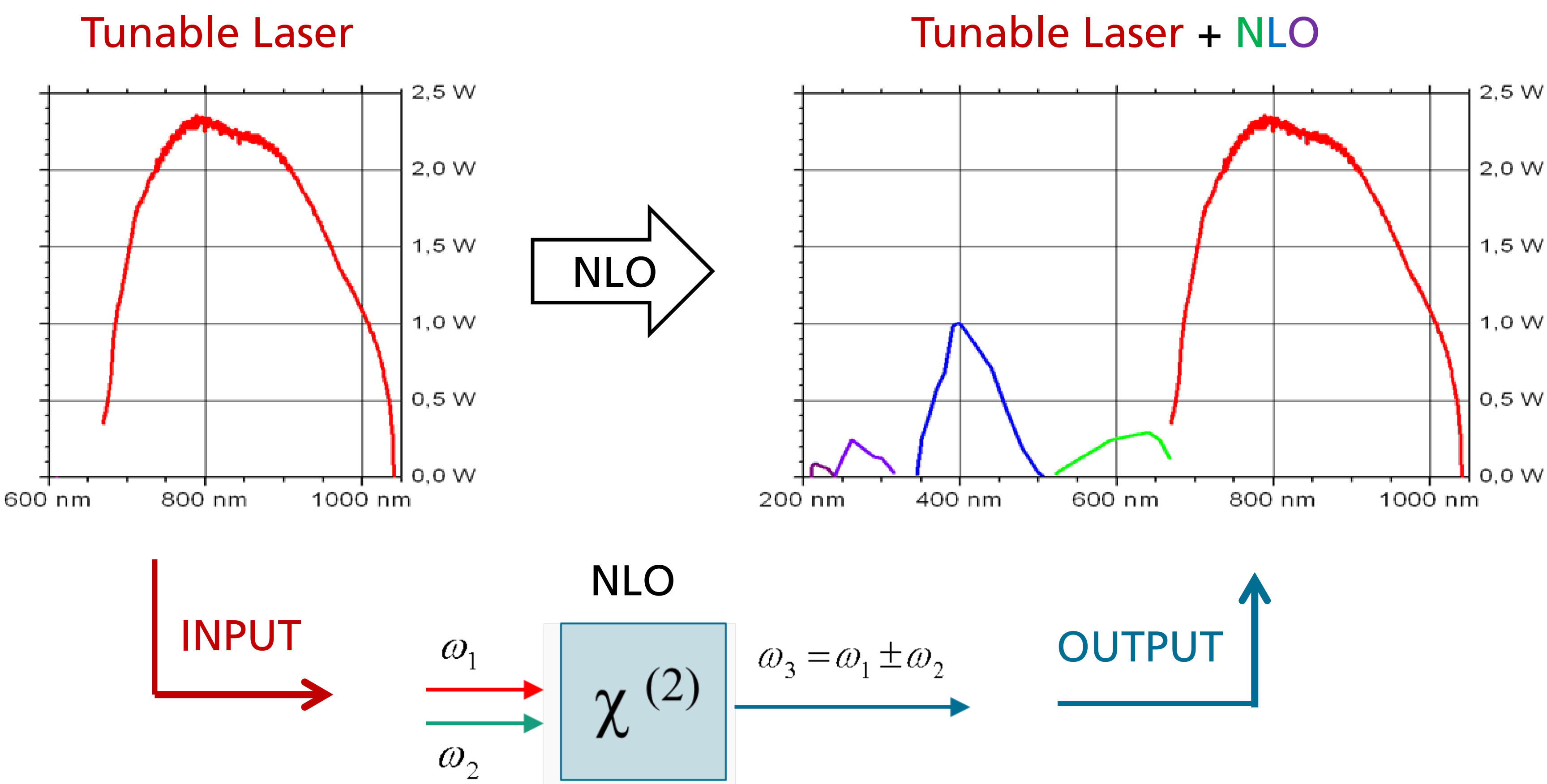


Nonlinear Frequency Mixing

– Extending the Tuning Range

Nonlinear Optical Three-Wave-Mixing

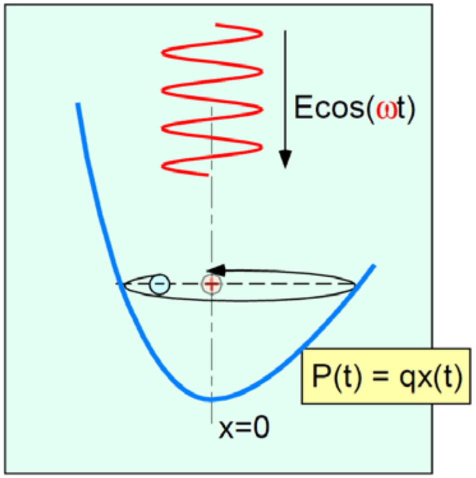
→ Extending the Tuning Range



Fraunhofer ILT

Nonlinear Three-Wave-Mixing

→ Nonlinear Coupling



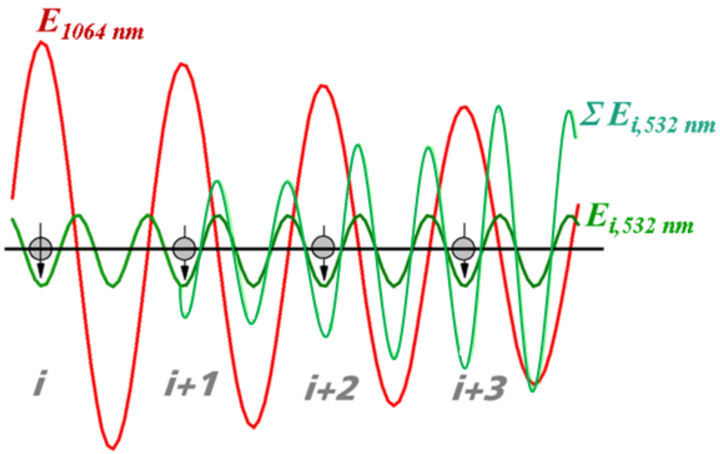
Anharmonic Field (from: Meschede, „Optik, Licht, Laser“)

Wave-Equation in Nonlinear Dielectrica

$$\nabla^2 \vec{E}(t) - \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}(t) = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}\left(\vec{P}_L(t) + \vec{P}_{NL}(t)\right)$$

with $P_{NL}(t) = \chi^{(2)}\left(E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c.\right)^2$ (for 3-wave-mixing)

$$\Rightarrow \begin{cases} \dfrac{\partial E_3}{\partial z} \propto d_{eff} E_1 E_2 e^{i\Delta kz} \\ \dfrac{\partial E_2}{\partial z} \propto d_{eff} E_3 E_1^* e^{-i\Delta kz} \\ \dfrac{\partial E_1}{\partial z} \propto d_{eff} E_2^* E_3 e^{-i\Delta kz} \end{cases}$$



with d_{eff} (effective nonlinearity) , and $\Delta k = k_3 - k_2 - k_1$ (phase mismatch)

Fraunhofer ILT

Nonlinear Three-Wave-Mixing

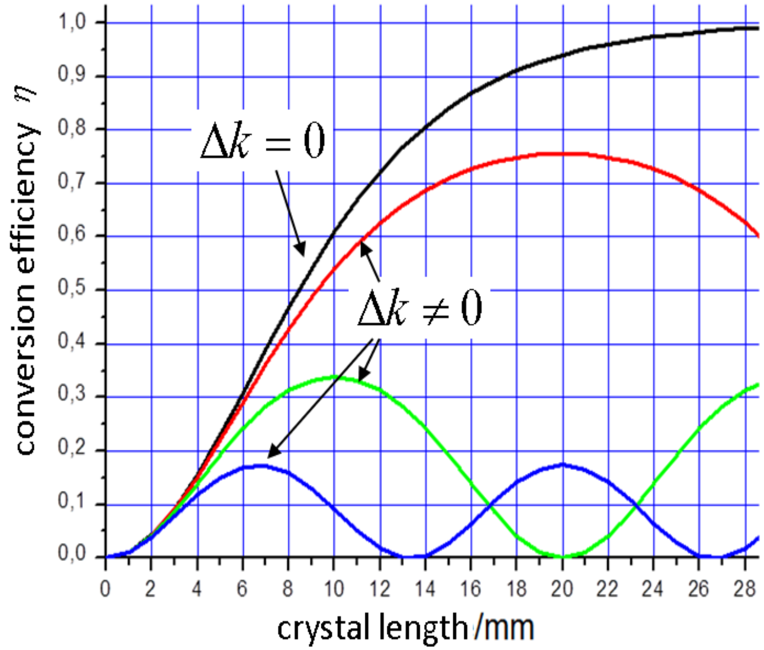
→ Nonlinear Coupling

Wave-Equation in Nonlinear Dielectrica

$$\nabla^2 \vec{E}(t) - \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}(t) = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}\left(\vec{P}_L(t) + \vec{P}_{NL}(t)\right)$$

with $P_{NL}(t) = \chi^{(2)}\left(E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + c.c.\right)^2$

$$\Rightarrow \begin{cases} \dfrac{\partial E_3}{\partial z} \propto d_{eff} E_1 E_2 e^{i\Delta kz} \\ \dfrac{\partial E_2}{\partial z} \propto d_{eff} E_3 E_1^* e^{-i\Delta kz} \\ \dfrac{\partial E_1}{\partial z} \propto d_{eff} E_2^* E_3 e^{-i\Delta kz} \end{cases}$$



⇒ Efficient operation requires phase matching: $\Delta k = 0$

with d_{eff} (effective nonlinearity), and $\Delta k = k_3 - k_2 - k_1$ (phase mismatch)

Fraunhofer ILT

Nonlinear Three-Wave-Mixing

→ Phase Matching

$$\Delta k = 0 \quad \Leftrightarrow \omega_3 n(\omega_3) - \omega_2 n(\omega_2) - \omega_1 n(\omega_1) = 0$$

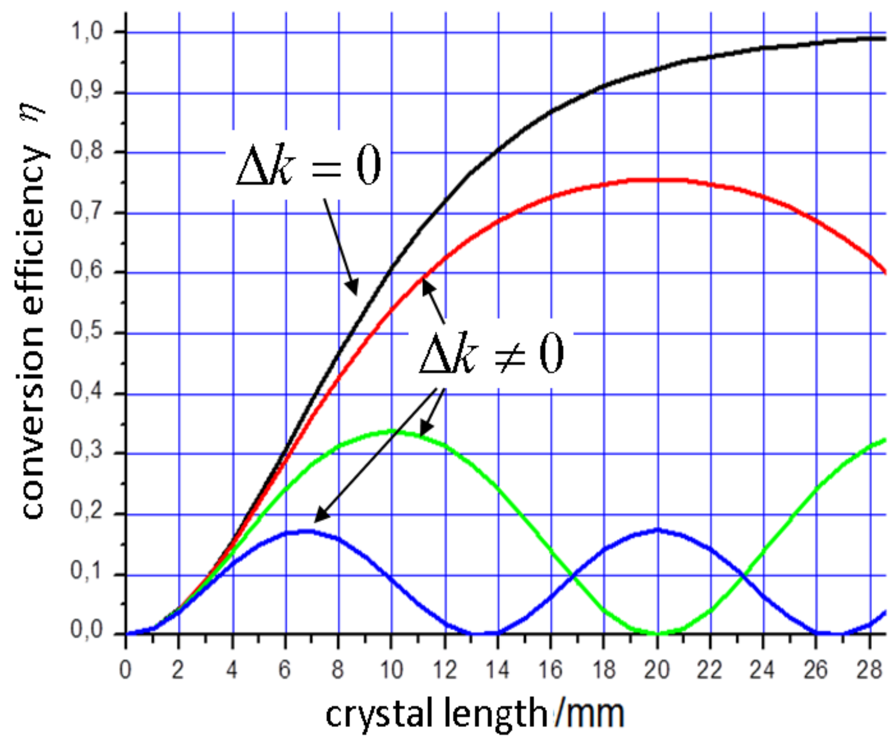
→ Requirement to obtain high conversion efficiency !!!

→ Boundary condition of the refractive index n_1, n_2, n_3 of the three waves

Example: SHG

$$\omega_1 = \omega_2 = \omega$$
$$\omega_3 = 2\omega$$

→ $n(\omega) = n(2\omega)$



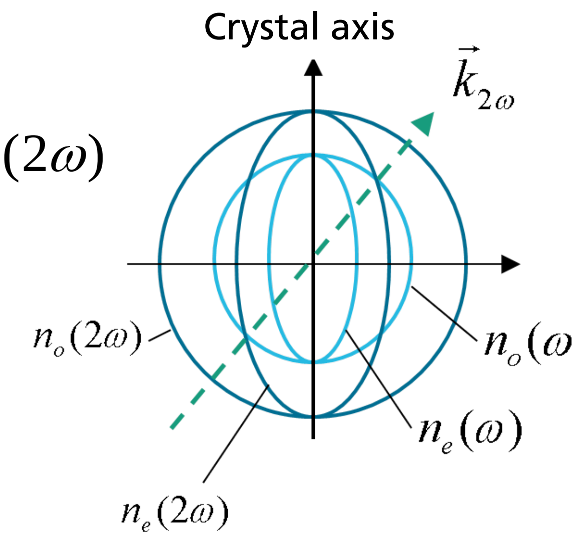
→ Due to dispersion phase matching usually can not be obtained in isotropic media

→ Use of **birefringent crystals** or **periodically poled crystals**

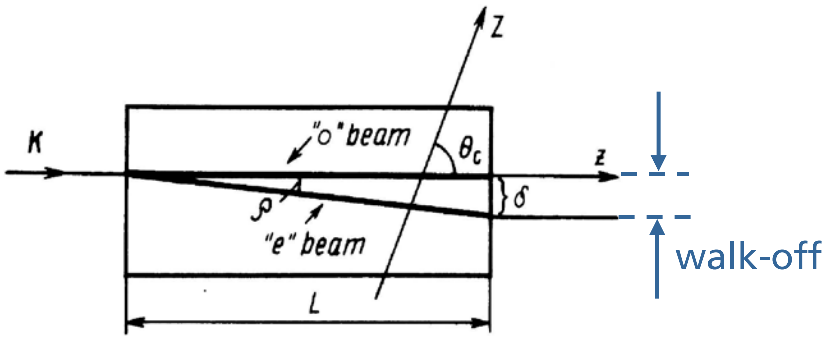
Nonlinear Three-Wave-Mixing

→ Phase Matching

$$n_o(\omega) = n_e(2\omega)$$



with birefringent NLO crystals



[from: V. G. Dmitriev: Handbook of Nonlinear Optical Crystals]

Classification of
birefringent crystals
$n_o > n_e$: negativ
$n_o < n_e$: positiv

→ In many cases phase matching can be achieved by a proper choice of polarization, crystal orientaion and crystal temperature

e-beam: extra-ordinary
o-beam: ordinar) polarisiert

Type	E_1	E_2	E_3	crystal
I	e	e	o	negative
I	o	o	e	positive
II	o	e	e	negative
II	o	e	o	positive

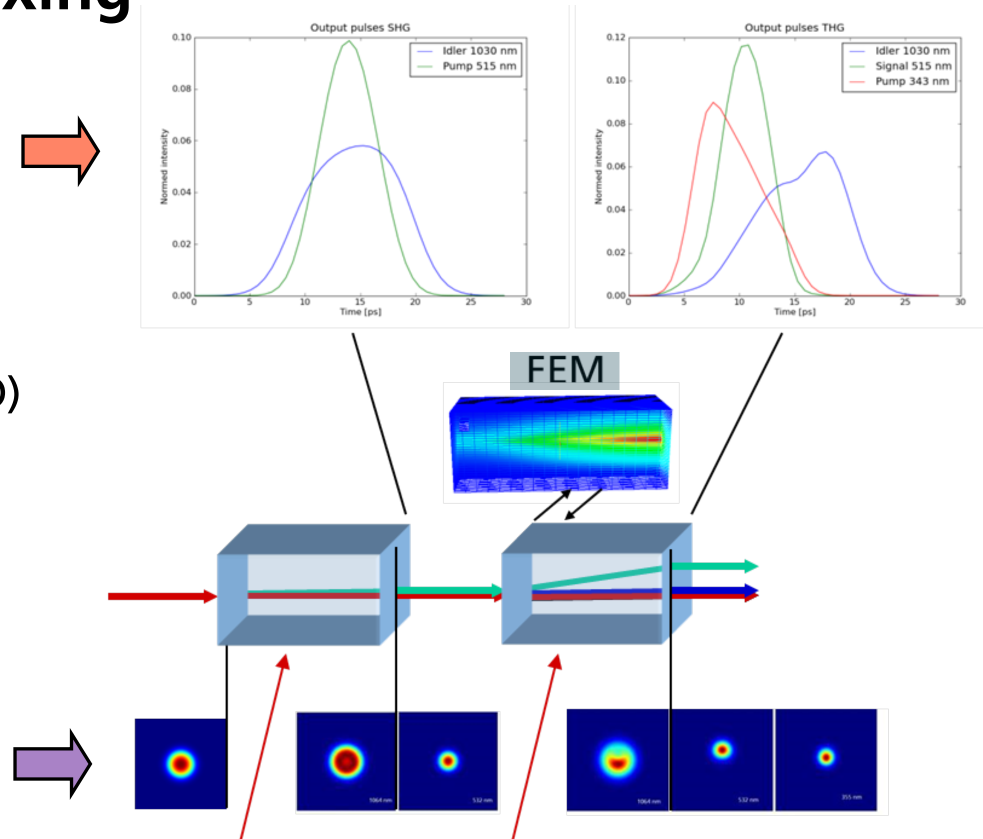
Nonlinear Three-Wave-Mixing

→ Modeling tools

Analytical solutions exist only for
a few special cases

→ Numerical Modeling (e.g. OPT, SNLO)

- Phase and intensity are defined, propagated, amplified and converted (…) on grids
- Consideration of:
  - Diffraction
  - Walk-Off
  - Nonlinear coupling
  - Absorption → dn/dT (FEM)
  - Thermomechanics → dσ/dT
  - Beam profile and quality
  - Temporal pulse shape
  - Group delay effects (GVD)



$$\frac{\partial \varepsilon_j}{\partial z} = \frac{i}{2k_j}\left[\frac{\partial^2 \varepsilon_j}{\partial x^2} + \frac{\partial^2 \varepsilon_j}{\partial y^2}\right] - \tan(\rho_j) + P_{jkl} - \alpha_j \varepsilon_j$$

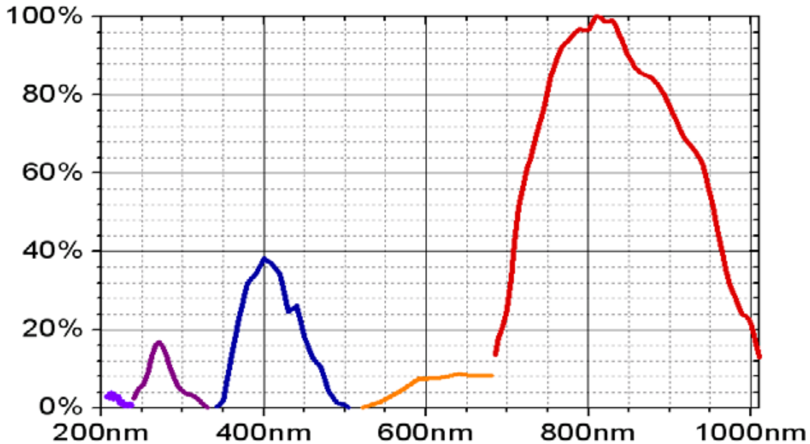
$$j \in \{1, 2, 3\}, \quad k \in \{1, 2, 3\} \setminus j, \quad l \in \{1, 2, 3\} \setminus \{j, k\}$$

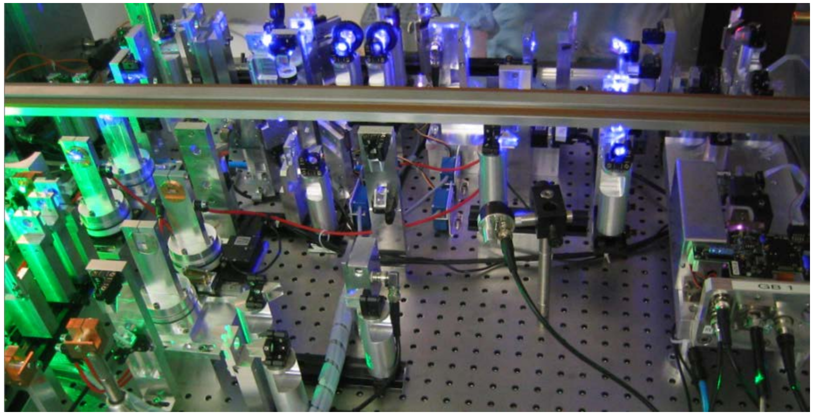
Fraunhofer ILT

Design Examples II

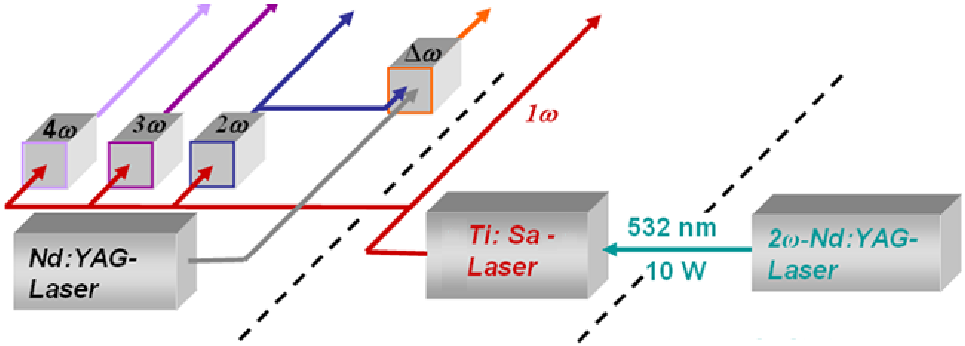
– Frequency Converters and Parametric Devices

Widely Tunable Ti:Sapphire Laser System





Laser Prototype



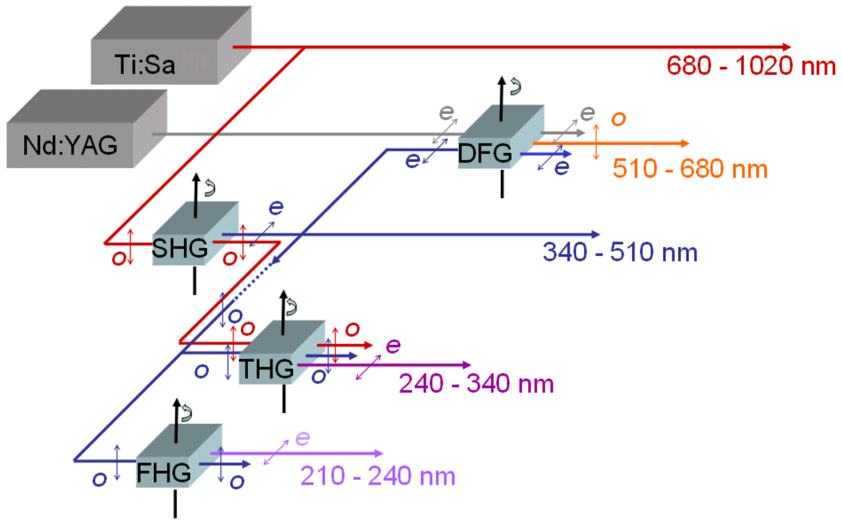
Fundamental Ti:Sapphire Laser:

Tuning Range	680-1020 nm
Laser Linewidth	10 GHz (0,33 cm^{-1})
Pulse Energy	3 mJ
Pulse Duration	10 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	1 kHz

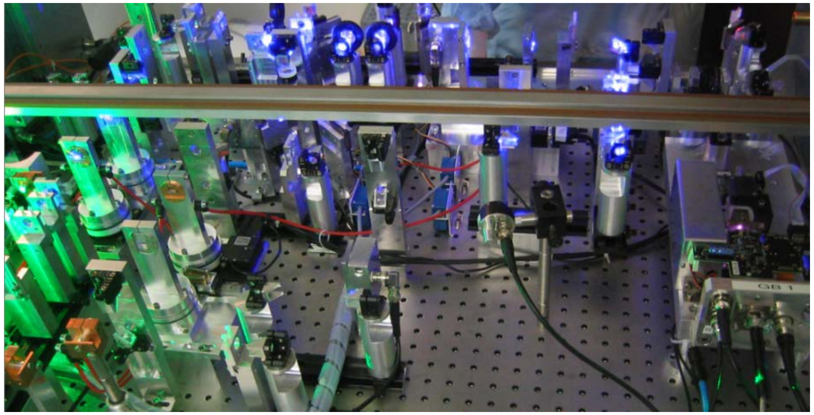
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Widely Tunable Ti:Sapphire Laser System

Basic Conception



Stage	Crystal	Output Wavelength / nm	Phase Matching		d_{eff} / pmV^{-1}
			Type	Angle /°	
DFG	BBO	510 - 680	eoe	32,1 - 27,6	1,72 - 2,01
SHG	BBO	340 – 510	ooe	34,8 - 23,6	0,81 - 1,55
THG	BBO	240 – 340	ooe	51,8 - 32,8	1,95 - 2,01
FHG	BBO	210 – 240	ooe	75,9 - 56,0	2,01 - 2,02



Laser Prototype

Fundamental Ti:Sapphire Laser:

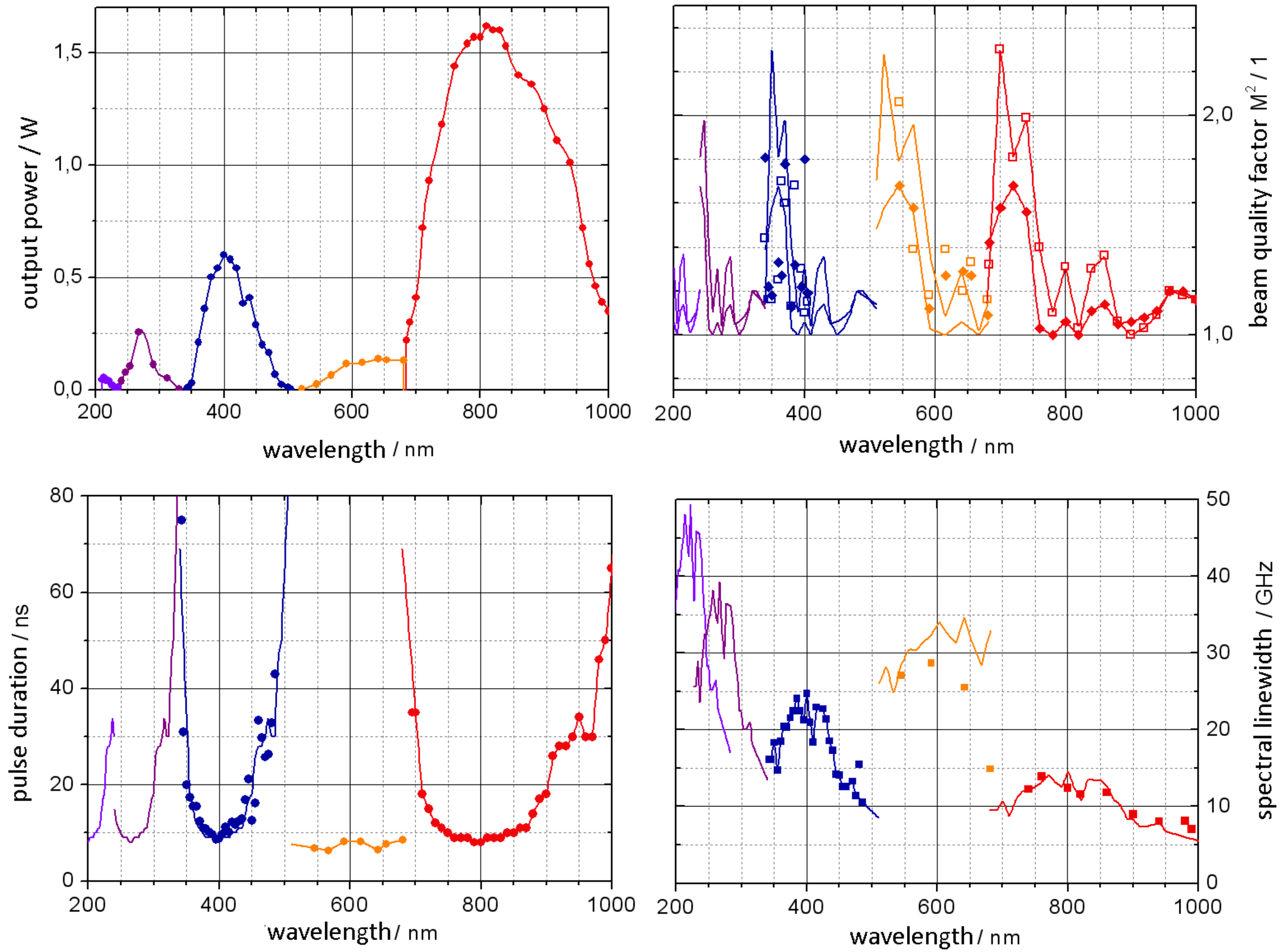
- Tuning Range 680-1020 nm
- Laser Linewidth 10 GHz (0,33 cm^{-1})
- Pulse Energy 3 mJ
- Pulse Duration 10 ns
- Beam Quality $M^2 < 1,5$
- Pulse Frequency 1 kHz

from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich"

Fraunhofer ILT

Widely Tunable Ti:Sapphire Laser System

Performance

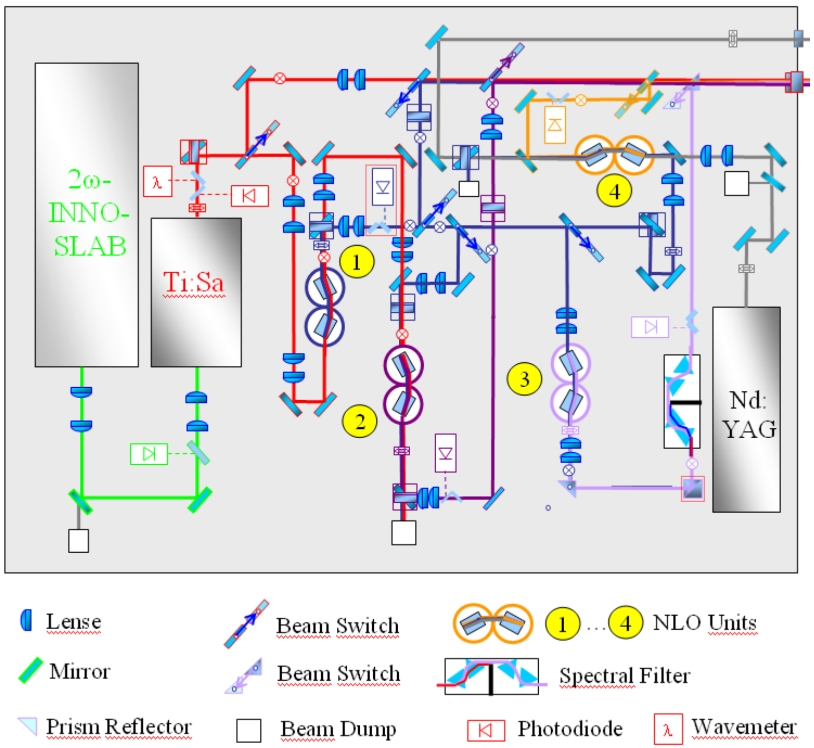


from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

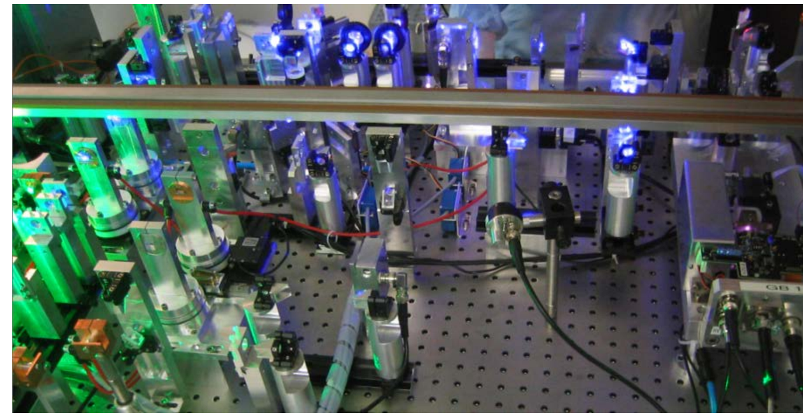
Fraunhofer ILT

Widely Tunable Ti:Sapphire Laser System

Detailed Conception



- High comlexity
- Large footprint



Laser Prototype

Fundamental Ti:Sapphire Laser

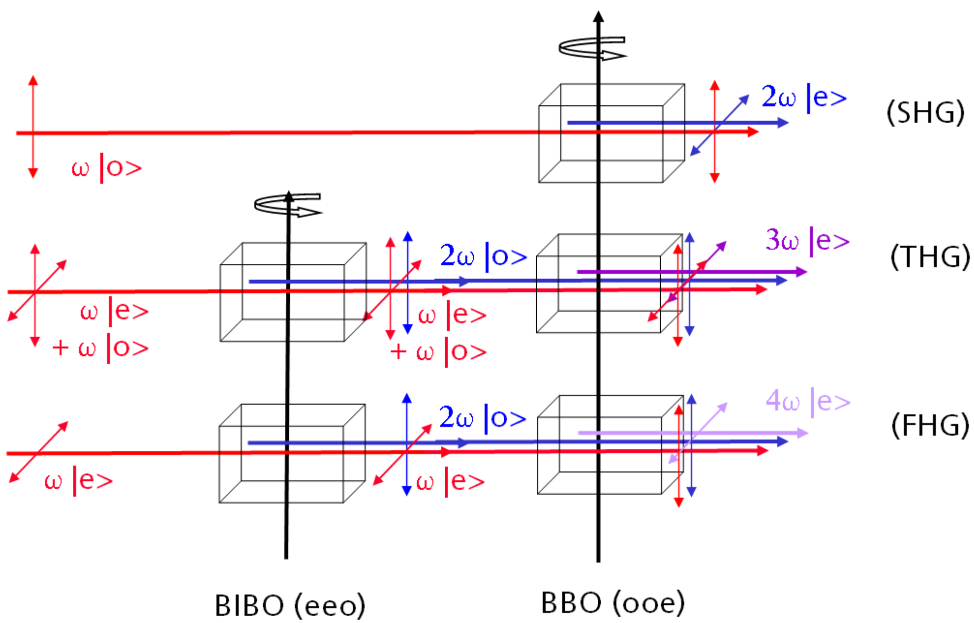
Tuning Range	680-1020 nm
Laser Linewidth	15 GHz (0,5 cm^{-1})
Pulse Energy	1.7 mJ
Pulse Duration	10 ns
Pulse Frequency	1 kHz

from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich

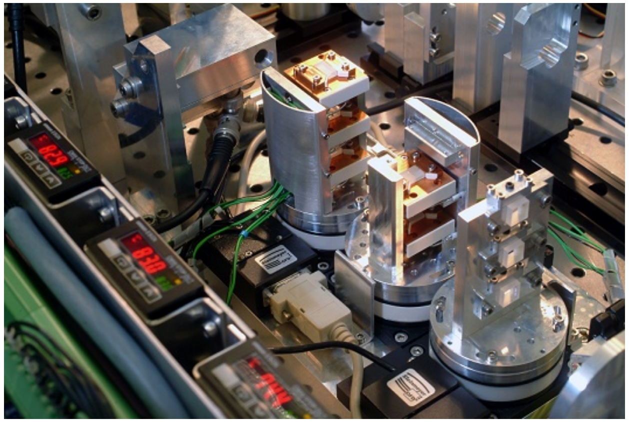
Fraunhofer ILT

Widely Tunable Ti:Sapphire Laser System

Optical Redesign



- Less complex
- Smaller footprint



Laser Prototype

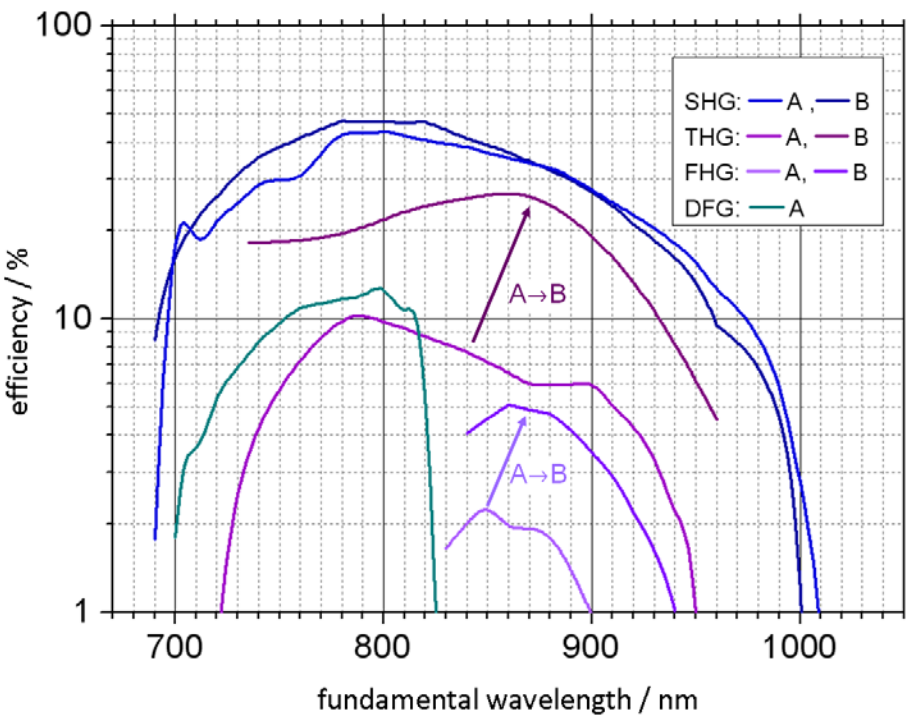
Fundamental Ti:Sapphire Laser:

Tuning Range	680-1020 nm
Laser Linewidth	10 GHz (0,33 cm^{-1})
Pulse Energy	3 mJ
Pulse Duration	10 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	1 kHz

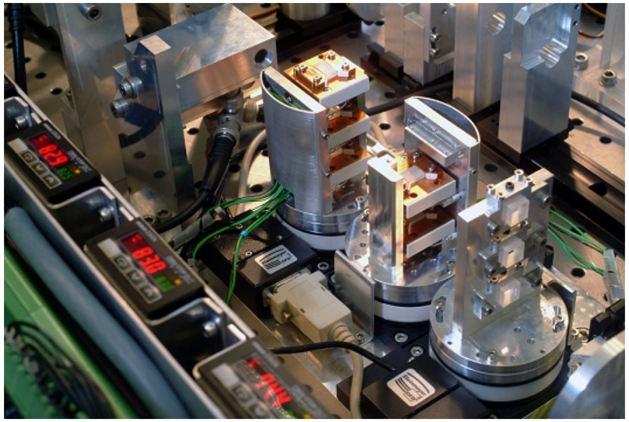
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich

Widely Tunable Ti:Sapphire Laser System

Optical Redesign, Performance



- Less complex
- Smaller footprint
- More efficient



Laser Prototype

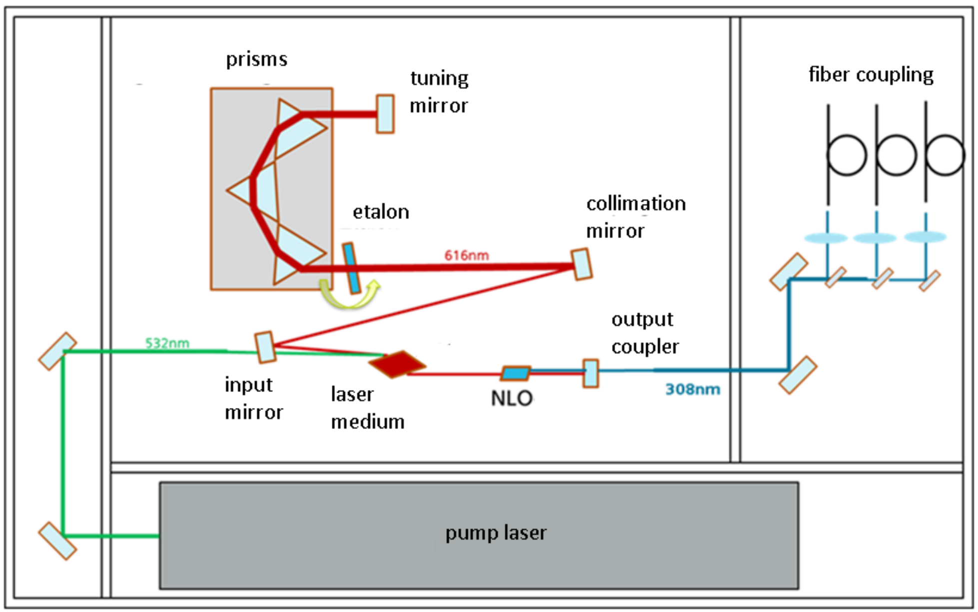
Fundamental Ti:Sapphire Laser:

- Tuning Range 680-1020 nm
- Laser Linewidth 10 GHz (0,33 cm^{-1})
- Pulse Energy 3 mJ
- Pulse Duration 10 ns
- Beam Quality $M^2 < 1,5$
- Pulse Frequency 1 kHz

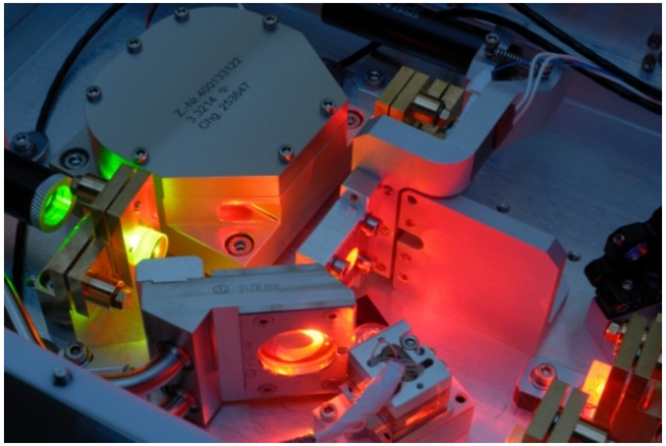
from: Jungbluth, „Gewinngeschaltete Ti:Saphir-Laser mit ultrabreitem Abstimmbereich“

Tunable UV Laser for Airborne LIF Measurements

Intracavity frequency doubled Dye laser



(Laser Conception)



Laser Prototype

- Tuning Range 100 GHz @ 308 nm
- Laser Linewidth 3 GHz
- Output power 200 mW
- Pulse Duration 20 ns
- Beam Quality $M^2 < 1,5$
- Pulse Frequency 8.5 kHz

From Strotkamp et.al., SPIE Lase Conference, 2013

Fraunhofer ILT

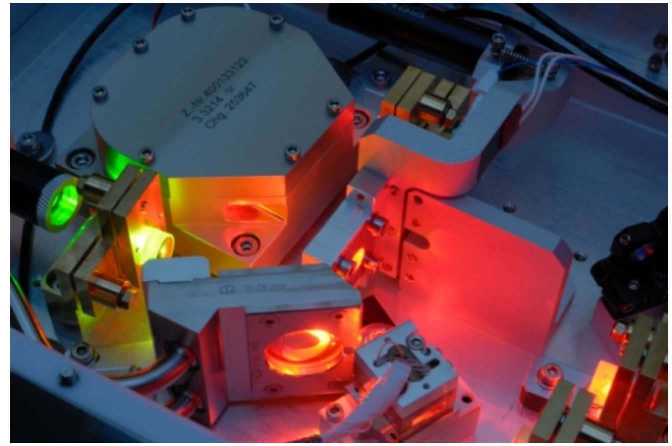
Tunable UV Laser for Airborne LIF Measurements

Intracavity frequency doubled Dye laser

Zeppelin NT for Pan-European PEGASOS campaign (FZJ)

Atmospherically OH-Measurement with LIF

- Airborne operation with airship and HALO
- T = 10 – 40 °C, p = 800 – 1000 mbar



Laser Prototype

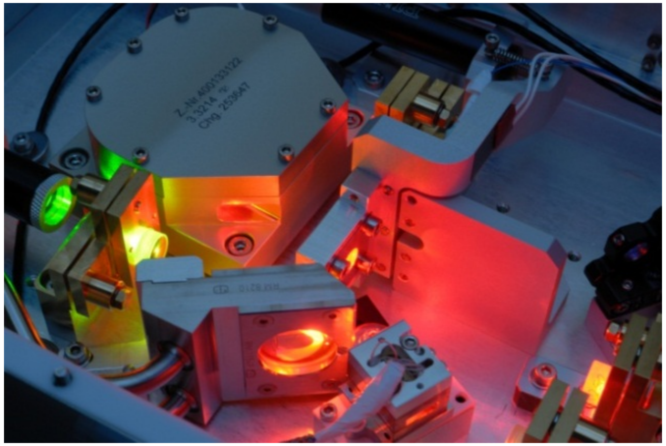
- Tuning Range 100 GHz @ 308 nm
- Laser Linewidth 3 GHz
- Output power 200 mW
- Pulse Duration 20 ns
- Beam Quality $M^2 < 1,5$
- Pulse Frequency 8.5 kHz

From Strotkamp et.al., SPIE Lase Conference, 2013

Tunable UV Laser for Airborne LIF Measurements

Intracavity frequency doubled Dye laser

Pan-European PEGASOS campaign with Zeppelin NT (from FZJ)



Laser Prototype

Tuning Range	100 GHz @ 308 nm
Laser Linewidth	3 GHz
Output power	200 mW
Pulse Duration	20 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	8.5 kHz

From Strotkamp et.al., SPIE Lase Conference, 2013

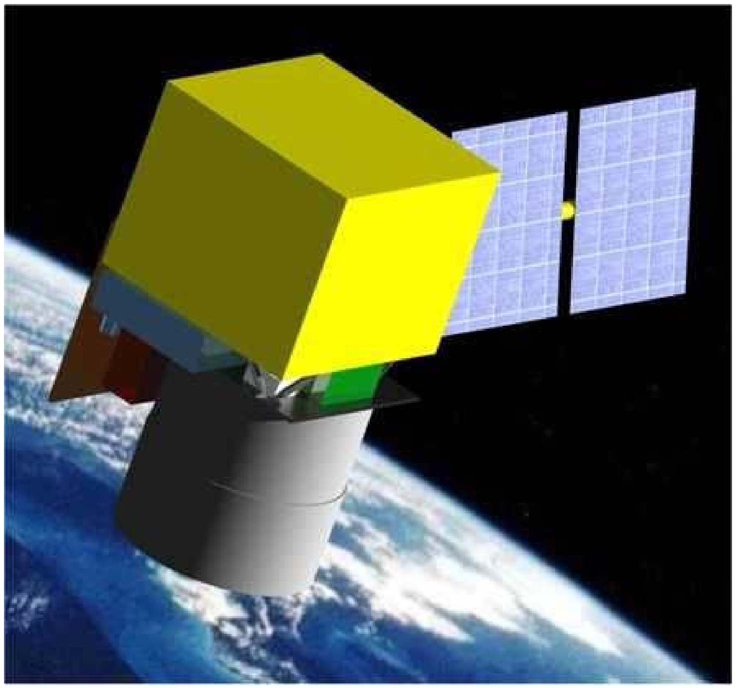
Atmospherically OH-Measurement with LIF

- Airborne operation with airship and HALO
- T = 10 – 40 °C, p = 800 – 1000 mbar
- 2012/2013: Routine operation on Zeppelin NT in different field campaigns

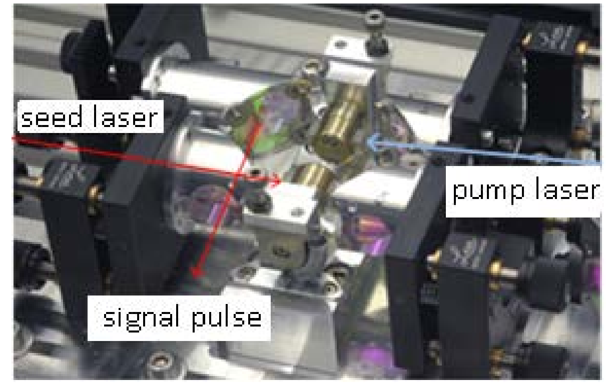
Fraunhofer ILT

OPO for Spaceborne Methane Measurements (MERLIN)

French-German Climate Mission



from www.dlr.de



Laboratory Prototype (ILT)

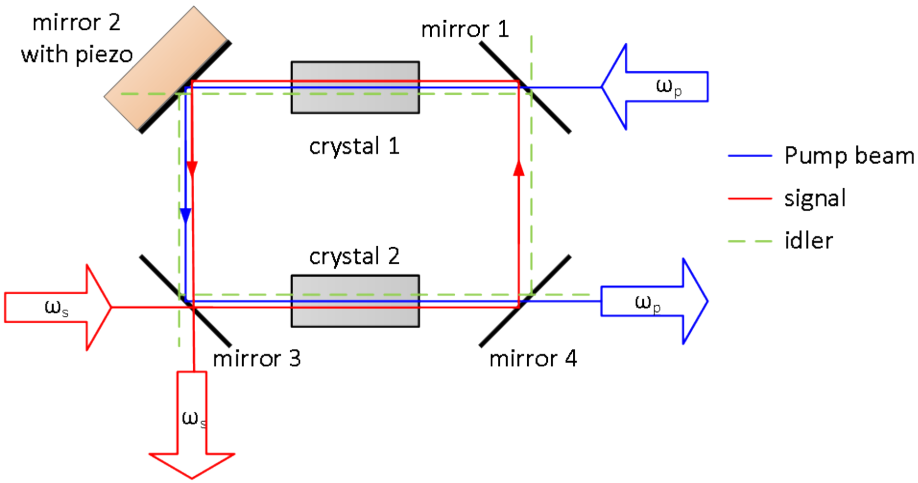
Laser Wavelength	1645nm
Pulse Energy	9 mJ
Efficiency	> 25%
Pulse Duration	20 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	2 x 25 Hz

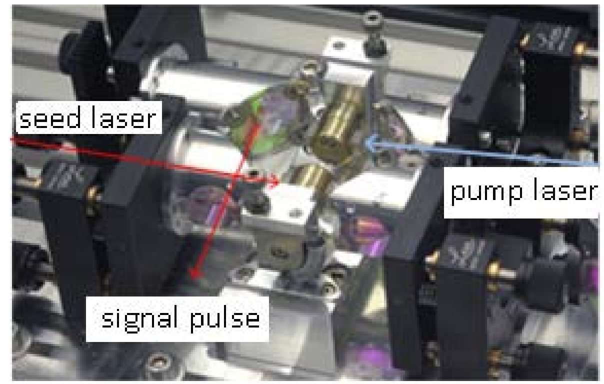
MERLIN: **Me**thane **R**emote Sensing **Li**dar Missio**n**

Fraunhofer ILT

OPO for Spaceborne Methane Measurements (MERLIN)

OPO Conception by DLR IPA





Laboratory Prototype (ILT)

- 1064nm pumped OPO with KTP
- Double Pulse Operation (on- and off-resonance of methane)
- Single frequency seeded
- Cavity Length Control by Heterodyne

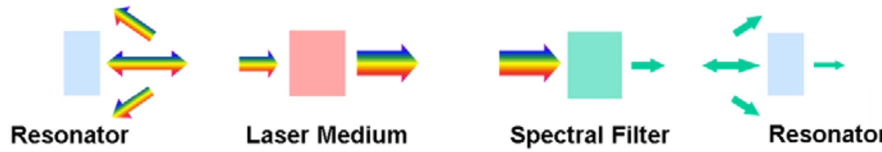
Laser Wavelength	1645nm
Pulse Energy	9 mJ
Efficiency	> 25%
Pulse Duration	20 ns
Beam Quality	$M^2 < 1,5$
Pulse Frequency	2 x 25 Hz

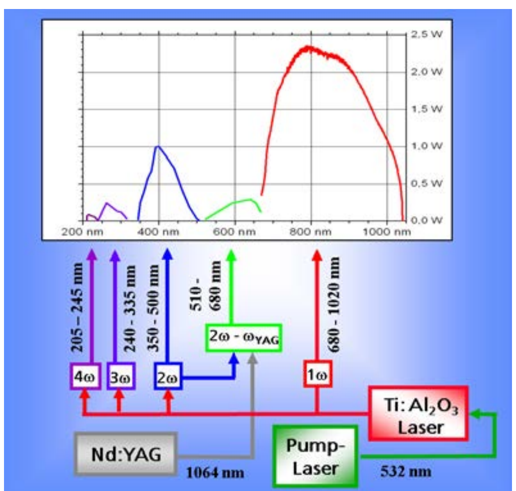
Summary

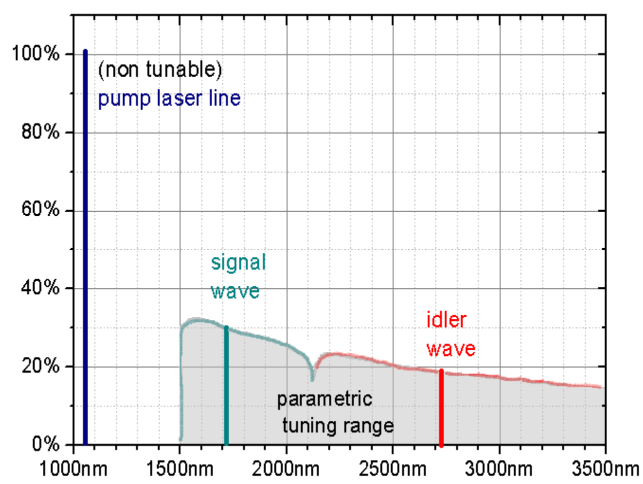
– Lessons Learned

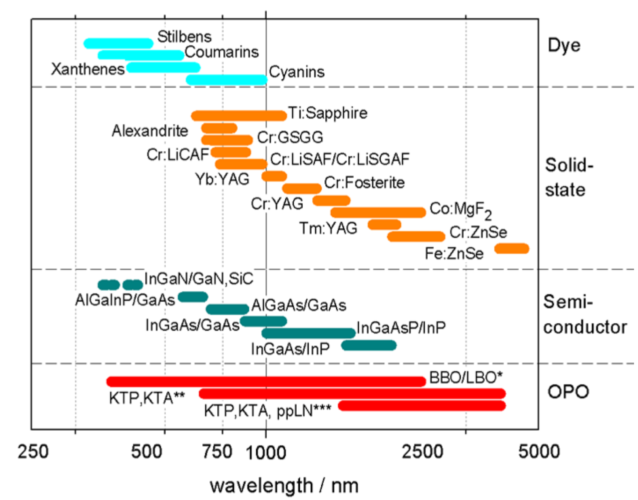
SUMMARY

- Tunable Coherent Light Sources – *Introduction and Overview*
  - *Working Principle of Tunable Lasers*
  - *Larger Tuning Range with NLO*
  - *Parametric Devices*
  - *Overview*



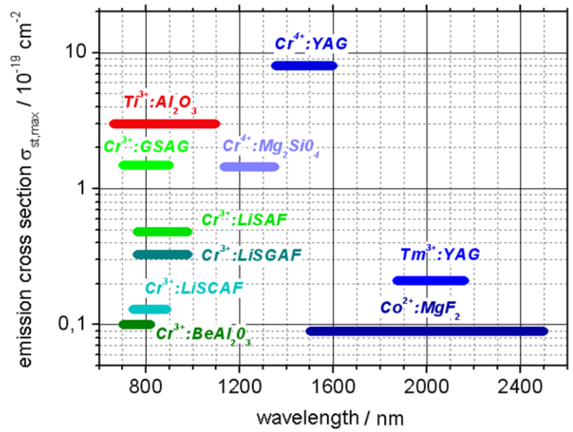


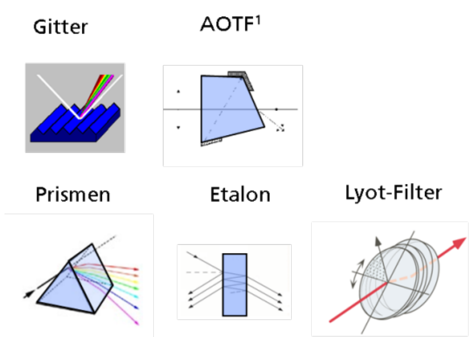




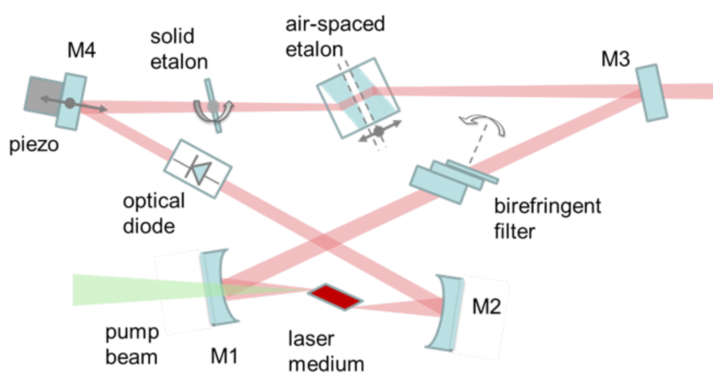
SUMMARY

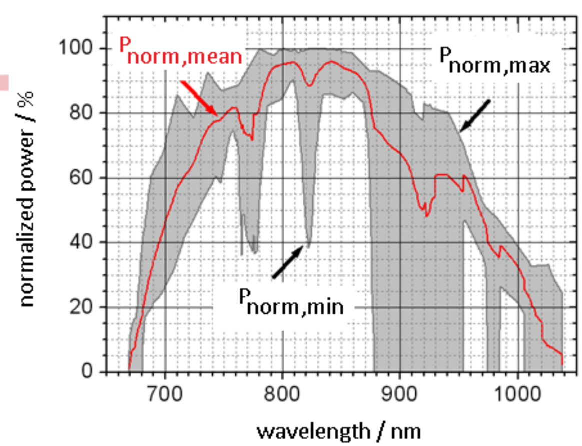
- Tunable Lasers – *Design Basics and Challenges*
  - *Gain media of tunable lasers*
  - *Spectral Filtering*
  - *Resonator Designs*
  - *Technical limits of broadband optics*





[1] AOTF = acousto optical tuning filter.

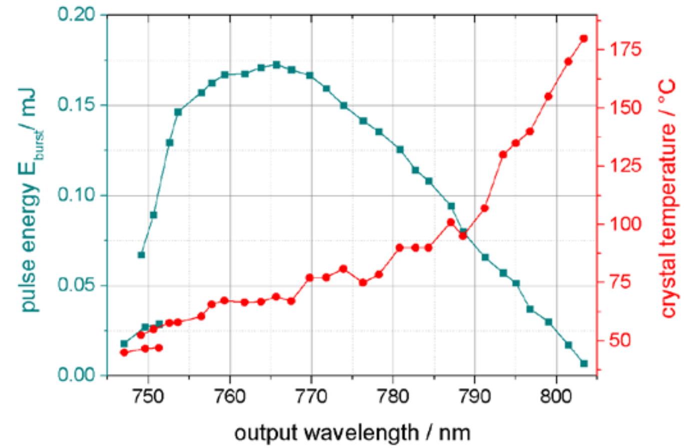


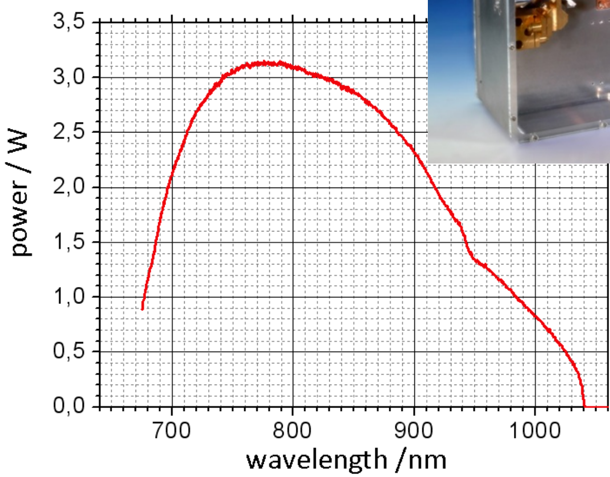


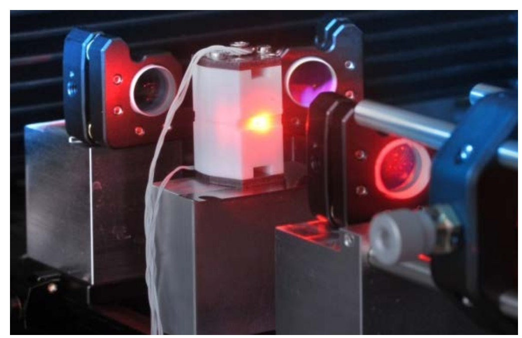
Fraunhofer ILT

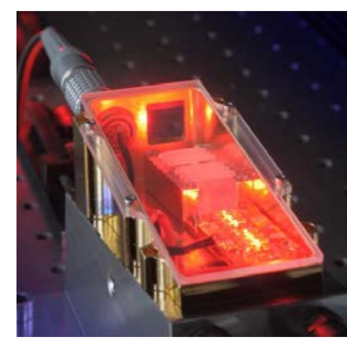
SUMMARY

- Design Examples I – *Tunable Lasers*
  - *Gain switched Ti:Saphire Laser*
  - *Diode Pumped Alexandrite Laser*





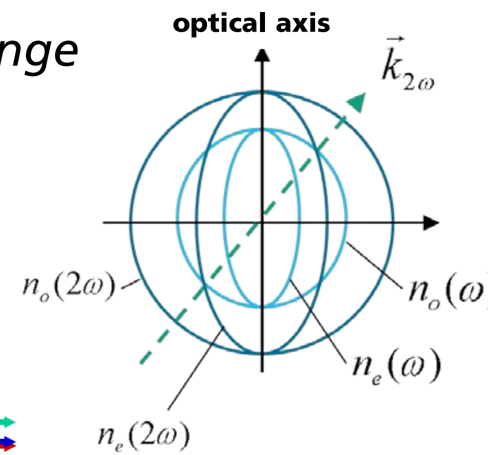


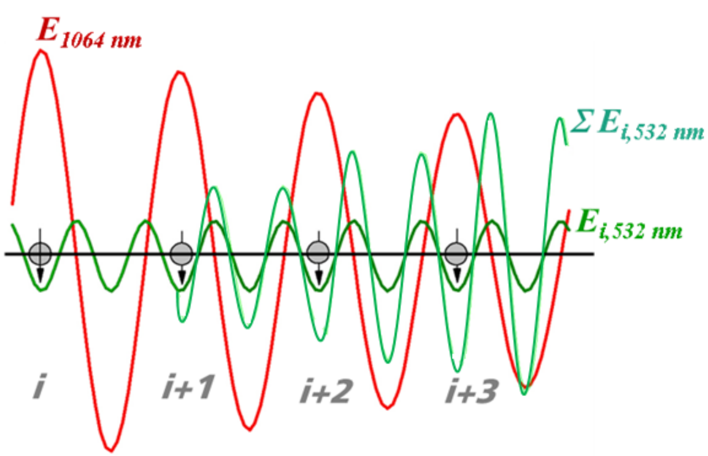


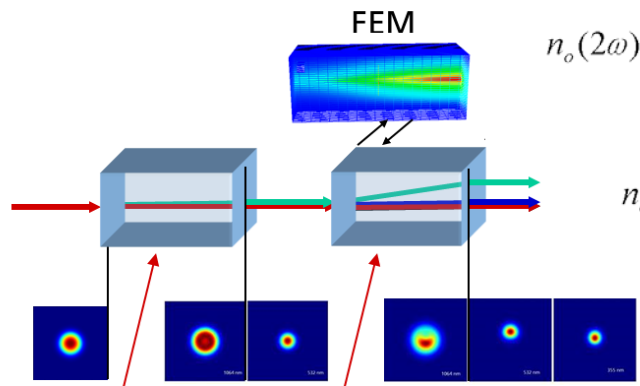
Fraunhofer ILT

SUMMARY

- Nonlinear Frequency Mixing – *Extending the Tuning Range*
  - *Nonlinear Coupling*
  - *Modeling tools*
  - *Phase Matching*







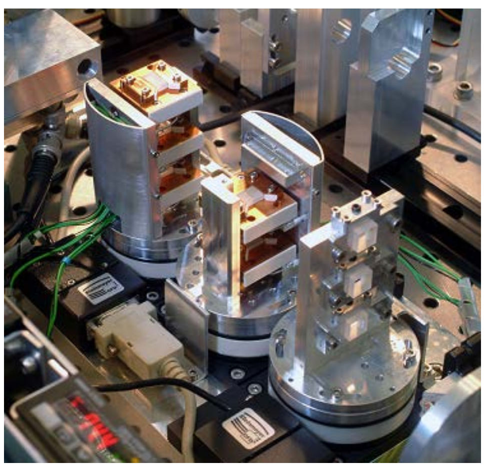
$$\frac{\partial \varepsilon_j}{\partial z} = \frac{i}{2k_j}\left[\frac{\partial^2 \varepsilon_j}{\partial x^2} + \frac{\partial^2 \varepsilon_j}{\partial y^2}\right] - \tan(\rho_j) + P_{jkl} - \alpha_j \varepsilon_j$$

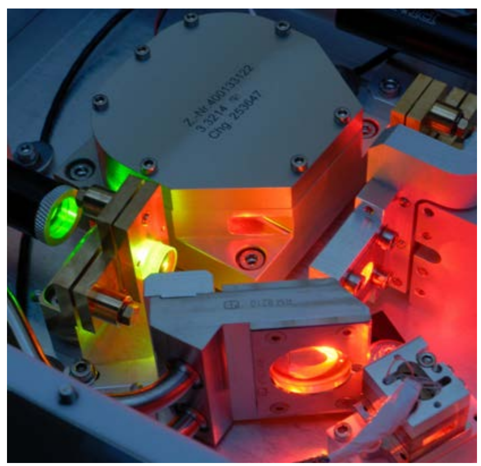
$$j \in \{1, 2, 3\}, \quad k \in \{1, 2, 3\} \setminus j, \quad l \in \{1, 2, 3\} \setminus \{j, k\}$$

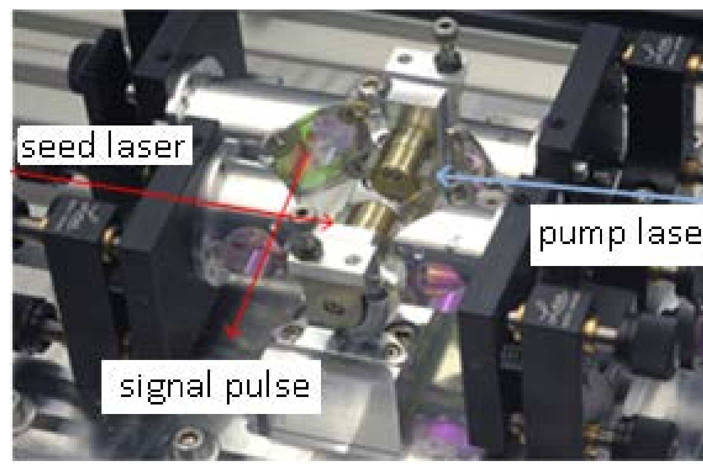
Fraunhofer ILT

SUMMARY

- Design Examples II – *Frequency Converters and Parametric Devices*
  - *Compact UV to VIS Converter*
  - *Intracavity doubled Tunable Dye Laser*
  - *IRB Tunable OPO*







Fraunhofer ILT