Ultrafast Optical Physics II (SoSe 2021)
Lecture 21, June 17

1) Ultrashort Pulse Optical Parametric Amplification

2) Non-collinear Optical Parametric Amplification

3) Optical Parametric Chirped Pulse Amplifier (OPCPA)

4) Optical Synthesis from OPAs

[5] Largely follows the review paper of Cerullo et al., “Ultrafast Optical Parametric Amplifiers” Rev. Sci. Instr. 74, pp 1-17 (2003)

Ultrashort Pulse Optical Parametric Amplification

$$\vec{E}_{p,s,i}(z,t) = \mathrm{Re}\left\{E_{p,s,i}(z,t)\ e^{j(\omega_{p,s,i}t - k_{p,s,i}\ z)}\vec{e}_{p,s,i}\right\}$$

Pulse envelopes

$$\begin{aligned}
\frac{\partial E_p}{\partial z} + \frac{1}{v_p}\frac{\partial E_p}{\partial t} &= -j\kappa_p\ E_s E_i\ e^{j\Delta k z}\ , \\
\frac{\partial E_s}{\partial z} + \frac{1}{v_s}\frac{\partial E_s}{\partial t} &= -j\kappa_s\ E_p E_i^*\ e^{-j\Delta k z}, \\
\frac{\partial E_i}{\partial z} + \frac{1}{v_i}\frac{\partial E_s}{\partial t} &= -j\kappa_i\ E_p E_s^*\ e^{-j\Delta k z},
\end{aligned}$$

$v_{p,s,i} = dk/d\omega|_{\omega_{p,s,i}}$ are the corresponding group velocities

$t' = t - z/v_p$

$$\begin{aligned}
\frac{\partial E_p}{\partial z} &= -j\kappa_p\ E_s E_i\ e^{j\Delta k z}\ , \\
\frac{\partial E_s}{\partial z} + \left(\frac{1}{v_s} - \frac{1}{v_p}\right)\frac{\partial E_s}{\partial t} &= -j\kappa_s\ E_p E_i^*\ e^{-j\Delta k z}, \\
\frac{\partial E_i}{\partial z} + \left(\frac{1}{v_i} - \frac{1}{v_p}\right)\frac{\partial E_s}{\partial t} &= -j\kappa_i\ E_p E_s^*\ e^{-j\Delta k z}.
\end{aligned}$$

Temporal walkoff
Group Velocity Mismatch (GVM)

Pump pulse width

$$\ell_{jp} = \frac{\tau}{\delta_{jp}}, \text{ with } \delta_{jp} = \left(\frac{1}{v_j} - \frac{1}{v_p}\right)$$

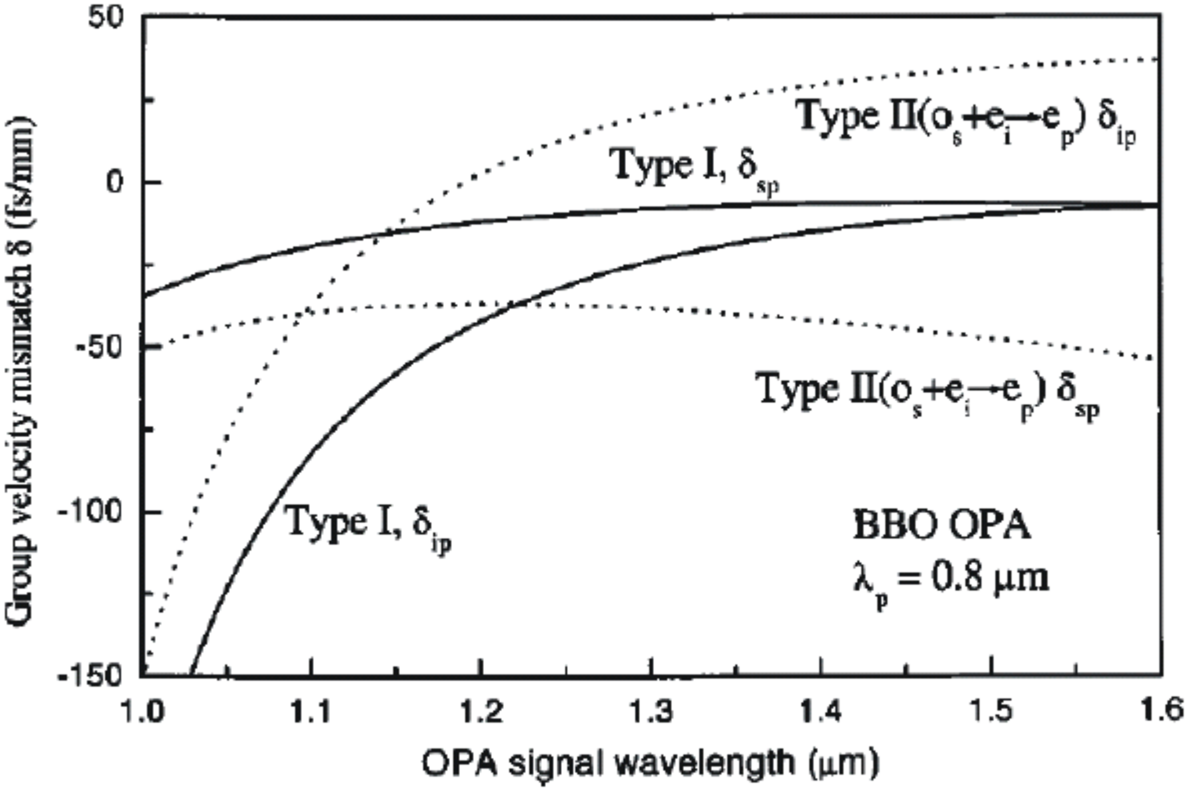


Fig. 12.31: Pump-signal (δ_{sp}) and pump-idler (δ_{ip}) group velocity mismatch curves for a BBO OPA at the pump wavelength λ_p=0.8 µm for type I phase matching (solid line) and type II ($o_s + e_i \rightarrow e_p$) phase matching (dashed line).

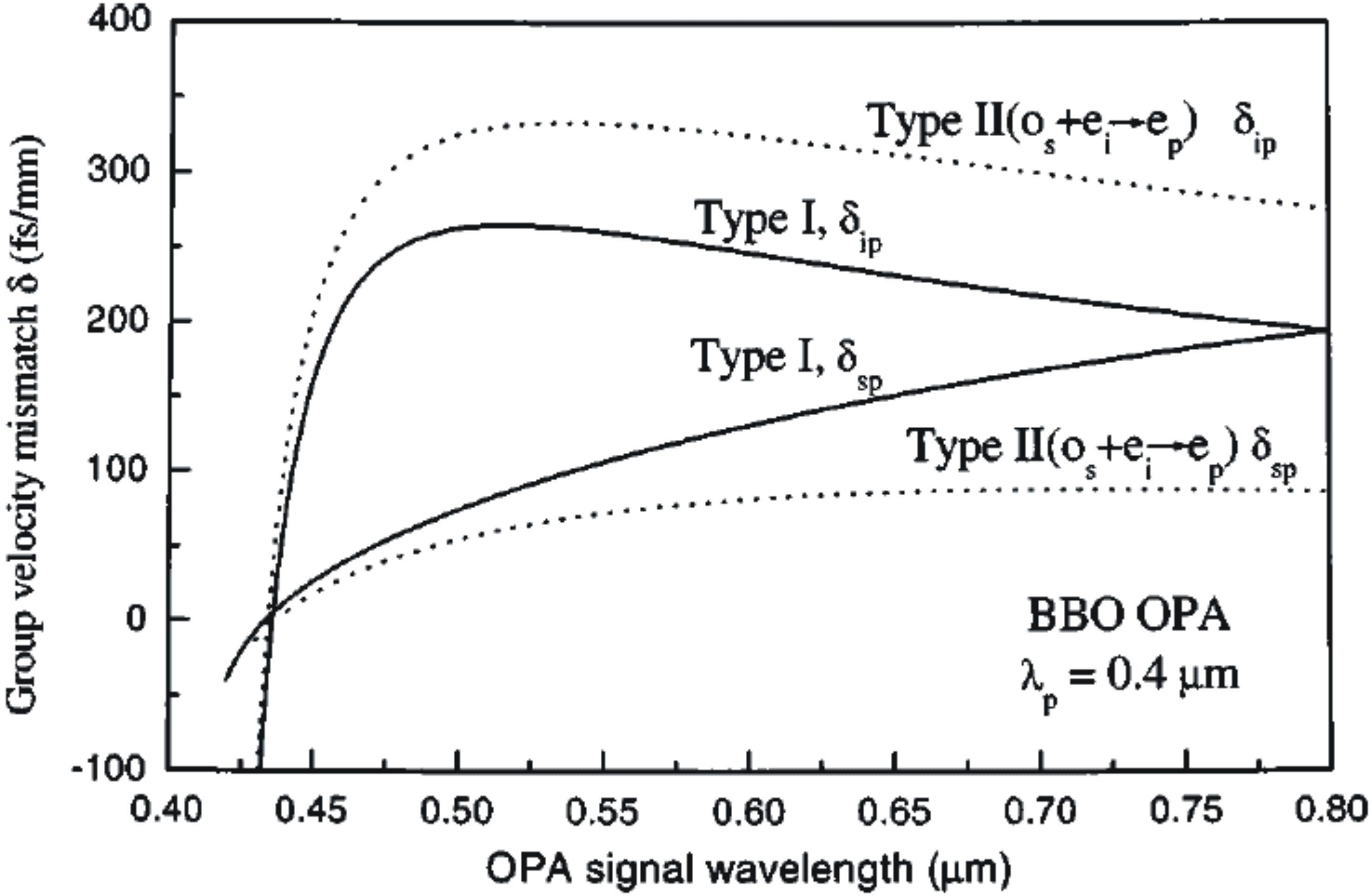


Fig. 12.32: Pump-signal (δ_{sp}) and pump-idler (δ_{ip}) group velocity mismatch curves for a BBO OPA at the pump wavelength λ_p=0.4 µm for type I phase matching (solid line) and type II ($o_s + e_i \rightarrow e_p$) phase matching (dashed line).

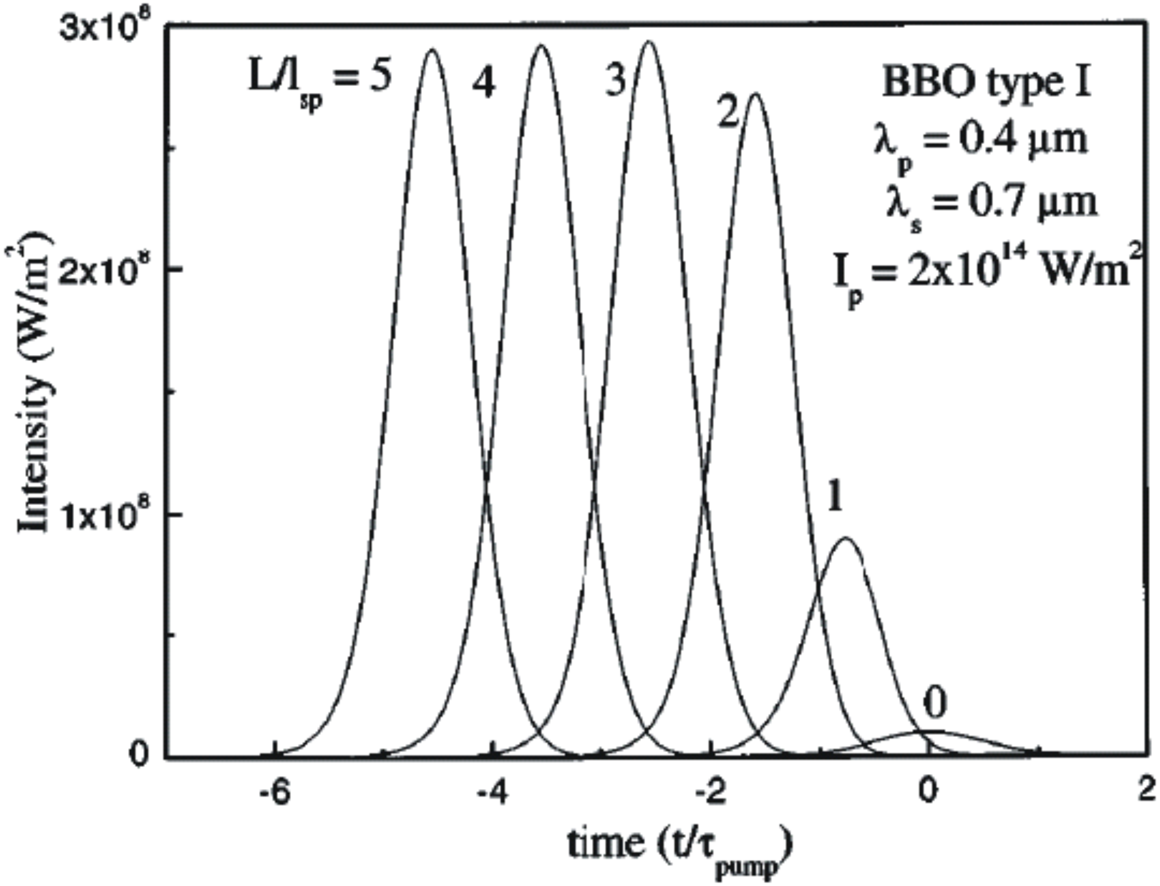


Figure 12.34: Signal pulse evolution for a BBO type I OPA with λ_p = 0.4 µm, λ_s = 0.7 µm, for different lengths L of the nonlinear crystal. Pump intensity is 20 GW/cm^2. Time is normalized to the pump pulse duration and the crystal length to the pump-signal pulse splitting length. [5]

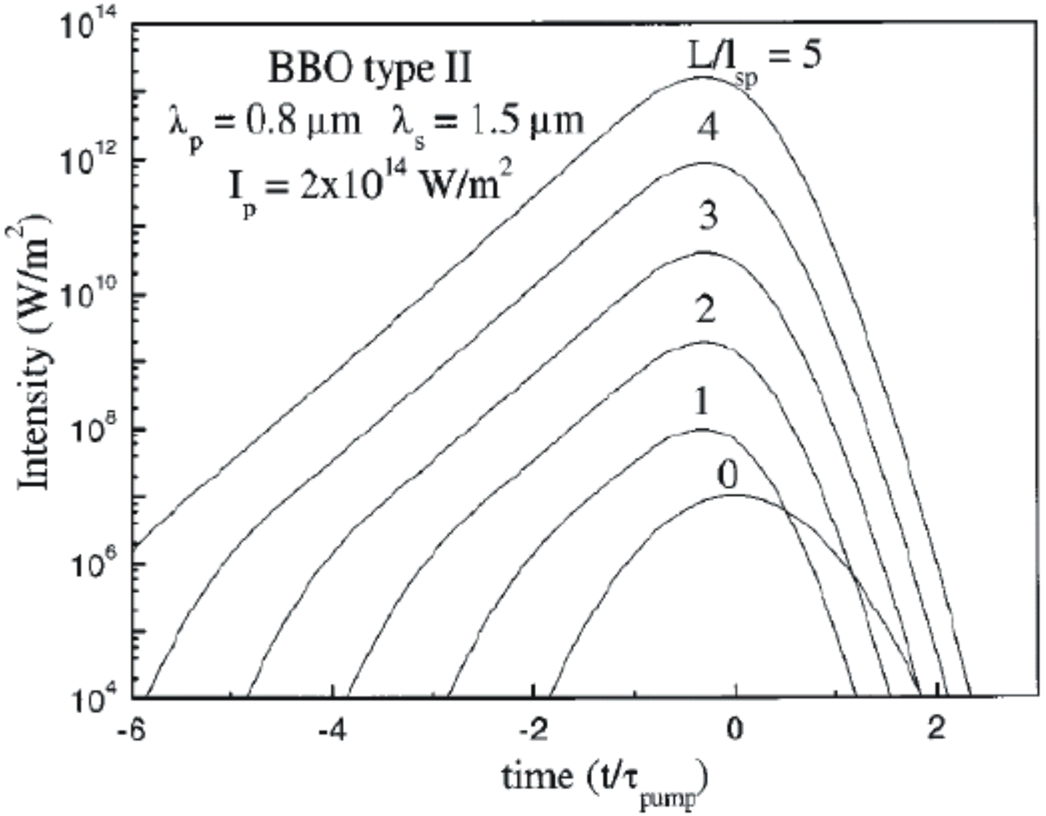


Figure 12.35: Signal pulse evolution for a BBO type II OPA with λ_p = 0.8 µm, λ_s = 1.5 µm, for different lengths L of the nonlinear crystal. Pump intensity is 20 GW/cm^2. Time is normalized to the pump pulse duration and the crystal length to the pump-signal pulse splitting length. [5]

OPA Bandwidth

$$\omega_s \longrightarrow \omega_s + \Delta\omega \qquad \omega_i \longrightarrow \omega_i - \Delta\omega$$

$$\Delta k = -\frac{dk_s}{d\omega}\Delta\omega + \frac{dk_i}{d\omega}\Delta\omega = \left(\frac{1}{v_i} - \frac{1}{v_s}\right)\Delta\omega$$

Bandwidth limitation due to GVM

$$\Delta f = -\frac{2\sqrt{\ln 2}}{\pi}\sqrt{\frac{\Gamma}{L}}\frac{1}{\left|\frac{1}{v_i} - \frac{1}{v_s}\right|}$$

For vanishing dispersion:

$$\Delta f = -\frac{2\sqrt[4]{\ln 2}}{\pi}\sqrt[4]{\frac{\Gamma}{L}}\frac{1}{\left|\frac{d^2k_s}{d\omega^2} + \frac{d^2k_s}{d\omega^2}\right|}$$

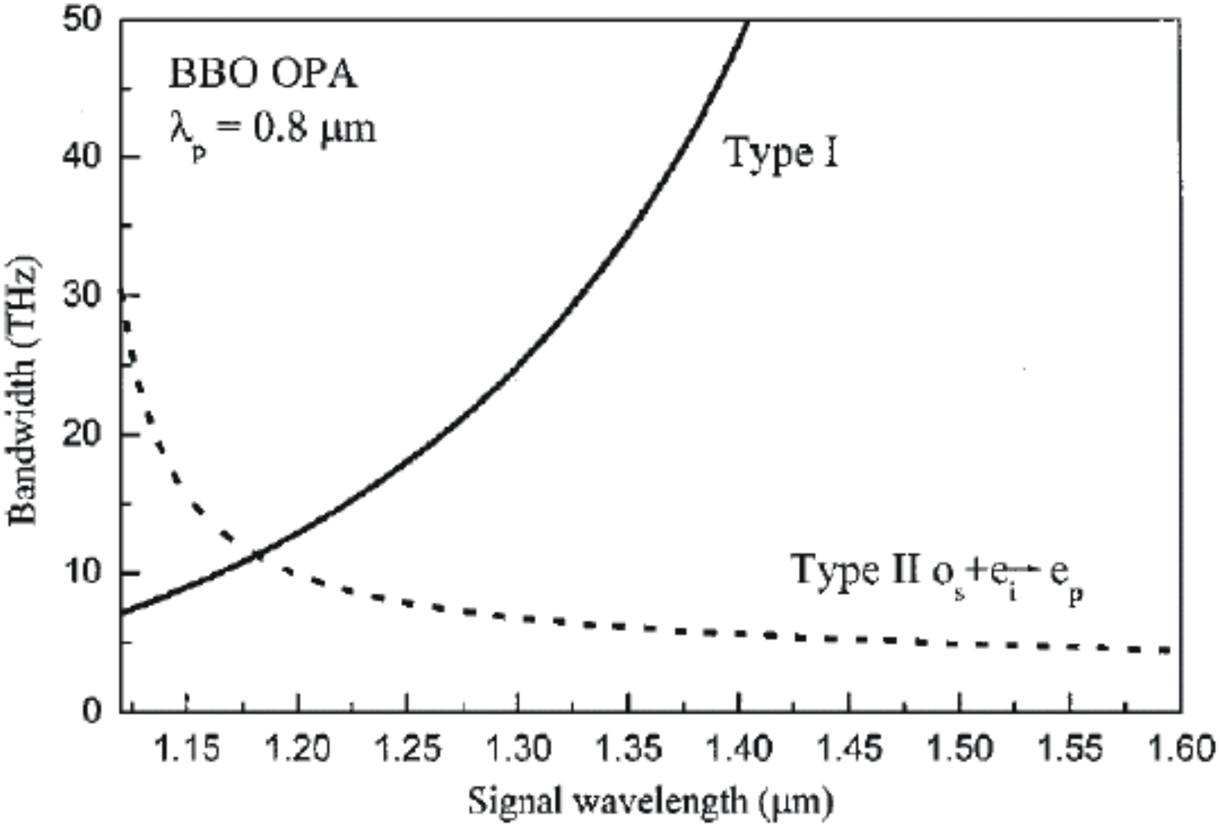


Figure 12.35: Phase matching bandwidth for a BBO OPA at the pump wavelength λ_p=0.8 µm for type I phase matching (solid line) and type II (o_s + $e_i \rightarrow e_p$) phase matching (dashed line). Crystal length is 4 mm and pump intensity 50 GW/cm^2.

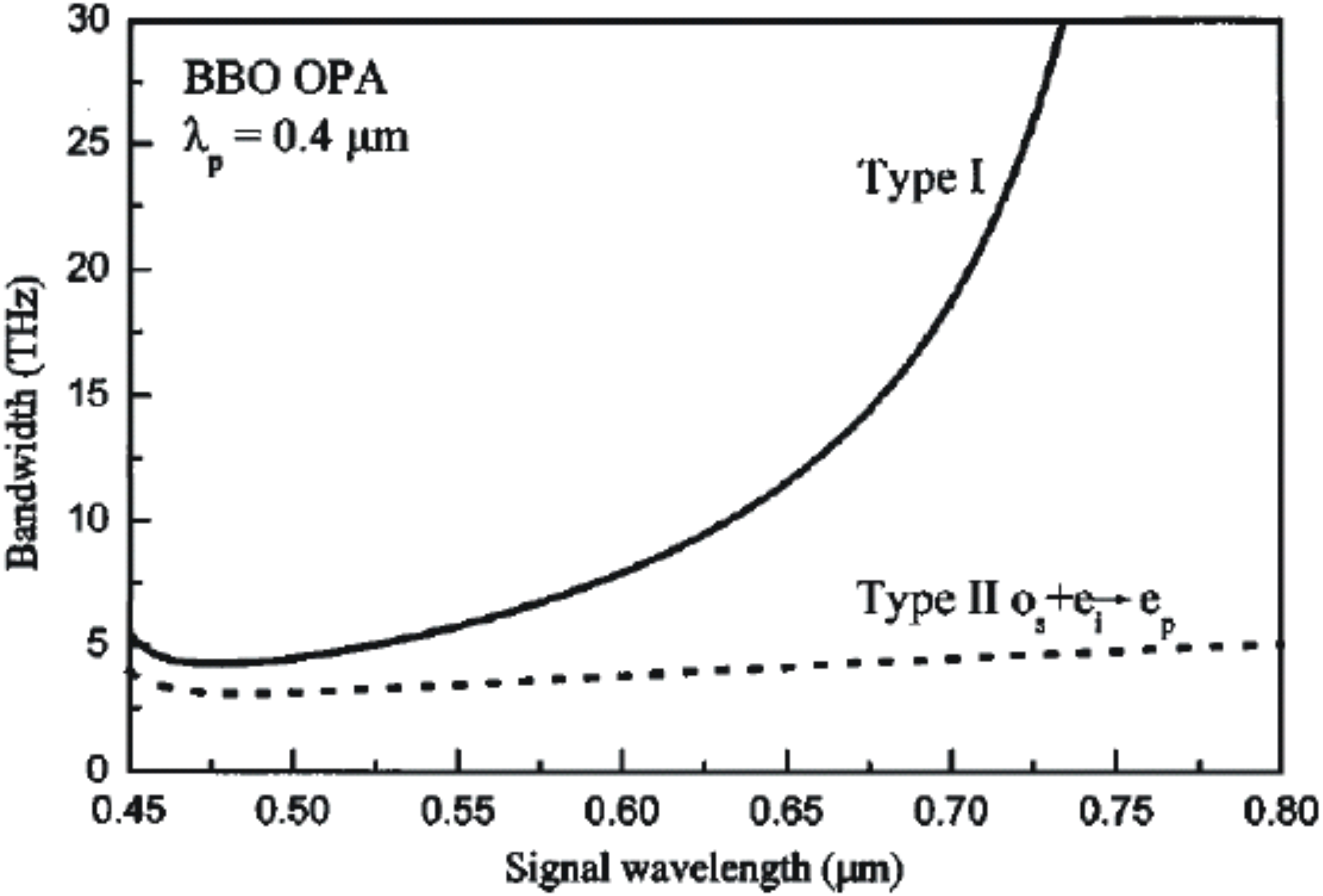


Figure 12.36: Phase matching bandwidth for a BBO OPA at the pump wavelength λ_p=0.4 µm for type I phase matching (solid line) and type II ($o_s + e_i \rightarrow e_p$) phase matching (dashed line). Crystal length is 2 mm and pump intensity 100 GW/cm^2.

Optical Parametric Amplifier Designs

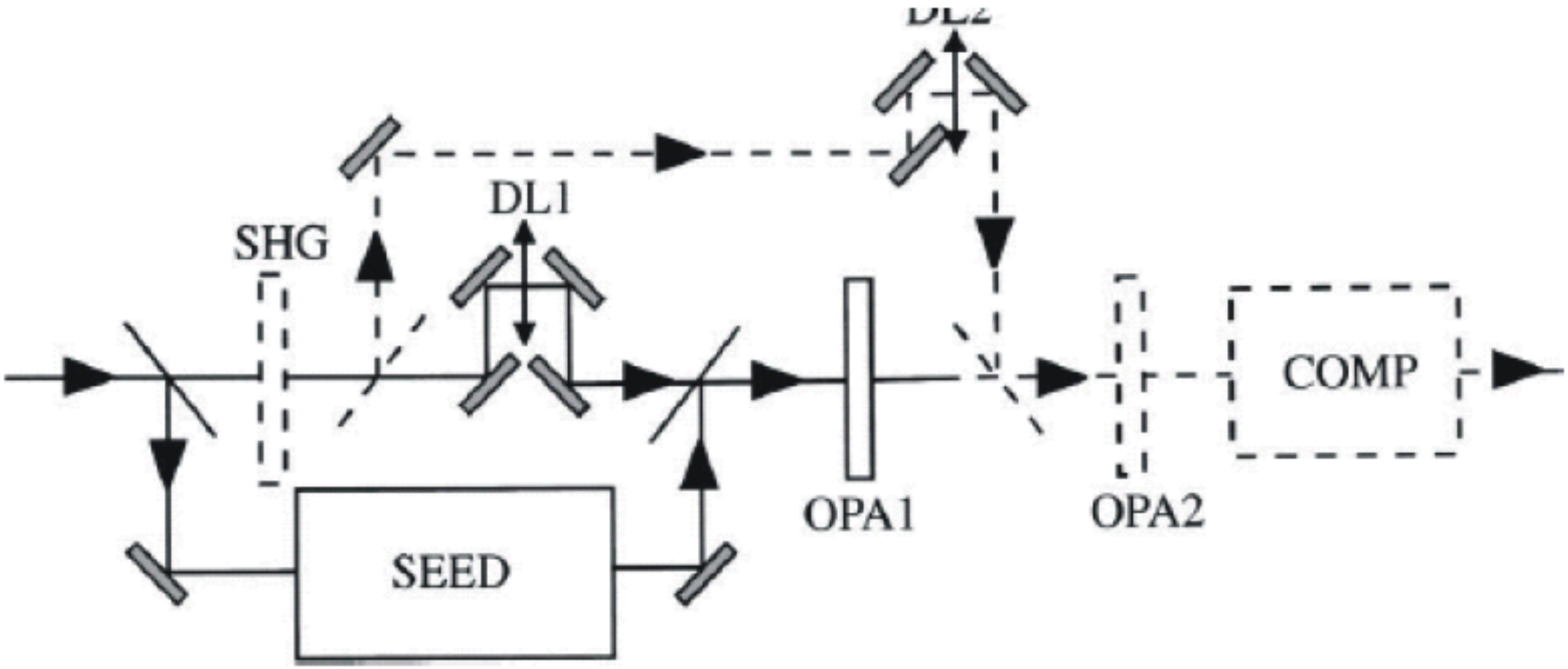


Figure 12.37: Scheme of an ultrafast optical parametric amplifier. SEED: seed generation stage; DL1, DL2: delay lines; OPA1, OPA2 parametric amplification stages; COMP: compressor.

Near-IR OPA

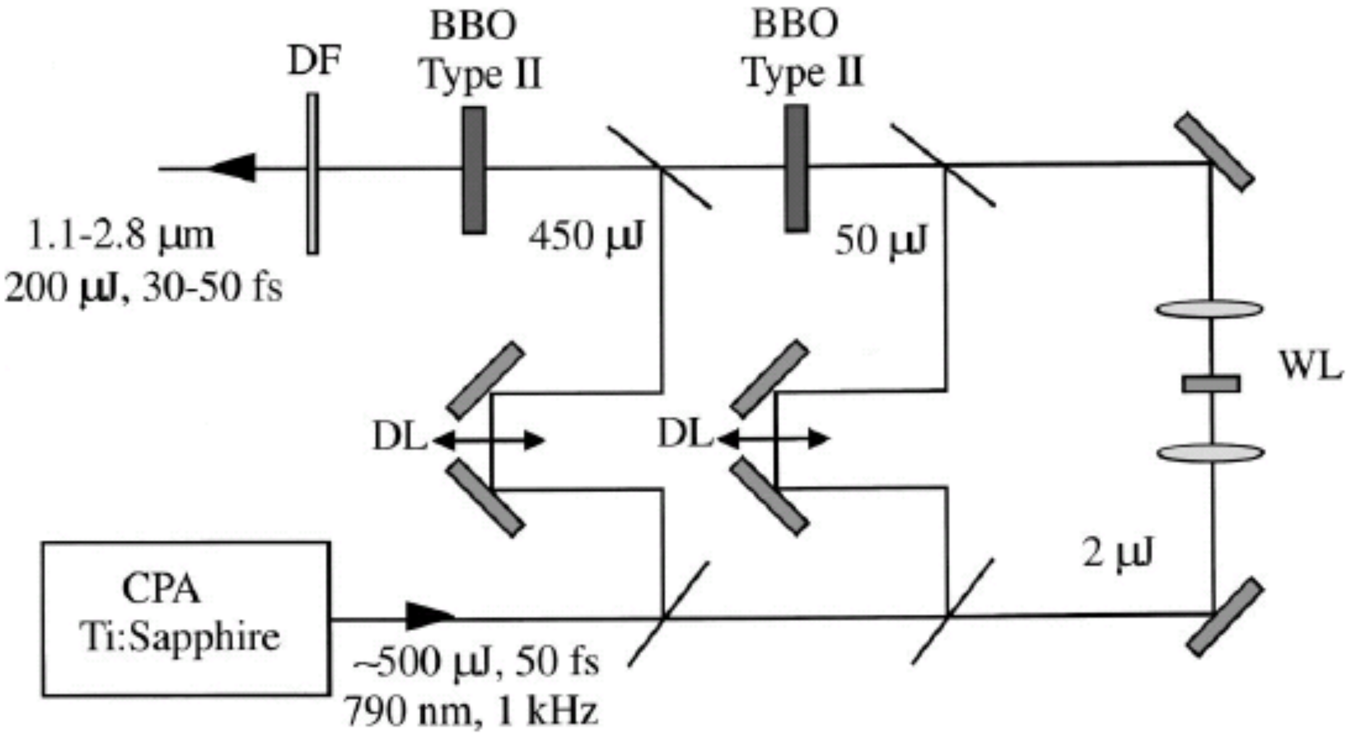


Figure 12.38: Scheme of a near-IR OPA DL: delay lines; WL: white light generation stage; DF: dichroic filter. [5]

Noncollinear Optical Parametric Amplifier (NOPA)

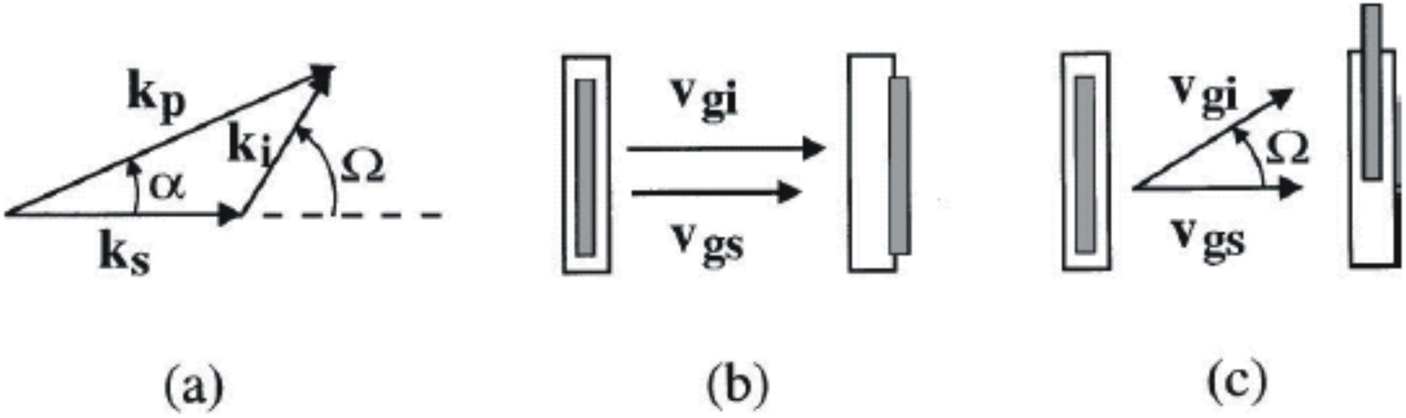


Figure 12.39: a) Schematic of a noncollinear interaction geometry; b) representation of signal and idler pulses in the case of collinear interaction; and c) same as b) for noncollinear interaction.

Phase Matching Condition: Vector Condition:

$$
\begin{aligned}
\Delta k_{par} &= k_p \cos\alpha - k_s - k_i \cos\Omega = 0 \\
\Delta k_{perp} &= k_p \sin\alpha - k_i \sin\Omega = 0
\end{aligned}
$$

Variation on phase matching condition by $\Delta\omega$

$$\begin{aligned}
\Delta k_{par} &= -\frac{dk_s}{d\omega_s}\Delta\omega + \frac{dk_i}{d\omega_i}\cos\Omega\ \Delta\omega - k_i\sin\Omega\frac{d\Omega}{d\omega_i}\Delta\omega = 0 \qquad \mathbf{X}\ \ \cos(\Omega) \\
\Delta k_{perp} &= \frac{dk_i}{d\omega_i}\sin\Omega\ \Delta\omega + k_i\cos\Omega\frac{d\Omega}{d\omega_i}\Delta\omega = 0 \qquad \mathbf{X}\ \ \sin(\Omega)
\end{aligned}$$

And addition

$$\frac{dk_i}{d\omega_i} - \cos\Omega\frac{dk_s}{d\omega_s} = 0$$

Correct index

$$\boxed{v_{gs} - v_{gi}\ \cos\Omega = 0}$$

Only possible if: $v_{gi} > v_{gs}$

$$\alpha = \arcsin\left[\frac{1-\frac{v_s^2}{v_i^2}}{1+2v_s n_s\lambda_i/v_i n_i\lambda_s + (n_s\lambda_i/n_i\lambda_s)^2}\right]$$

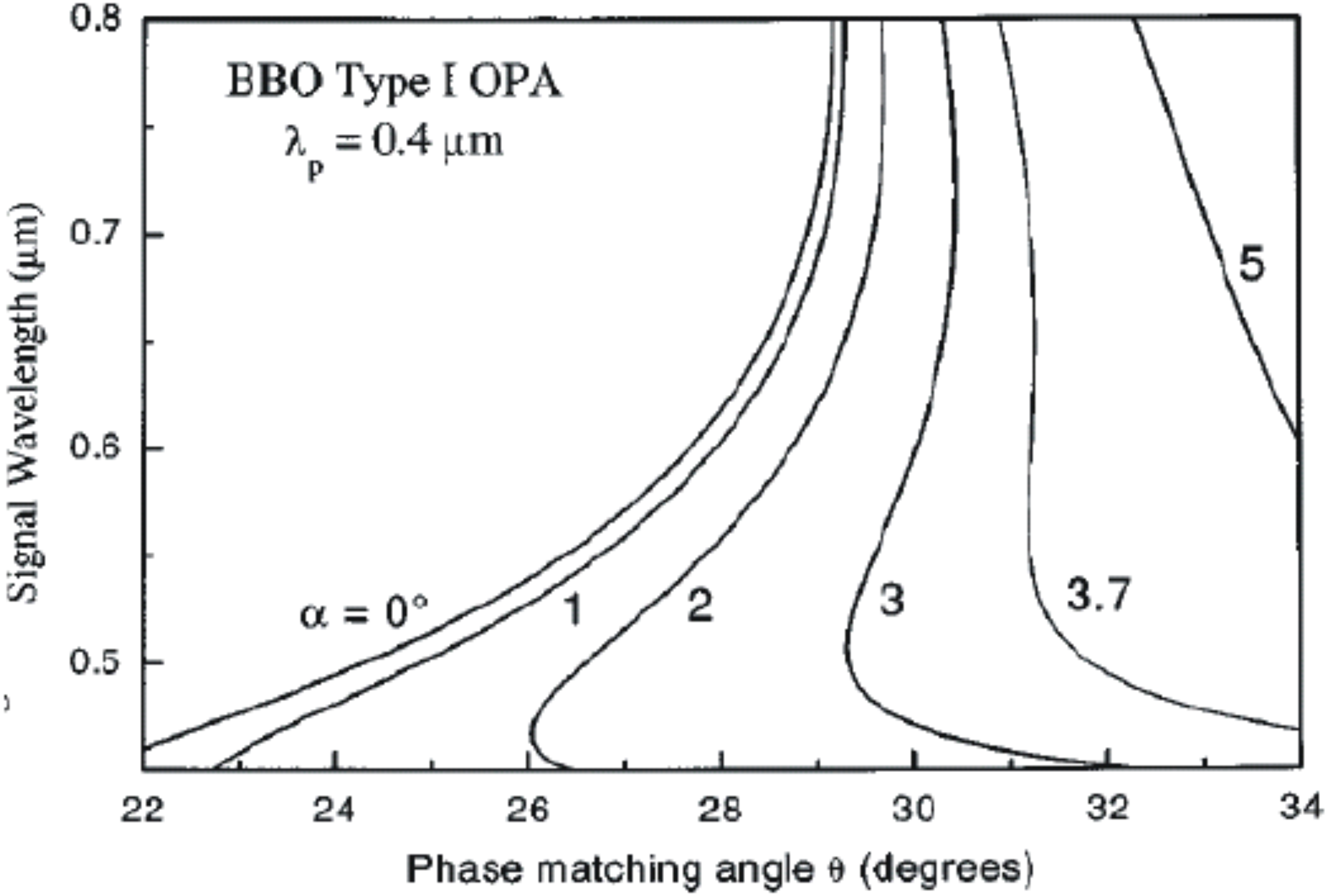


Figure 12.40: Phase-matching curves for a noncollinear type I BBO OPA pumped atpumped at λ_p=0.4 μm, as a function of the pump-signal angle a. [5]

NOPA Layout

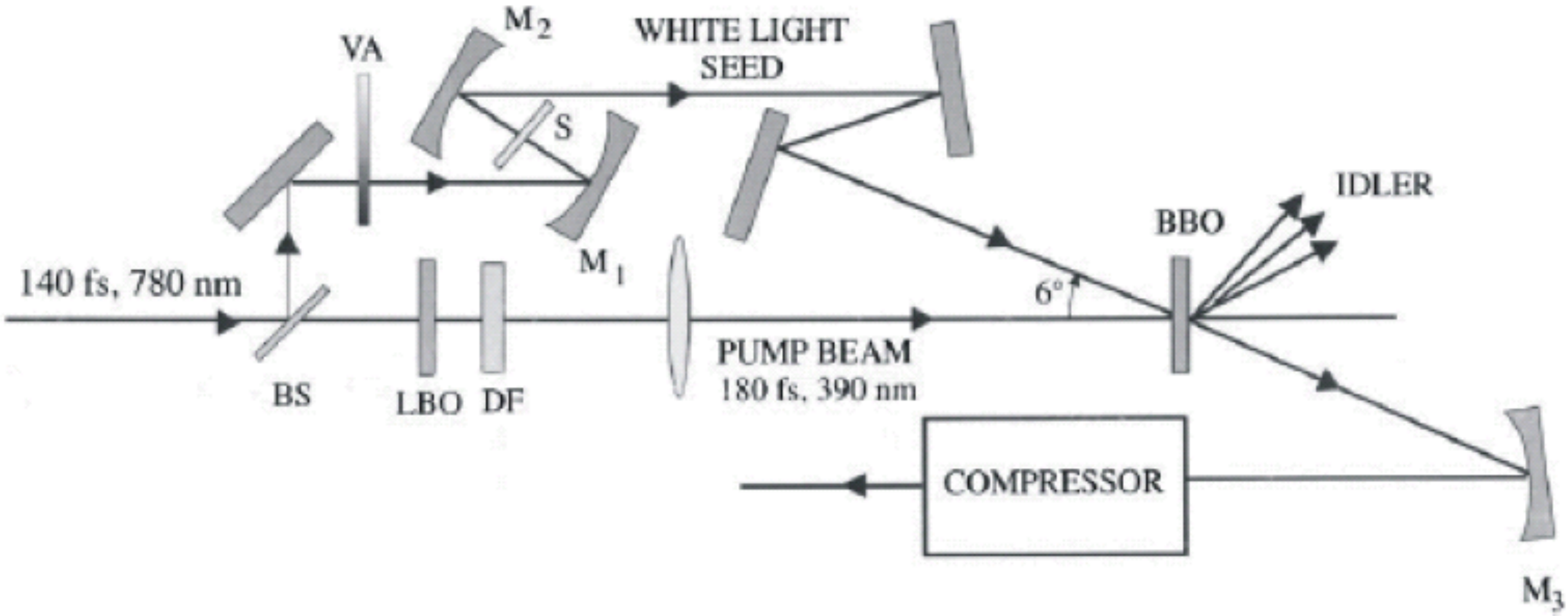


Figure 12.41: Scheme of a noncollinear visible OPA. BS: beam splitter; VA: variable attenuator; S: 1-mm-thick sapphire plate; DF: dichroic filter; M1 ,M2 , M3 , spherical mirrors.[5]

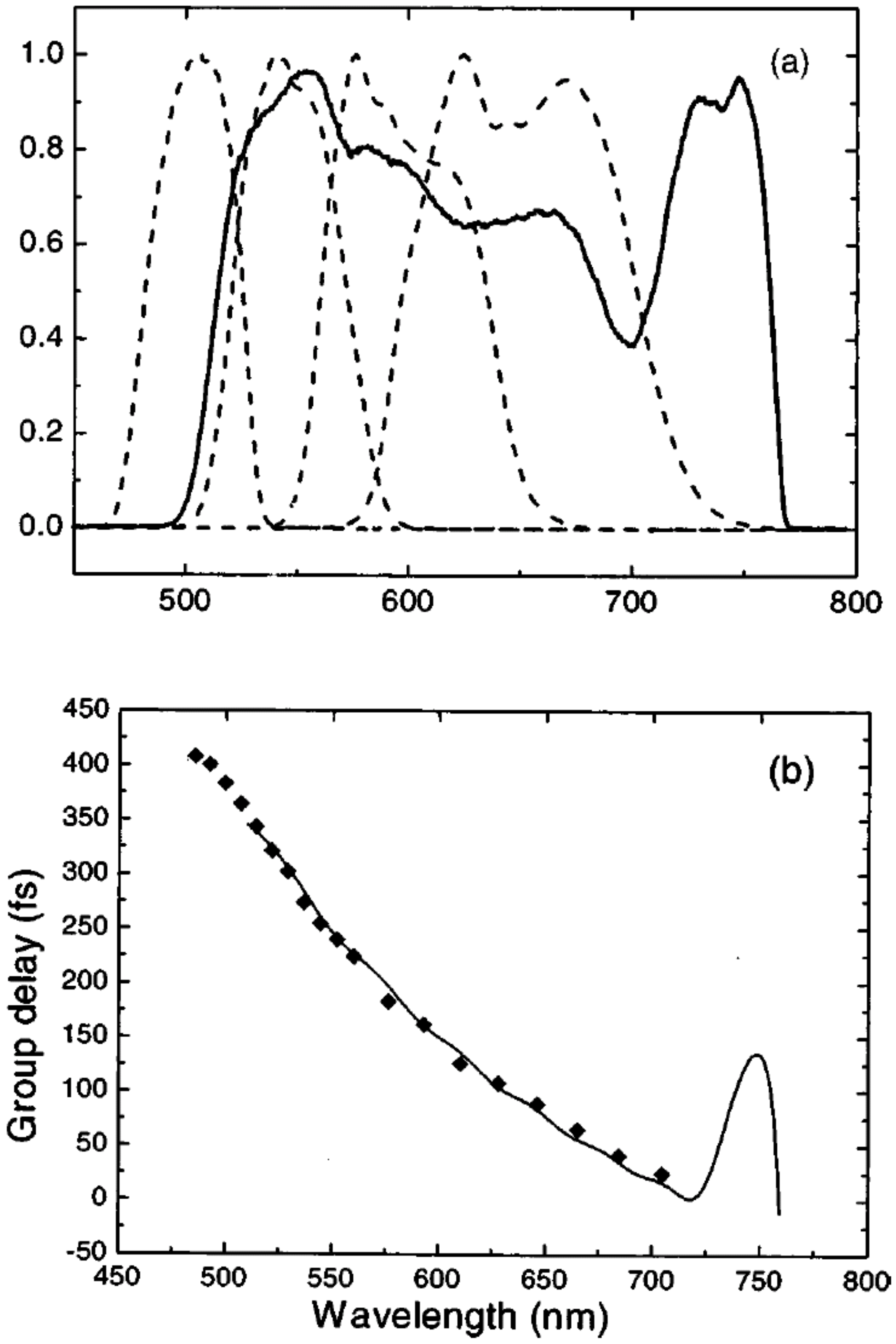


Figure 12.42:

a) Solid line: NOPA spectrum under optimum alignment conditions; dashed line: sequence of spectra obtained by increasing the white light chirp;

b) points: measured GD of the NOPA pulses; dashed line: GD after ten bounces on the ultrabroadband chirped mirrors.

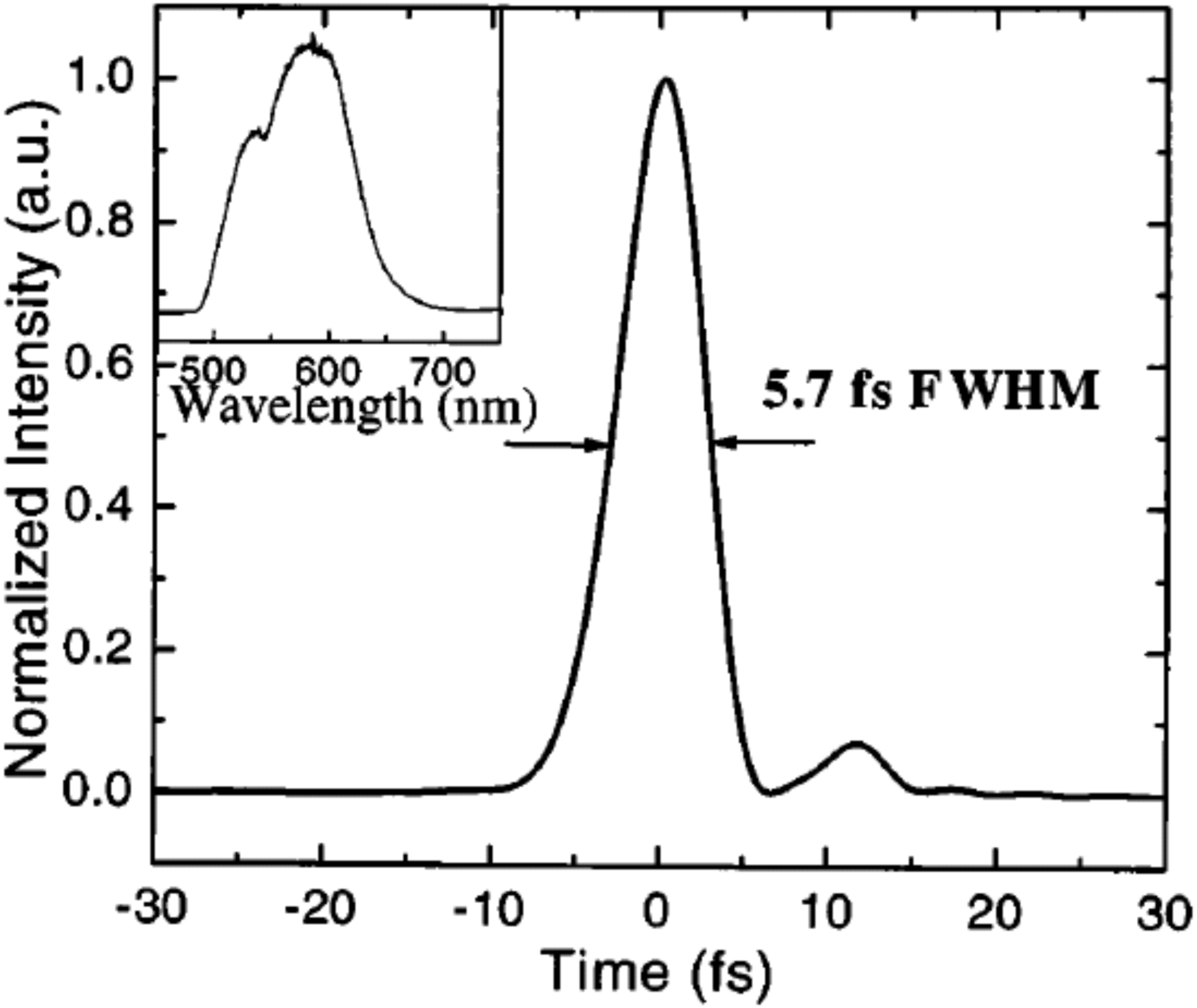
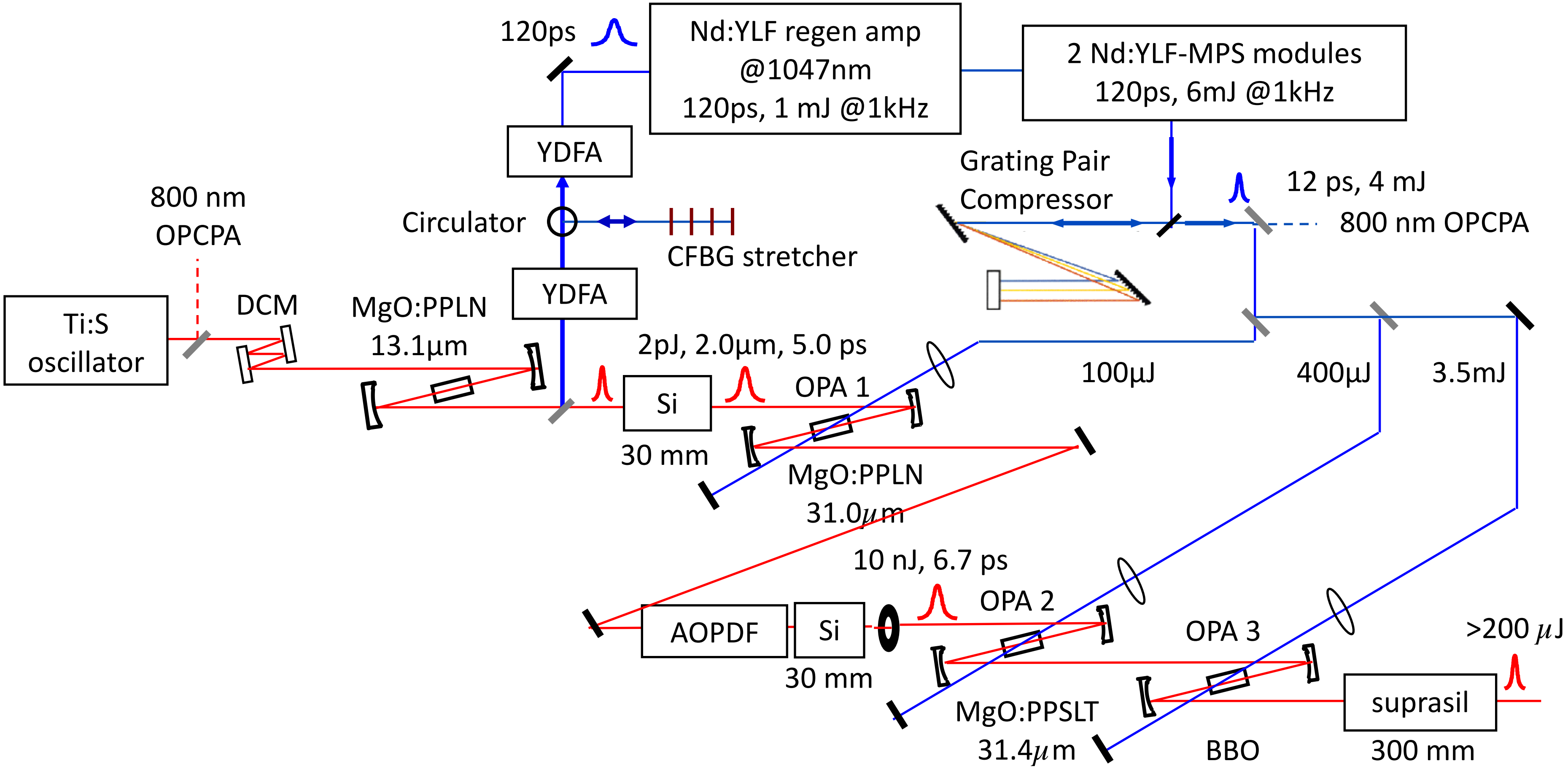


Figure 12.43: Reconstructed temporal intensity of the compressed NOPA pulse measured by the SPIDER technique. The inset shows the corresponding pulse pectrum.[5]

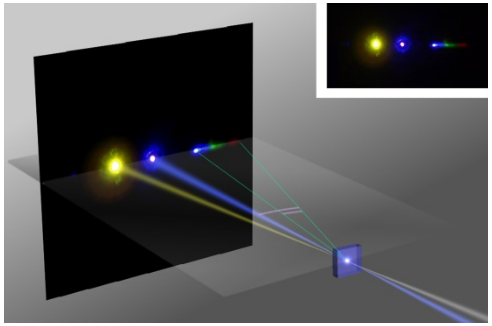
Optical Parametric Chirped Pulse Amplifier (OPCPA)

2-μm OPCPA

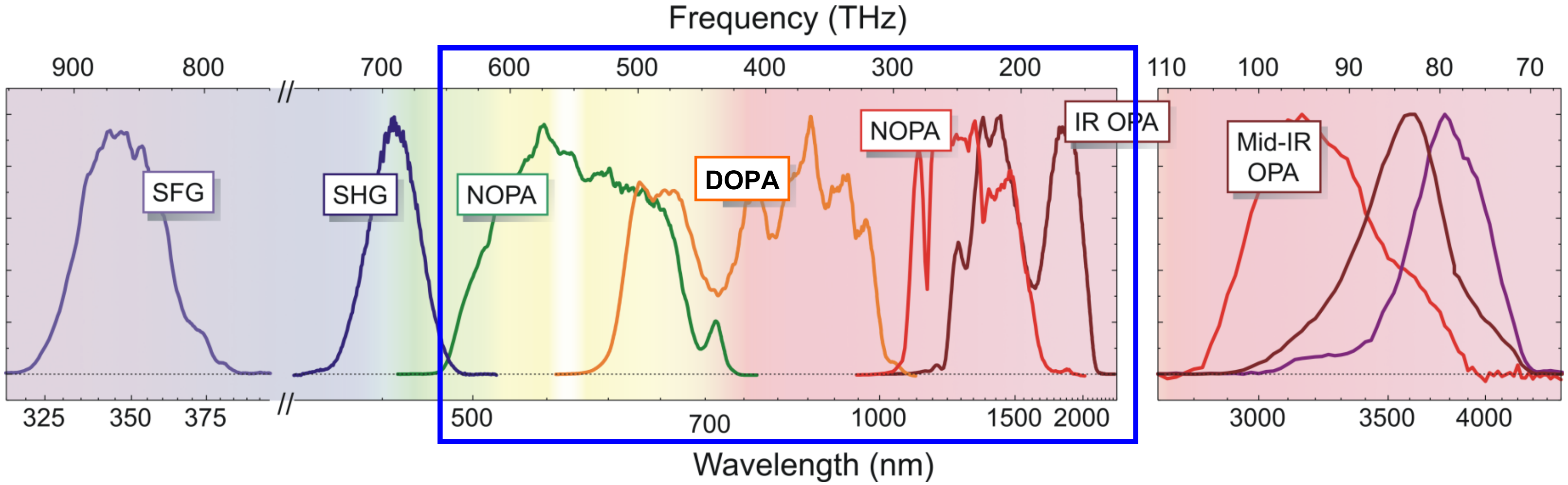


Optical Synthesis from OPAs

Combination of light from broadband Optical Parametric Amplifiers.



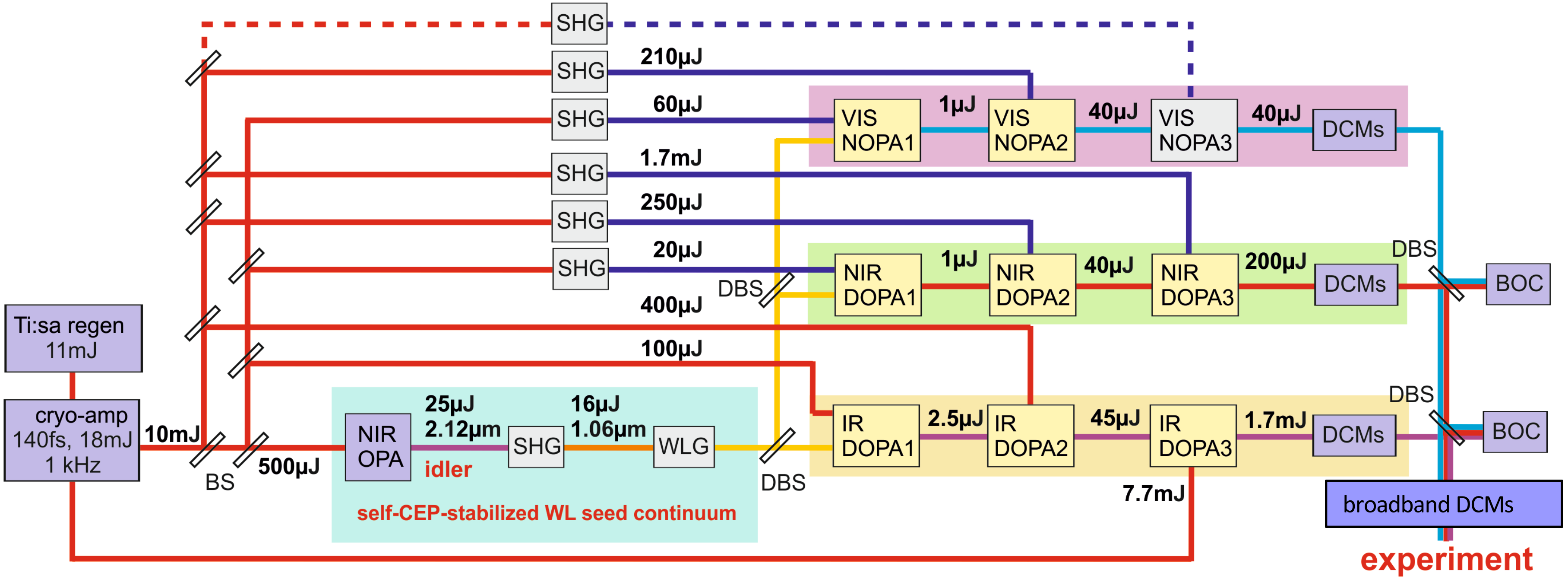
$\chi^{(2)}$ optical process in nonlinear crystals
Broadband phase-matching



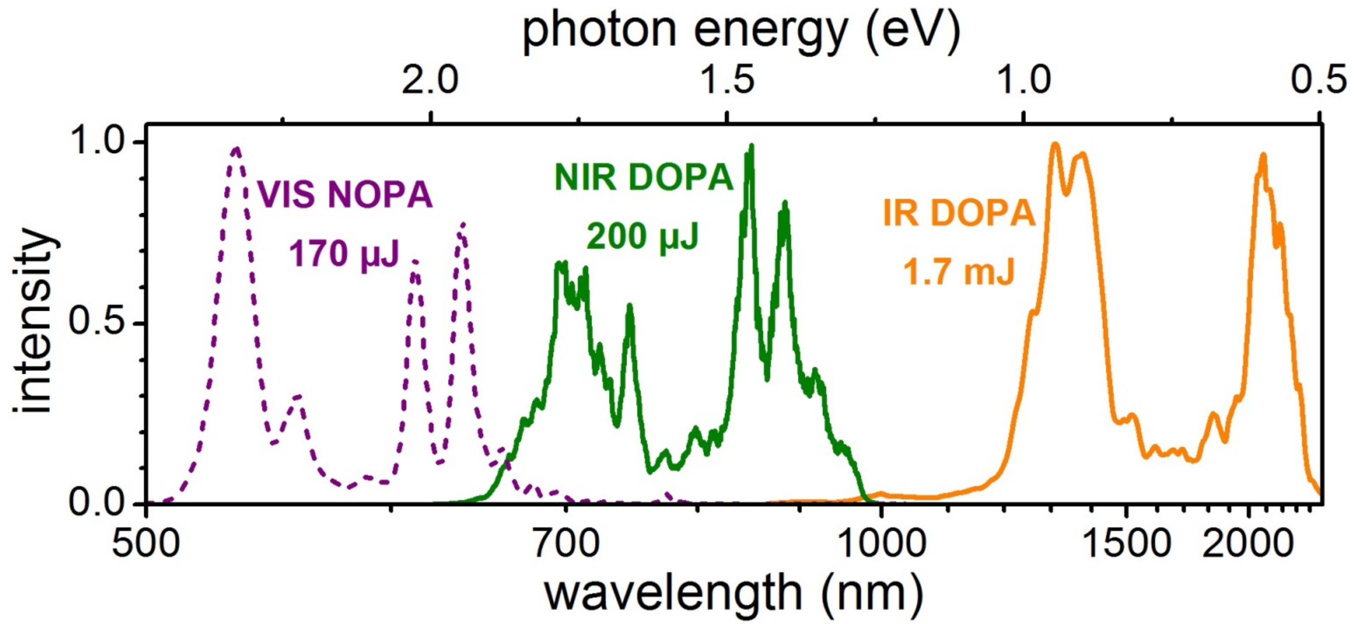
D. Brida et al., Journal of Optics A 12, 013001 (2010)

Multi-millijoule Pulse Synthesis with OPAs

- **Two-octave-wide** waveform synthesis from OPAs at the **multi-mJ energy level**
- **passively CEP-stable** WLG seed [G. Cerullo *et al.*, Laser Photonics Rev. **5**, 323 (2010)]
- WLG seed split into 3 wavelength channels and amplified in 3 OPA stages each
- Three channels are individually compressed and coherently recombined
- relative timing is tightly locked using balanced optical cross-correlators (BOCs)



Optical Pulse Synthesizer



VIS NOPA	NIR DOPA	IR DOPA
0.17 mJ signal	**0.20-0.25 mJ signal**	**1.7 mJ octave-spanning signal**
20% (0.8 mJ pump) pump-signal conversion efficiency	**12-15%** (1.7 mJ pump) pump-signal conversion efficiency	**22%** (7.7 mJ pump) pump-signal conversion efficiency
TL 5.6 fs	TL 5.2 fs	TL 5.2 fs
2.9 optical cycles @ λ_c=573nm	2.1 optical cycles @ λ_c=750nm	**1.1** optical cycle @ λ_c=1.4um