Synchronization of a Ti:Sapphire laser to the optical reference system

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on behalf of the Laser-based Synchronization Team at DESY-Hamburg:

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Motivation

- Optical synchronization with beam based stabilization of the arrival time
- High precision synchronization of lasers via optical cross-correlation
- Point-to-point synchronization ~ 10 fs rms
- Distribution over actively length-stabilized fiber links
- Permanent operation and long term stability
Input in the OCC from the diagnostic laser:
\( \lambda_1 = 800 \text{ nm}, \delta \lambda_1 = \sim 60 \text{ nm}, \tau_1 \sim 100 \text{ fs}, P_1 \sim 50 \text{ mW}, f_{\text{rep}} = 81 \text{ MHz} \)

Input in the OCC from the link:
\( \lambda_2 = 1560 \text{ nm}, \delta \lambda_1 = \sim 70 \text{ nm}, \tau_1 \sim 200 \text{ fs}, P_1 \sim 15 \text{ mW}, f_{\text{rep}} = 216 \text{ MHz} \)
Layout of the balanced detection set-up

DM1 – dichroic mirror HT@ $\lambda_1$ and $\lambda_2$, HR @ $\lambda_{SF}$
DM2 – dichroic mirror HR@ $\lambda_1$ and $\lambda_2$, HT @ $\lambda_{SF}$
SFG – non-linear crystal, e.g. BBO
GD – group delay adjustment
F – band pass filter, HT @ $\lambda_{SF}$
Design of the two-wavelength optical cross-correlator: group delay adjustment

Assume Gaussian pulses

\[ I_i(t) = \frac{1}{\sqrt{\pi} \sigma_i} \exp \left( -\frac{(t-t_i)^2}{\sigma_i^2} \right) \]

The convolution of two Gaussian pulses is also a Gaussian pulse:

\[ I_i(t) = I_1 * I_2 = \int_{-\infty}^{\infty} I_1(\tau) \cdot I_2(t-\tau) \, d\tau = \frac{1}{\sqrt{\pi (\sigma_1^2 + \sigma_2^2)}} \exp \left( -\frac{(t-t_1-t_2)^2}{\sigma_1^2 + \sigma_2^2} \right) \]
Design of the two-wavelength optical cross-correlator: group delay adjustment

The biggest change $S$ in the overlap is given by the derivative of the convolution:

$$ S = (I_1 * I_2)' = \frac{2(t - \tau)}{\sqrt{\pi \left( \sigma_1^2 + \sigma_2^2 \right)^{3/2}}} \exp \left( -\frac{(t - \tau)^2}{\sigma_1^2 + \sigma_2^2} \right) $$

Delay between the extrema in terms of pulse lengths (FWHM): $\tau = \sqrt{\left( \tau_1^2 + \tau_2^2 \right)/2 \ln(2)}$

Examples (after accounting the group velocity delays in the crystal and the lenses):

Ti:Sa + EDFA: $\tau_1 = 100$ fs and $\tau_2 = 200$ fs: $\tau = 190$ fs
   → need a 65 - 80 fs additional delay: a double pass through a 2 – 3 mm silica slab

Nd:YLF + EDFA: $\tau_1 = 11$ ps and $\tau_2 = 200$ fs: $\tau = 9$ ps
   → if the same swapping technique is to be used: 20 cm SF66! → delay stage
Design of the two-wavelength optical cross-correlator: choice of the crystal

Guiding criteria:
• highest possible efficiency
• highest bandwidths
• smallest background

→ type of interaction: Type I or Type II

Parameters to calculate:
• phase matching angles
• phase and group velocities
• relative group delays
• walk-off angle
• reflection losses at the crystal surfaces
• effective non-linear coefficients
• group velocity dispersion, group delay dispersion
• chirp, pulse broadening
• effective lengths
• phase mismatch – mix acceptance bandwidth, mix acceptance angle, internal angular BW etc…
Design of the two-wavelength optical cross-correlator: choice of the crystal

Equations from:

Geometric factors:
→ phase matching
→ cut angle
→ crystal thickness
→ focusing
Phase matching angles for BBO

\( \lambda_1 = 1550 \text{ nm}, \; \lambda_2 = 800 \text{ nm}, \; \lambda_{\text{SFG}} = 528 \text{ nm} \)

Type I\((\cdot)(\text{ooe})\): \( \Theta = 22.2^\circ \)
Type II\((\cdot)(\text{oe})\): \( \Theta = 27.2^\circ \)
Type II\((\cdot)(\text{ee})\): \( \Theta = 38.8^\circ \)

Phase velocities in BBO

\[ V_{\text{Ph}} = \frac{c}{n(\lambda, \Theta)} \]

Type I\((\cdot)(\text{ooe})\)
\[
n(\lambda = 1550, \Theta = 0^\circ) = 1.647 \\
n(\lambda = 800, \Theta = 0^\circ) = 1.661 \\
n(\lambda = 528, \Theta = 0^\circ) = 1.656
\]

\[ n^e(\Theta) = n_0 \sqrt{\frac{1 + \tan^2(\Theta)}{1 + \left( \frac{n_o}{n_e} \right)^2 \tan^2(\Theta)}} \]

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Group velocities in BBO

$$u_g(\lambda, \Theta) = \frac{1}{k'} = \frac{c}{\tilde{n}(\lambda, \Theta)}$$

$$k' = \frac{dk}{d\omega} = \frac{1}{c} \left[ n(\lambda, \Theta) - \lambda \frac{dn(\lambda, \Theta)}{d\lambda} \right]$$

$$\tilde{n}(\lambda = 1550, 0^\circ) = 1.671$$

Type I(-)(ooe):
$$\tilde{n}(\lambda = 800, 0^\circ) = 1.684$$
$$\tilde{n}(\lambda = 528, 22.2^\circ) = 1.702$$

Relative group delay:

$$\tau_g(\lambda_1, \lambda_2, \Theta_1, \Theta_2) = L_{qs} \left( \frac{1}{u_g(\lambda_1, \Theta_1)} - \frac{1}{u_g(\lambda_2, \Theta_2)} \right)$$

Type I(-)(ooe):
$$\tau_g(\lambda_1 = 1550, \lambda_2 = 800) = -0.44 \quad fs/mm$$
Walk-off angles for BBO

For an e-wave:
S – direction of propagation of the energy
K – direction of propagation of the phase

\[
\rho(\lambda, \Theta) = -\frac{1}{n_e(\lambda, \Theta)} \frac{\partial n_e(\lambda, \Theta)}{\partial \Theta}
\]

Type I(-)(ooe):
\[
\rho(528, 22.2^\circ) = 54.7 \text{ mrad}
\]

Type II(-)(ee):
\[
\rho(1550, 27.2^\circ) = 61.7 \text{ mrad}
\]
\[
\rho(528, 27.2^\circ) = 62.9 \text{ mrad}
\]

Type II(-)(oe):
\[
\rho(800, 38.8^\circ) = 71.8 \text{ mrad}
\]
\[
\rho(528, 38.8^\circ) = 73.4 \text{ mrad}
\]

linear walk-off:
\[
\delta = L \tan \rho
\]
Beam walk-off

Type I(−)(ooe):
\[ \lambda = 528 \text{ nm}, \quad \Theta = 22.2^\circ \]
\[ \rho = 54.7 \quad \text{mrad} \]
\[ \delta = 54.7 \quad \mu m / mm \]
\[ \alpha = 5^\circ \]
\[ \delta_1 = 100 \quad \mu m / mm \]

Reflection at the crystal surface

- normal incidence
- the crystal is not coated ~6% losses
- difficult to simultaneously satisfy the requirements for high bandwidth for all three wavelengths
Effective nonlinear coefficients $d_{\text{eff}}$ [pm/V] for point group 3m

Type I

$$d_{\text{ooe}}^{\text{eff}} = d_{31} \sin(\theta + \rho) - d_{22} \cos(\theta + \rho) \sin(3\phi)$$

Type II

$$d_{\text{eoe}}^{\text{eff}} = d_{\text{eoe}}^{\text{eff}} = d_{22} \cos^2(\theta + \rho) \cos(3\phi)$$

Available values for BBO (a negative 3m crystal):

   $$d_{22} = 2.3 \text{ pm/V}; \ d_{31} = 0.16 \text{ pm/V}$$

   $$d_{22} = 1.6 \text{ pm/V}; \ d_{31} = 0.08 \text{ pm/V}$$

   $$d_{22} = 2.2 \text{ pm/V}; \ d_{31} = ??? \text{ pm/V}$$

4) SNLO
   $$d_{22} = 2.2 \text{ pm/V}; \ d_{31} = 0.08 \text{ pm/V}$$

Type I

$$d_{\text{ooe}}^{\text{eff}}(2.3 \text{ pm/V, 0.16 pm/V, 22.2°, 528 nm}) = 2.15 \text{ pm/V}$$
$$d_{\text{ooe}}^{\text{eff}}(2.2 \text{ pm/V, 0.08 pm/V, 22.2°, 528 nm}) = 2.02 \text{ pm/V}$$

Type II

$$d_{\text{eoe}}^{\text{eff}}(2.2 \text{ pm/V, 27.2°, 528 nm}) = 1.62 \text{ pm/V}$$
$$d_{\text{ooe}}^{\text{eff}}(2.2 \text{ pm/V, 38.8°, 528 nm}) = 1.18 \text{ pm/V}$$

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Design of the two-wavelength optical cross-correlator: influence of the crystal thickness on the bandwidth (mix acceptance bandwidth)


Example: Type I (ooe)

\[
\Delta \nu = \frac{0.886}{L} \left| n_{o2} - n^e_3(\Theta) - \lambda_2 \frac{\partial n_{o2}}{\partial \lambda_2} + \lambda_3 \frac{\partial n^e_3(\Theta)}{\partial \lambda_3} \right|^{-1}
\]

Mix acceptance BW for 0.5 mm BBO

<table>
<thead>
<tr>
<th></th>
<th>(\lambda = 1550) nm</th>
<th>(\lambda = 800) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ooe</td>
<td>(\Delta \lambda = 139) nm</td>
<td>(\Delta \lambda = 65) nm</td>
</tr>
<tr>
<td>eoe</td>
<td>(\Delta \lambda = 91) nm</td>
<td>(\Delta \lambda = 161) nm</td>
</tr>
<tr>
<td>oee</td>
<td>(\Delta \lambda = 631) nm</td>
<td>(\Delta \lambda = 35) nm</td>
</tr>
</tbody>
</table>
Design of the two-wavelength optical cross-correlator

non-linear conversion efficiency for Type I (ooe) interaction between a Ti:Sa laser and EDFA

choice of the crystal thickness:
- $\eta(L) < 1$
- $L < L_{\text{eff}}$

$\lambda_1 = 1550$ nm, $\tau_1 = 200$ fs, $P_1 = 15$ mW, $f_{\text{rep}} = 216$ MHz
$\lambda_2 = 800$ nm, $\tau_2 = 100$ fs, $P_2 = 50$ mW, $f_{\text{rep}} = 81$ MHz

$\rightarrow \eta = 2\% \ @ \ d_0 = 50 \ \mu\text{m}, \ L_{\text{BBO}} = 0.5 \ \text{mm}$

$\rightarrow \eta = 0.5\% \ @ \ d_0 = 100 \ \mu\text{m}, \ L_{\text{BBO}} = 0.5 \ \text{mm}$
Layout of the two-wavelength OCC for Ti:Sapphire+EDFA

Ti:sapphire
- 0.6 nJ
- 81.25 MHz
- ~ 40 fs

EDFA:
- 0.25 nJ
- 216.66 MHz
- > 60 fs
Two-wavelength OCC
First setup and signals
First results from the optical cross-correlator

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Emphasis on the technical issues

- 50 mW input from the Ti:Sapphire
- Built-in piezo motors in commercial Ti:Sapphire might be “slow” for an optical lock: 50 kHz instead of 100 kHz
- The temporal overlap between the two wavelengths requires a tool for an automatic VM scan
- When the Ti:Sapphire is optically locked, the VM cannot be used anymore for temporal overlap with the machine → an extra delay stage is required
Summary

- A balanced two-wavelength cross-correlator with a BBO crystal has been designed
- Collinear propagation of 1550 nm and 800 nm, normal incidence on the BBO
- SFG, Type I interaction (ooe)...
  ...not background free, but:
  - has the highest efficiency
  - has the least walk off
  - BBO thicknesses up to 0.5 mm are possible
  - bandwidths up to 140 nm for $\lambda = 1550$ nm and 65 nm for $\lambda = 800$ nm are supported
- Experimental characterization is ongoing
- A robust “cage” system (ThorLABS™) retains the alignment over months
- Packaging is foreseen
- First error signals have been measured
- Short term (~ 5 min) optical lock of the Ti:Sapphire has been achieved
- Out-of-loop measurements with two prototypes are ongoing
Thank you for your attention!
Layout of the two-wavelength OCC for the injector laser

- **λ₂=1562 nm**
- **λ₁=1047 nm**
- telescope
- DM1 – dichroic mirror HT@ 1562±20nm HR@ 1047 nm, AOI=45°
- DM2 – dichroic mirror HT@ 1562±20nm & 1047 nm HR@ 627 nm, AOI=45°

<table>
<thead>
<tr>
<th>λ, nm</th>
<th>EDFA: 1550</th>
<th>Nd:YLF: 1047</th>
<th>SFG: 0.62489</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δλ, nm (FWHM)</td>
<td>17.67</td>
<td>0.0806</td>
<td>0.0287</td>
</tr>
<tr>
<td>τ, ps (FWHM)</td>
<td>0.2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>f, MHz</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>P, mW</td>
<td>30</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>E, nJ</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Ppeak, W</td>
<td>5555.56</td>
<td>740.74</td>
<td></td>
</tr>
<tr>
<td>no (principal axis)</td>
<td>1.6466</td>
<td>1.6548</td>
<td>1.6677</td>
</tr>
<tr>
<td>ne (principal axis)</td>
<td>1.5310</td>
<td>1.5395</td>
<td>1.5499</td>
</tr>
</tbody>
</table>

- weak focusing: d₀ ~ 0.4 mm
- expected efficiency ~ 2.5 %
Design of the two-wavelength optical cross-correlator: phase matching (some basics)

- optical axis (Z-axis)
- principal plane: containing Z and k
- ordinary (o) beam: with polarization normal to the principal plane
- extraordinary (e) beam: with polarization in the principal plane

\[ n_o - n_e \neq 0 \]

\( n_o, n_e \) – principal values
\( n_o > n_e \) – negative crystal
\( n_o > n_e \) – positive crystal
Design of the two-wavelength optical cross-correlator: phase matching (some basics)

vector (noncollinear):

\[ \vec{k}_3 = \vec{k}_2 \pm \vec{k}_1 \]

\[ |\vec{k}_i| = \frac{\omega_i n(\omega_i)}{c} = \frac{\omega_i}{\nu(\omega_i)} = \frac{2\pi n_i}{\lambda_i} = 2\pi n_i \nu_i \]

scalar (collinear):

\[ k_3 = k_2 \pm k_1 \Leftrightarrow \omega_3 n_3 = \omega_2 n_2 + \omega_1 n_1 \]

\[ k_3 = 2k_1, \quad \omega_3 = 2\omega_1, \quad n_1 = n_3 \]

for isotropic crystals \( n_1 < n_3 \) (normal dispersion)

need an anisotropic crystal and different polarizations

SFG, SHG
Design of the two-wavelength optical cross-correlator: types of phase matching in the uniaxial crystals

I. Interacting waves $\parallel$, result $\perp$

Type I$^-(\text{ooe})$, negative crystals

$$k_{o1} + k_{o2} = k_3^e(\theta)$$

Type I$^+(\text{eeo})$, positive crystals

$$k_1^e(\theta) + k_2^e(\theta) = k_{o3}$$

II. Interacting waves $\perp$, result $\parallel$ to one and $\perp$ to the other

Type II$^-(\text{ooe})$ or (eeo), negative crystals

$$k_{o1} + k_2^e(\theta) = k_3^e(\theta)$$

$$k_1^e(\theta) + k_{o2} = k_3^e(\theta)$$

Type II$^+(\text{ooe})$ or (eeo), positive crystals

$$k_{o1} + k_2^e(\theta) = k_{o3}$$

$$k_1^e(\theta) + k_{o2} = k_{o3}$$

works in both directions:
sum frequency generation (SFG) $\leftrightarrow$ optical parametric luminescence (OPO)

$$\omega_1(\text{idler}) < \omega_2(\text{signal}) < \omega_3(\text{pump})$$
Design of the two-wavelength optical cross-correlator: choice of the crystal

Geometric factors: cut angle

- the phase matching depends on $\Theta$, but not on $\phi$
- the conversion efficiency depends on both $\Theta$ and $\phi$
The refractive index of the extraordinary wave is a function of the polar angle $\Theta$ between the axis $Z$ and the vector $k$

$$n^e(\Theta) = n_0 \sqrt{\frac{1 + \tan^2(\Theta)}{1 + \left(n_o/n_e\right)^2 \tan^2(\Theta)}}$$
Sellmeier equations for $\beta$-BaB$_2$O$_4$ (BBO)


\[
\begin{align*}
n_o^2 &= 2.7359 + \frac{0.01878}{\lambda^2 - 0.01822} - 0.01354\lambda^2 \\
n_e^2 &= 2.3753 + \frac{0.01224}{\lambda^2 - 0.01667} - 0.01516\lambda^2
\end{align*}
\]

$n_o, n_e$ – principal values of the refractive index for BBO $n_o > n_e$ (a negative uniaxial crystal)
Calculation of the nonlinear conversion efficiency

\[ \Delta \vec{E}(\vec{r},t) + \frac{\varepsilon_0}{c^2} \frac{\partial^2 \vec{E}(\vec{r},t)}{\partial t^2} = - \frac{4\pi}{c^2} \frac{\partial^2 \vec{P}_{NL}(\vec{r},t)}{\partial t^2} \]

with \[ \vec{P}_{NL}(\vec{r},t) = \chi^{(2)} \vec{E}^2(\vec{r},t) \]
\[ \chi_{ijk} = 2d_{ijk} = 2d_{i(9-j-k)} \quad i, j, k \in [X, Y, Z] \]

The field is a superposition of three interacting waves:

\[ \vec{E}(\vec{r},t) = \frac{1}{2} \sum_{i=1}^{3} \{ \vec{p}_i A_i(\vec{r},t) \exp[j(\omega_i t - \vec{k}_i \cdot \vec{r})] + CC \} \]

Assume slowly varying amplitudes → truncated equations:

\[ \hat{M}_1 A_1 = j\sigma_1 A_3 A_2^* \exp(j\Delta k z), \]
\[ \hat{M}_2 A_2 = j\sigma_2 A_3 A_1^* \exp(j\Delta k z), \]
\[ \hat{M}_3 A_3 = j\sigma_3 A_1 A_2 \exp(-j\Delta k z). \]

\[ \sigma_\xi, \Delta k, \hat{M}_\xi \to \]
Calculation of the nonlinear conversion efficiency

\[ \hat{M}_\xi = \frac{\partial}{\partial z} + \rho \frac{\partial}{\partial x} + \frac{j}{2k_\xi} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) + \frac{1}{u_{g,\xi}} \frac{\partial}{\partial t} + 2g_\xi(\lambda, \Theta) \frac{\partial^2}{\partial t^2} + \delta_\xi + Q_\xi(A) \]

- \( \sigma \) - non-linear coupling coefficients
- \( \Delta k \) – wave mismatch (spatial, thermal self-focusing, non-linear absorption, etc.)
- \( \rho \) - walk-off angle
- \( u_g \) – group velocity
- \( g \) – group velocity dispersion (GVD)
- \( \delta \) - linear absorption
- \( Q \) – nonlinear (e.g. two-photon) absorption

\[ \begin{align*}
\sigma_{1,2} &= \frac{4\pi k_{1,2} d_{eff}}{n_{1,2}^2} \\
\sigma_3 &= \frac{2\pi k_3 d_{eff}}{n_3^2}
\end{align*} \]
Non-linear conversion effective lengths $L_{\text{eff}}$

Fixed field approximation (FFA): $L < L_{\text{eff}}$

1. Aperture length ($2^{\text{nd}}$ term) (influence on the focal spot size)

   \[ L_a = \frac{d_0}{\rho} \]

2. Diffraction length ($3^{\text{rd}}$ term) (the length over which a gaussian beam would spread by $\sqrt{\rho}$)

   \[ L_{\text{diff}} = k d_0^2 \]

3. Quasi-static length ($4^{\text{th}}$ term) (influence of the group velocity mismatch)

   \[ L_{qs} = \frac{\tau}{u_{g,1} - u_{g,2}} \]

4. Dispersive spread length ($5^{\text{th}}$ term) (influence of the dispersion on the pulse shape)

   \[ L_{\text{dis}} = \frac{\tau^2}{g(\lambda, \Theta)} \]

5. Non-linear interaction length (influence of the input power and the non-linear coupling)

   \[ L_{NL} = \frac{1}{\sigma \sqrt{a_1^2(0) + a_2^2(0) + a_3^2(0)}} \]