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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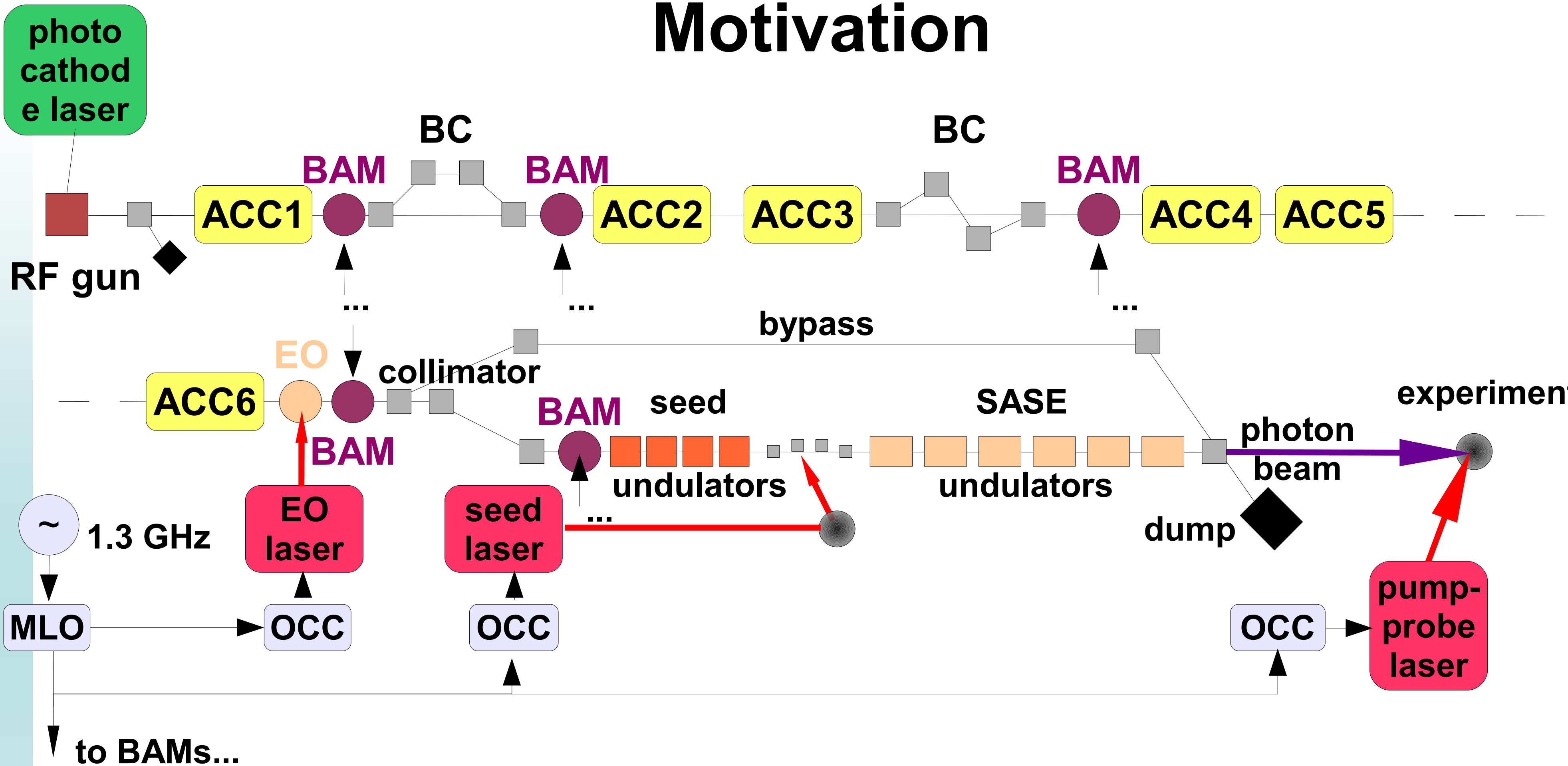
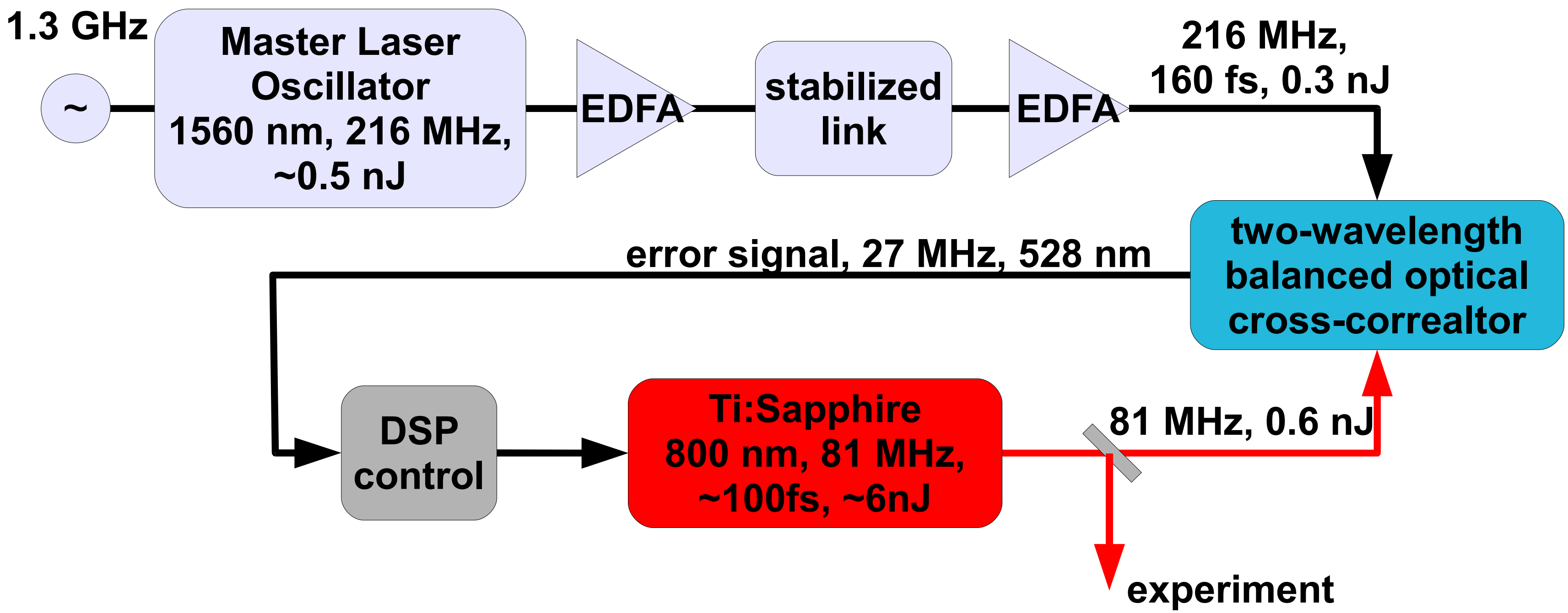
Motivation



- 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

Layout of the two-wavelength laser synchronization



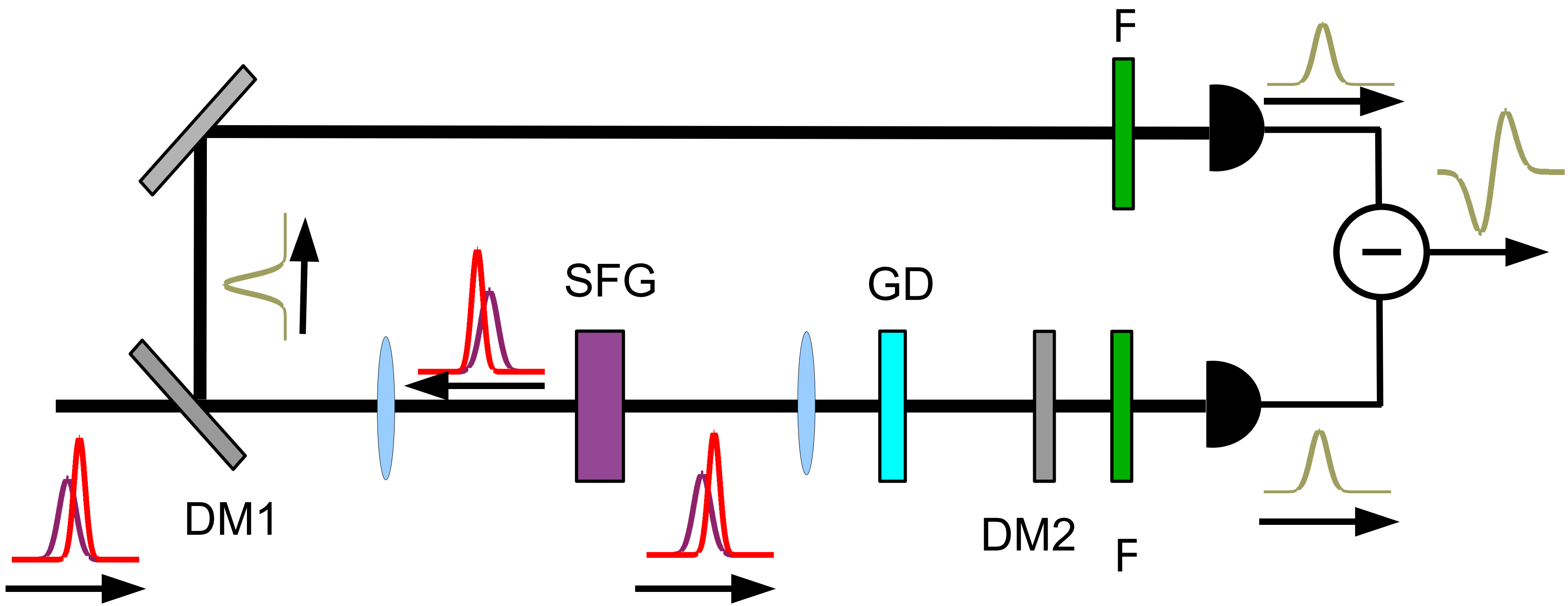
Input in the OCC from the diagnostic laser:

λ_1 = 800 nm, $\delta\lambda_1$ = ~60 nm, τ_1 ~100 fs, P_1 ~ 50 mW, f_{rep} = 81 MHz

Input in the OCC from the link:

λ_2 = 1560 nm, $\delta\lambda_1$ = ~70 nm, τ_1 ~200 fs, P_1 ~ 15 mW, f_{rep} = 216 MHz

Layout of the balanced detection set-up



DM1 – dichroic mirror HT@ λ_1 and λ_2, HR @ λ_{SF}

DM2 – dichroic mirror HR@ λ_1 and λ_2, HT @ λ_{SF}

SFG – non-linear crystal, e.g. BBO

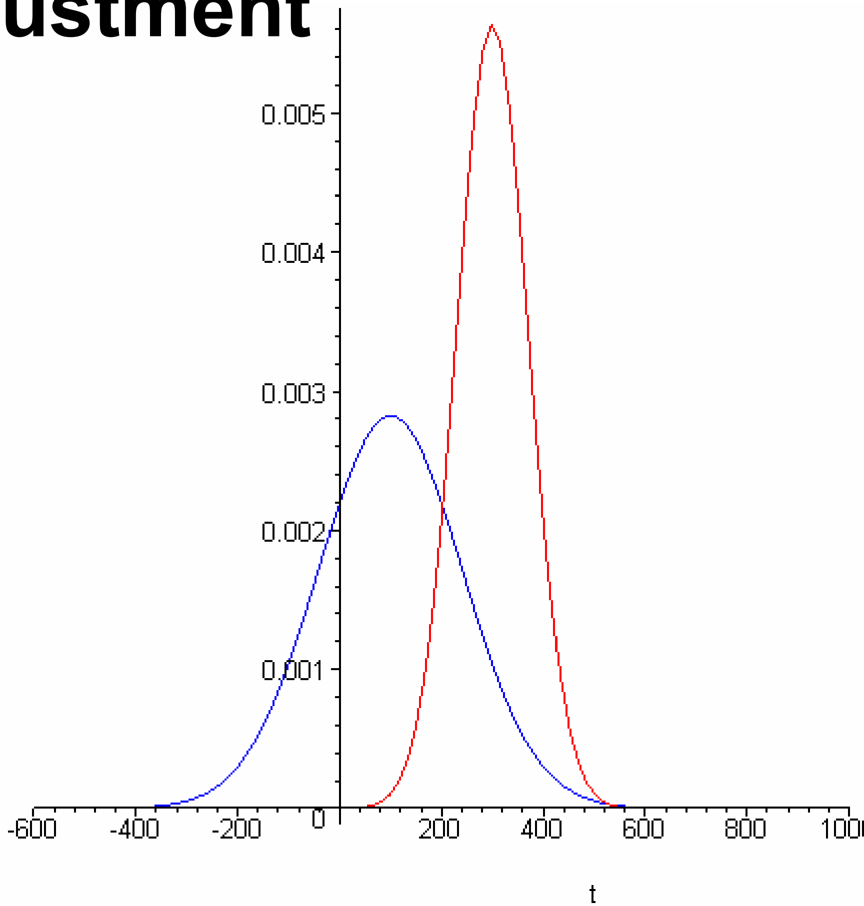
GD – group delay adjustment

F – band pass filter, HT @ λ_{SF}

Design of the two-wavelength optical cross-correlator: group delay adjustment

Assume Gaussian pulses

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



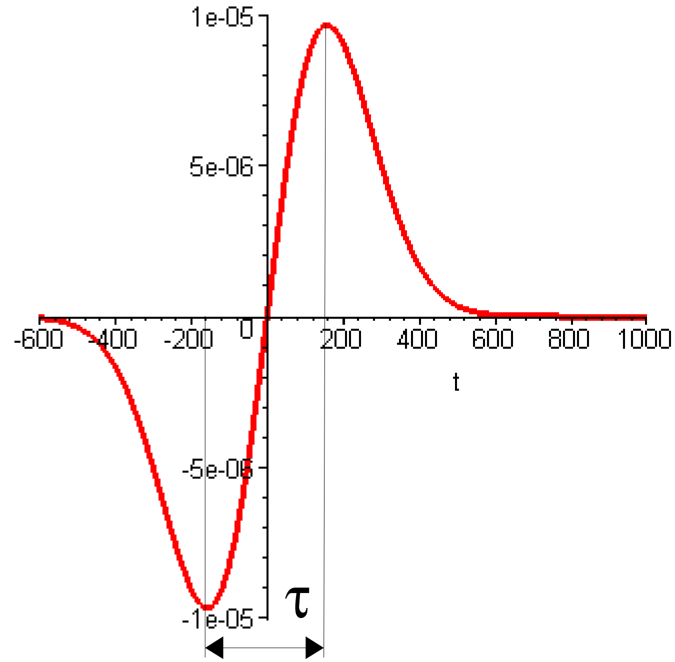
The convolution of two Gaussian pulses is also a Gaussian pulse:

$$I_i(t) = I_1 * I_2 = \int_{-\infty}^{\infty} I_1(\tau) \cdot I_2(t-\tau)\, d\tau = \frac{1}{\sqrt{\pi(\sigma_1^2+\sigma_2^2)}} \exp\left(-\frac{(t-t_1-t_2)^2}{\sigma_1^2+\sigma_2^2}\right)$$

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:

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



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

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

Ti:Sa + EDFA: τ_1 = 100 fs and τ_2= 200 fs: τ = 190 fs
→ need a 65 - 80 fs additional delay: a double pass through a 2 – 3 mm silica slab

Nd:YLF + EDFA: τ_1 = 11 ps and τ_2= 200 fs: τ = 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

<u>Parameters to calculate:</u>
- 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:
Handbook of nonlinear optical crystals, Dimitriev V.G., Gurzadyan G.G., Nikogosyan D.N., Springer Series of Optical Sciences, vol 64 (1999)

Geometric factors:
- phase matching
- cut angle
- crystal thickness
- focusing

Phase matching angles for BBO

λ_1 = 1550 nm, λ_2 = 800 nm, λ_{SFG} = 528 nm

Type $I^{(-)}$(ooe): Θ = 22.2°
Type $II^{(-)}$(eoe): Θ = 27.2°
Type $II^{(-)}$(oee): Θ = 38.8°

Phase velocities in BBO

$V_{Ph} = c / n(\lambda,\Theta)$ $\xrightarrow{\text{Type } I^{(-)}\text{(ooe)}}$

$n(\lambda = 1550, \Theta = 0°) = 1.647$
$n(\lambda = 800, \Theta = 0°) = 1.661$
$n(\lambda = 528, \Theta = 0°) = 1.656$

$$n^e(\Theta) = n_0 \sqrt{\frac{1 + \tan^2(\Theta)}{1 + (n_o/n_e)^2 \tan^2(\Theta)}}$$

Group velocities in BBO

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

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

Type I$^{(-)}$(ooe):

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

$$\tilde{n}(\lambda = 800, 0^\circ) = 1.684$$

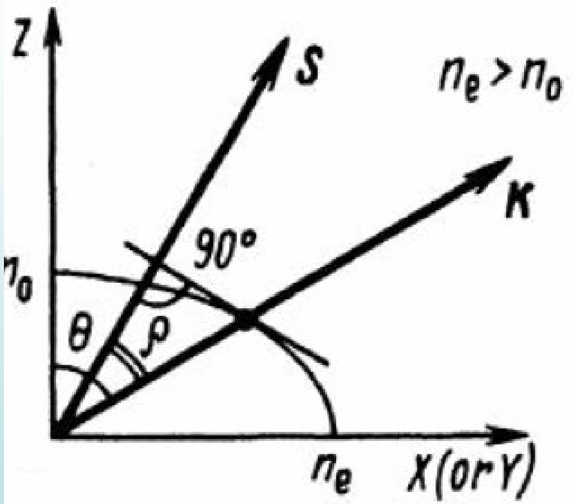
$$\tilde{n}(\lambda = 528, 22.2^\circ) = 1.702$$

Relative group delay:

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

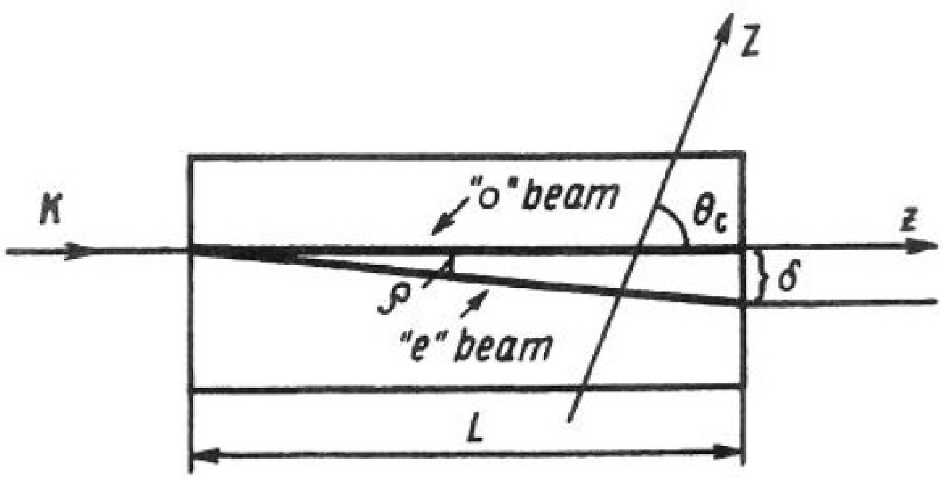
Type I$^{(-)}$(ooe): $\tau_g(\lambda_1 = 1550, \lambda_2 = 800) = -0.44 \quad fs/mm$

Walk-off angles for BBO



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

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



linear walk-off:

$$\delta = L \tan \rho$$

Type I(-)(ooe):

$$\rho(528, 22.2^\circ) = 54.7 \quad mrad$$

Type II(-)(eoe):

$$\rho(1550, 27.2^\circ) = 61.7 \quad mrad$$

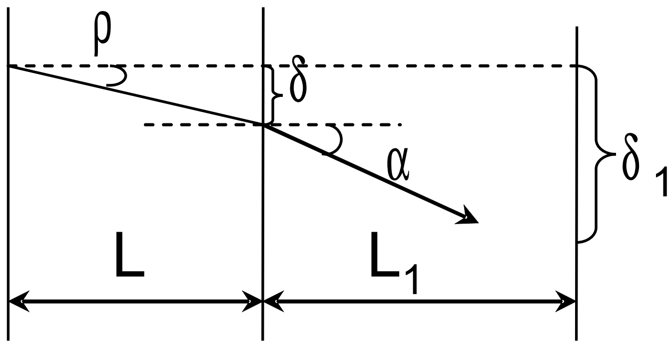
$$\rho(528, 27.2^\circ) = 62.9 \quad mrad$$

Type II(-)(oee):

$$\rho(800, 38.8^\circ) = 71.8 \quad mrad$$

$$\rho(528, 38.8^\circ) = 73.4 \quad mrad$$

Beam walk-off



Type I(-)(ooe):
λ = 528 nm,
Θ = 22.2°

$$\rho = 54.7 \quad mrad$$
$$\delta = 54.7 \quad \mu m / mm$$
$$\alpha = 5^{\circ}$$
$$\delta_1 = 100 \quad \mu m / mm$$

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^{eff} [pm/V] for point group 3m

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

Type II $$d_{eoe}^{eff} = d_{oee}^{eff} = d_{22}\cos^2(\Theta+\rho)\cos(3\phi)$$

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

1) Handbook of nonlinear optical crystals, Dimitriev V.G., Gurzadyan G.G., Nikogosyan D.N., Springer Series of Optical Sciences, vol 64 (1999)
   d_{22} = 2.3 pm/V; d_{31} = 0.16 pm/V;
2) Eimerl et al, J.Appl.Phys. 62(5), pp.1968-1983 (1967)
   d_{22} = 1.6 pm/V; d_{31} = 0.08 pm/V
3) Eckard et al, IEEE-QE, vol 26, Nr.5, pp.922-933 (1990)
   d_{22} = 2.2 pm/V; d_{31} = ??? pm/V
4) SNLO
   d_{22} = 2.2 pm/V; d_{31} = 0.08 pm/V

Type I

$$d_{ooe}^{eff}(2.3\ pm/V, 0.16\ pm/V, 22.2^{\circ}, 528\ nm) = 2.15\ pm/V$$

$$d_{ooe}^{eff}(2.2\ pm/V, 0.08\ pm/V, 22.2^{\circ}, 528\ nm) = 2.02\ pm/V$$

Type II

$$d_{eoe}^{eff}(2.2\ pm/V, 27.2^{\circ}, 528\ nm) = 1.62\ pm/V$$

$$d_{oee}^{eff}(2.2\ pm/V, 38.8^{\circ}, 528\ nm) = 1.18\ pm/V$$

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

Tables 2.20 and 2.21, *Handbook of nonlinear optical crystals, Dimitriev V.G., Gurzadyan G.G., Nikogosyan D.N., Springer Series of Optical Sciences, vol 64 (1999)*

Example: Type I (ooe)

$$\Delta \nu_2 = \frac{0.886}{L}\left| n_{o2} - n_3^e(\Theta) - \lambda_2 \frac{\partial n_{o2}}{\partial \lambda_2} + \lambda_3 \frac{\partial n_3^e(\Theta)}{\partial \lambda_3} \right|^{-1}$$

Mix acceptance BW for 0.5 mm BBO

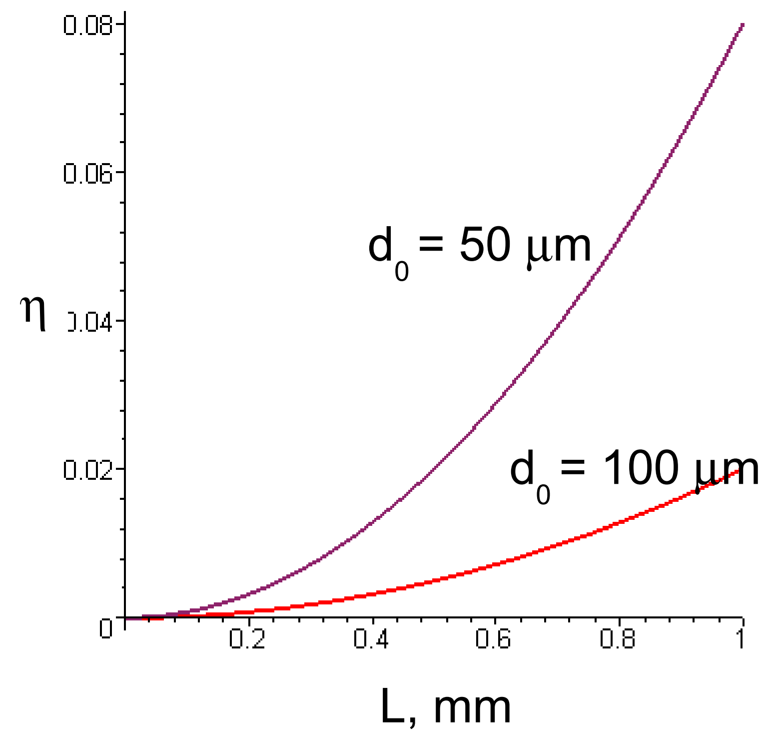
	$\lambda = 1550$ nm	$\lambda = 800$ nm
ooe	$\Delta\lambda = 139$ nm	$\Delta\lambda = 65$ nm
eoe	$\Delta\lambda = 91$ nm	$\Delta\lambda = 161$ nm
oee	$\Delta\lambda = 631$ nm	$\Delta\lambda = 35$ nm

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:

- $\eta(L) < 1$
- $L < L_{eff}$



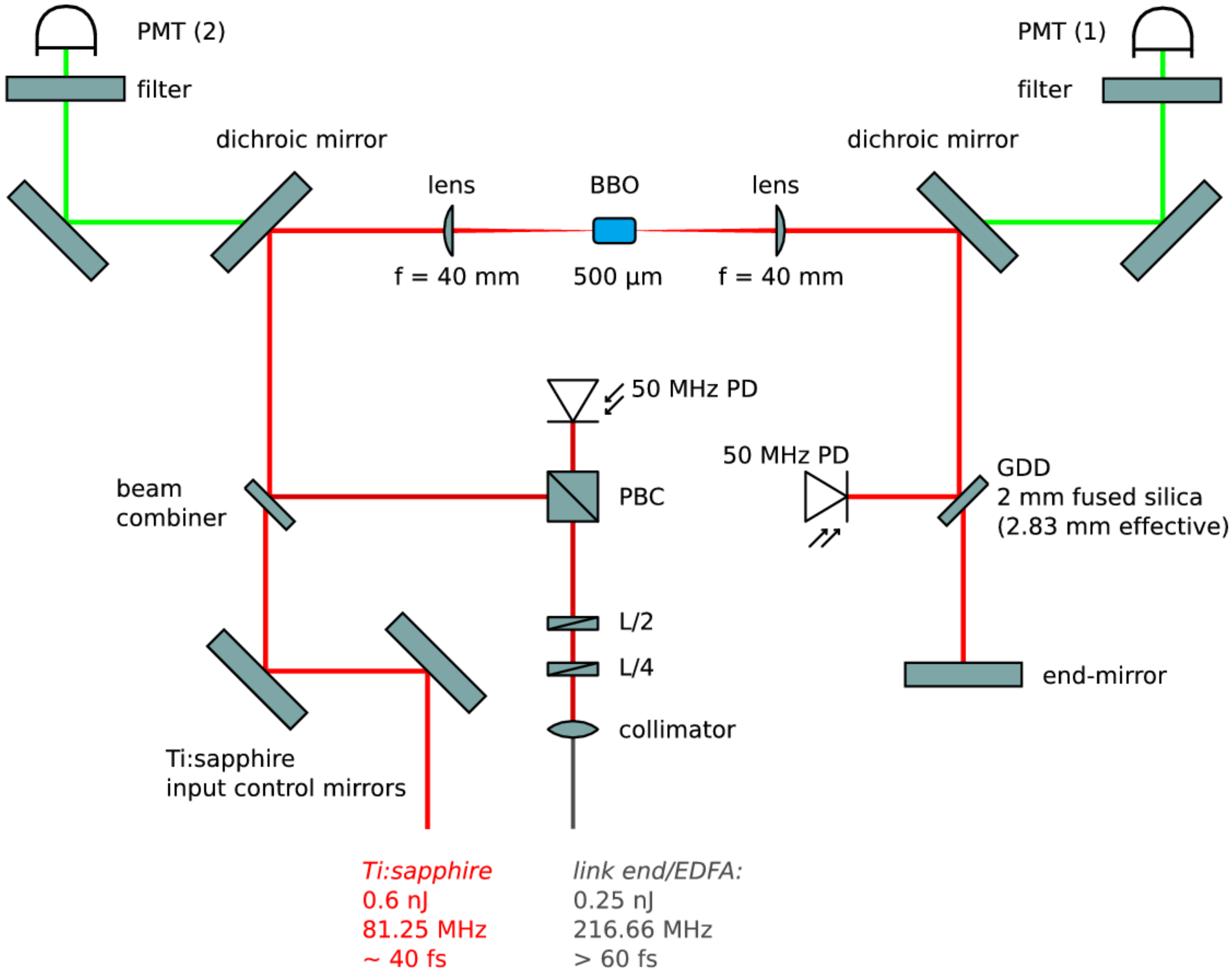
$\lambda_1 = 1550$ nm, $\tau_1 = 200$ fs, $P_1 = 15$ mW, f_{rep} =216 MHz

$\lambda_2 = 800$ nm, $\tau_2 = 100$ fs, $P_2 = 50$ mW, $f_{rep} = 81$ MHz

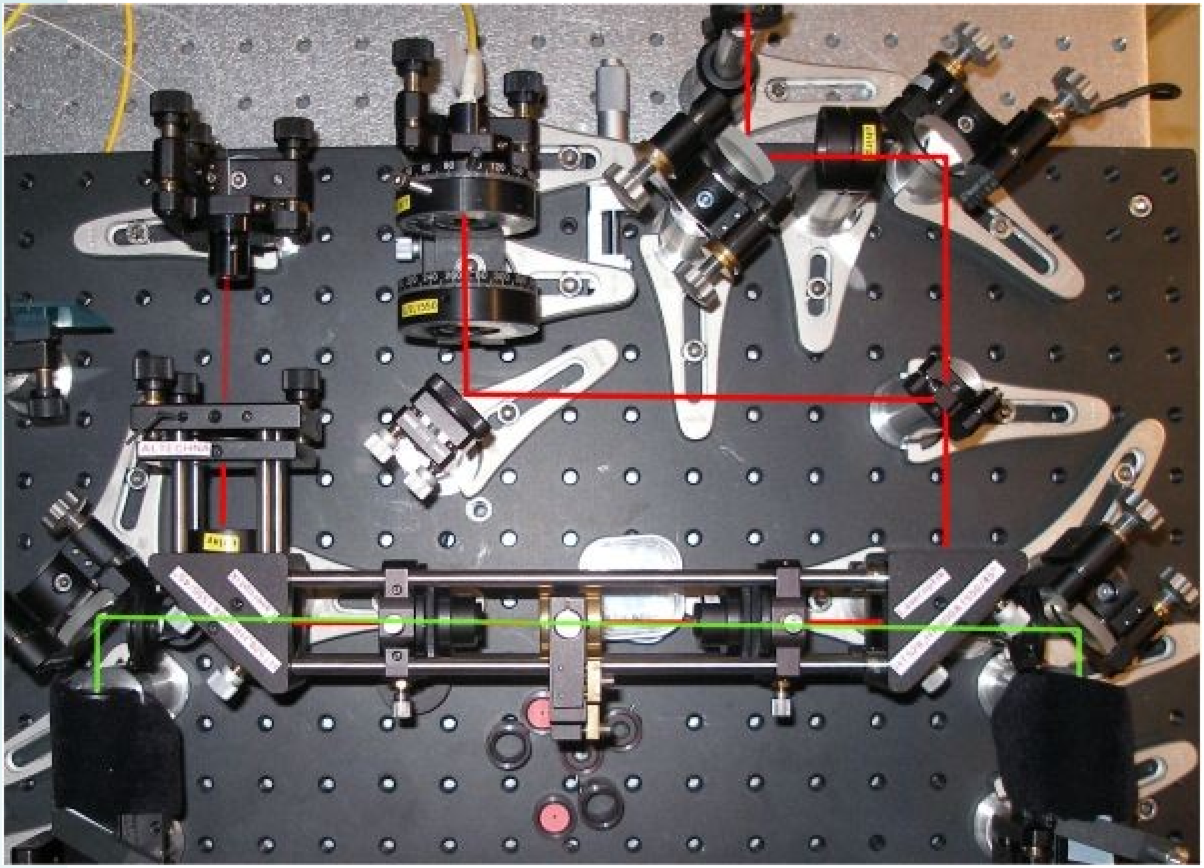
→ $\eta = 2\%$ @ $d_0 = 50\ \mu m$, $L_{BBO} = 0.5$ mm

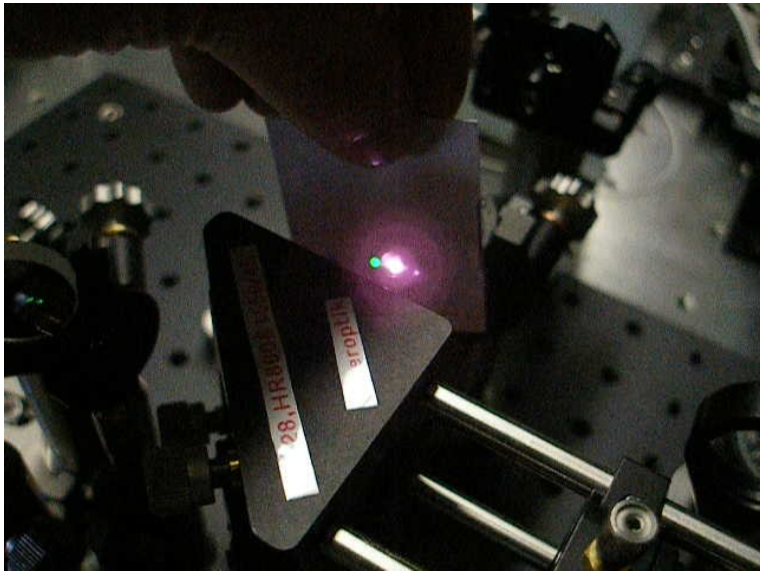
→ $\eta = 0.5\%$ @ $d_0 = 100\ \mu m$, $L_{BBO} = 0.5$ mm

Layout of the two-wavelength OCC for Ti:Sapphire+EDFA

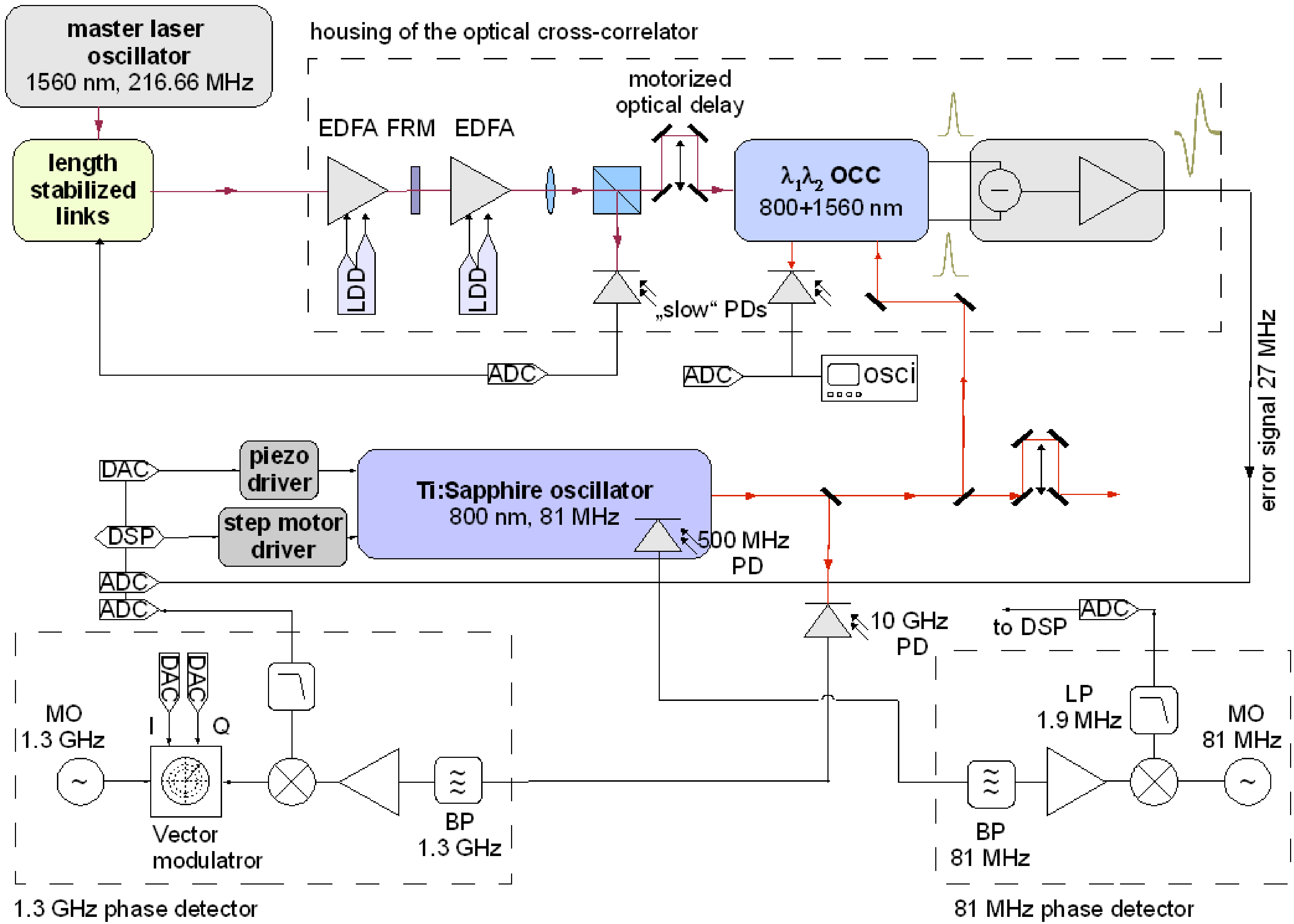


Two-wavelength OCC
First setup and signals

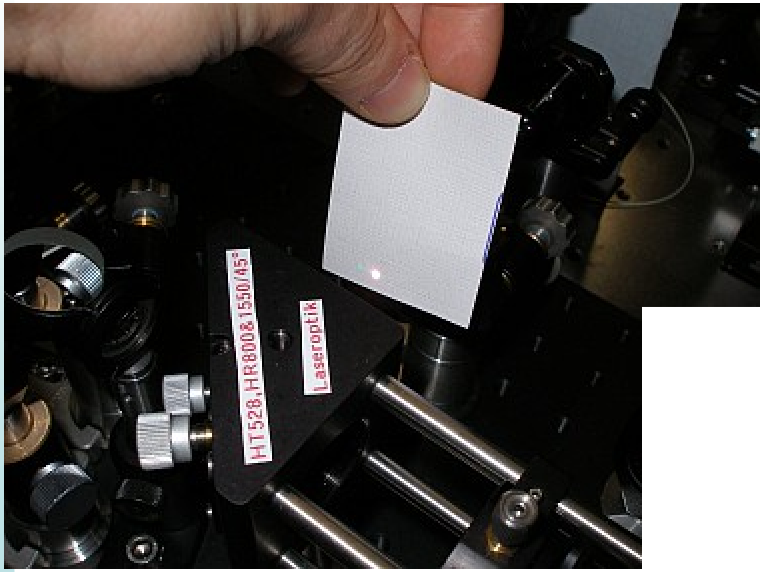


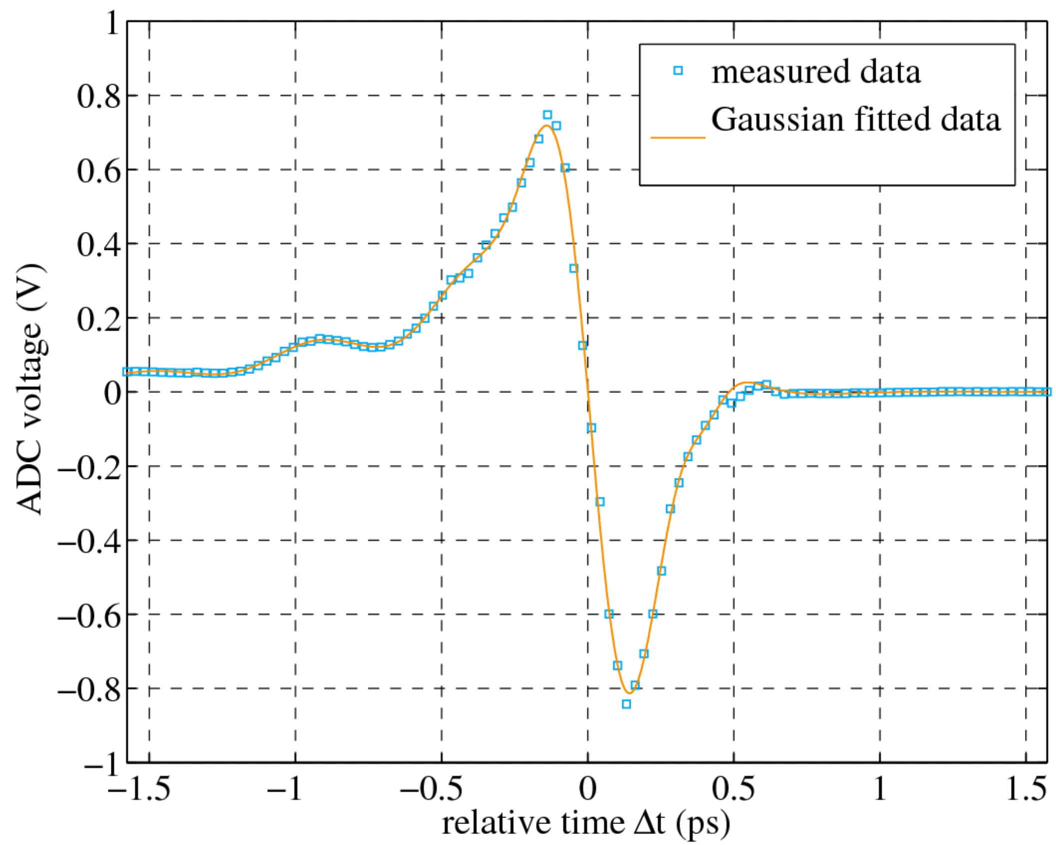


Layout of the Ti:Sa RF and optical synchronization



First results from the optical cross-correlator





Emphasis on the technical issues

- 50 mW input from the Ti:Saphire
- 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

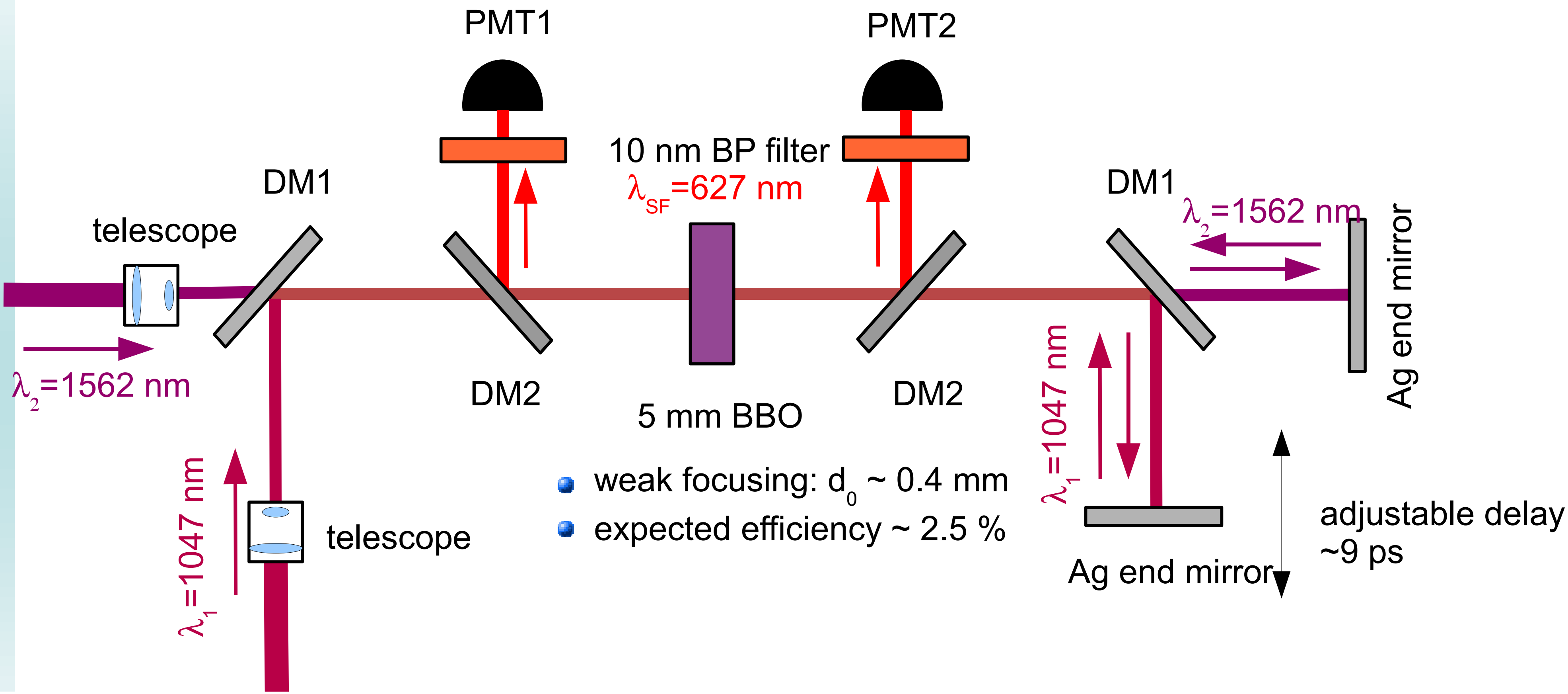
- A balanced two-wavelength cross-correlator with a BBO crystal has been designed
- Collinear propagation of 1550 nm and 800 nm, normal incidence on the BBO
- SFG, Type I interaction (ooe)...

  ...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 λ =1550 nm and 65 nm for λ = 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:Saphhire 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



- weak focusing: d_0 ~ 0.4 mm
- expected efficiency ~ 2.5 %

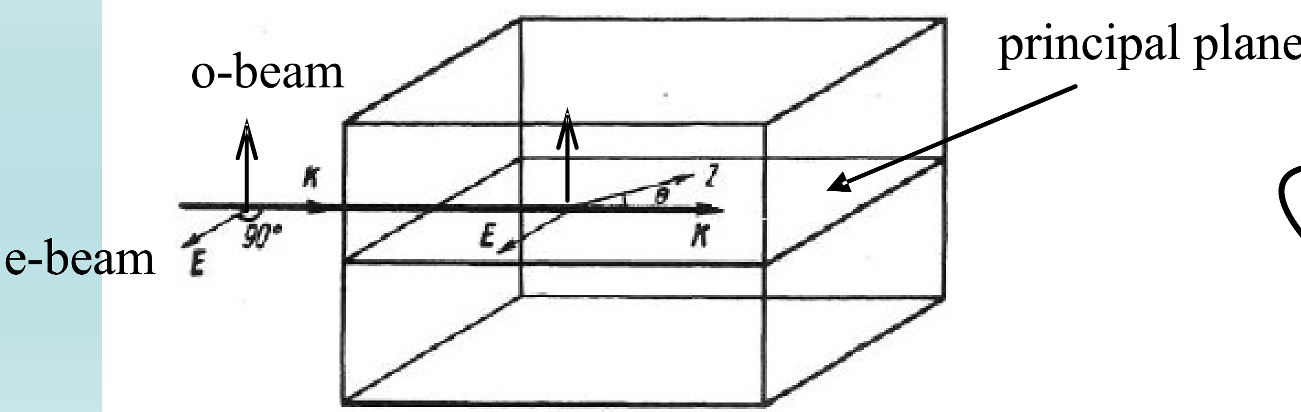
	EDFA:	Nd:YLF	SFG
λ, nm	1550	1047	0.62489
Δλ, nm (FWHM)	17.67	0.0806	0.0287
τ, ps (FWHM)	0.2	20	20
f, MHz	27	27	27
P, mW	30	400	
E, nJ	1	15	
Ppeak, W	5555.56	740.74	
no (principal axis)	1.6466	1.6548	1.6677
ne (principal axis)	1.5310	1.5395	1.5499

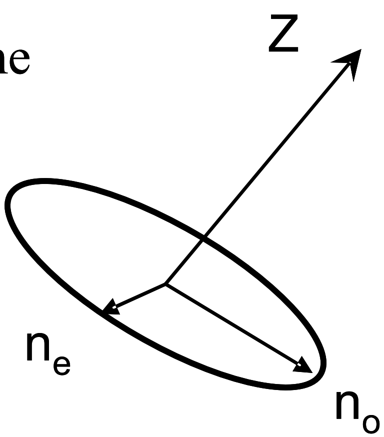
DM1 – dichroic mirror HT@ 1562±20nm
HR@ 1047 nm, AOI=45°

DM2 – dichroic mirror HT@ 1562±20nm & 1047 nm
HR@ 627 nm, AOI=45°

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***

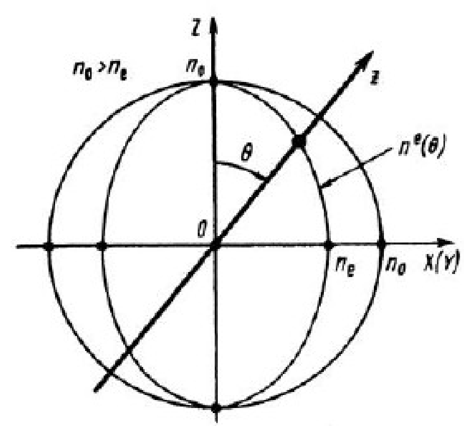


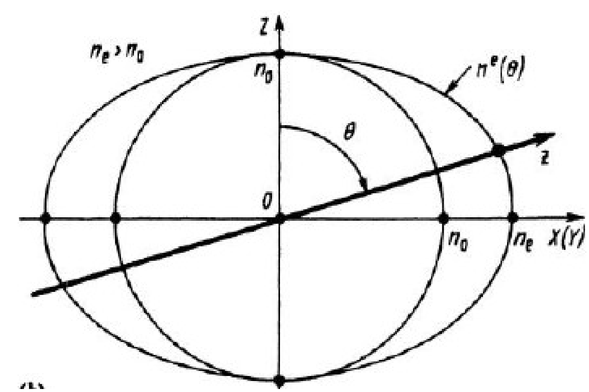


birefringence:

$$n_o - n_e \neq 0$$

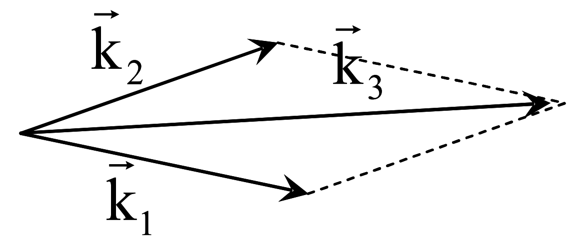
n_o, n_e – principal values
$n_o > n_e$ – negative crystal
$n_o > n_e$ – positive crystal





Design of the two-wavelength optical cross-correlator: phase matching (some basics)

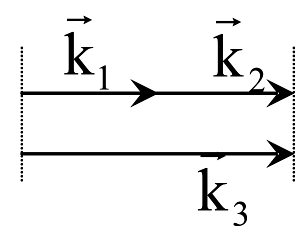
vector (noncollinear):



$$\vec{k}_3 = \vec{k}_2 \pm \vec{k}_1$$

$$\left|\vec{k}_i\right| = \frac{\omega_i n(\omega_i)}{c} = \frac{\omega_i}{v(\omega_i)} = \frac{2\pi n_i}{\lambda_i} = 2\pi n_i \nu_i$$

scalar (collinear):



SFG, SHG

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

$$k_3 = 2k_1, \quad \omega_3 = 2\omega_1, \quad n_1 = n_3$$

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

need an anisotropic crysatal and different polarizations

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

I. Interacting waves ||, result ⊥

II. Interacting waves ⊥, result || to one and ⊥ to the other

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

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

Type II$^{(-)}$(oee) or (eoe) , negative crystals

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

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

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

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

Type II$^{(+)}$(oeo) or (eoo) , positive crystals

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

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

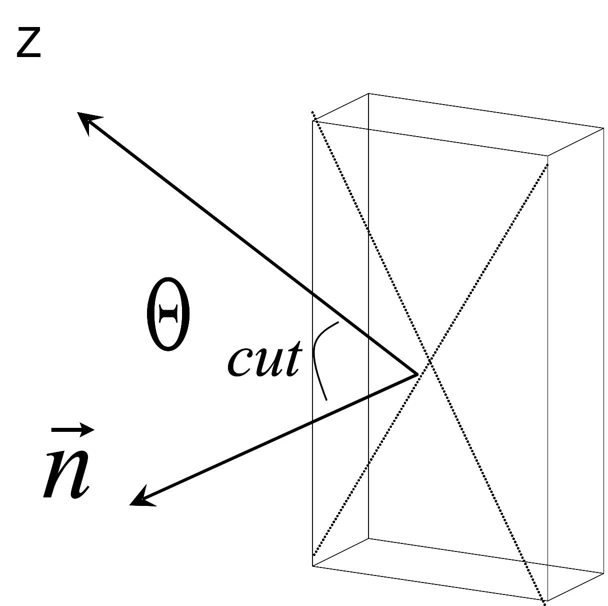
works in both directions:
sum frequency generation (SFG) ↔ optical parametric luminescence (OPO)

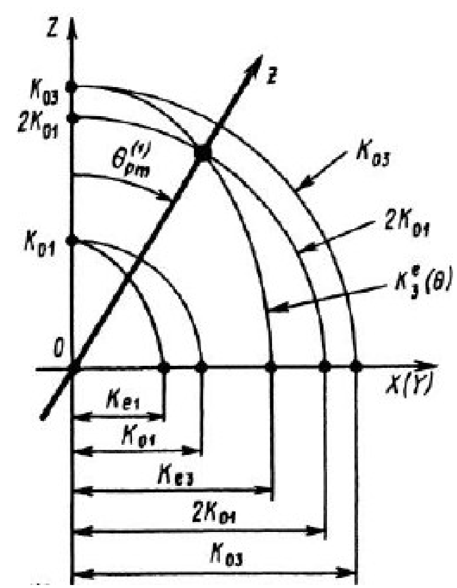
$$\omega_1(idler) < \omega_2(signal) < \omega_3(pump)$$

Design of the two-wavelength optical cross-correlator: choice of the crystal

Geometric factors:cut angle

- the phase matching depends on Θ, but not on ϕ
- the conversion efficiency depends on both Θ and ϕ

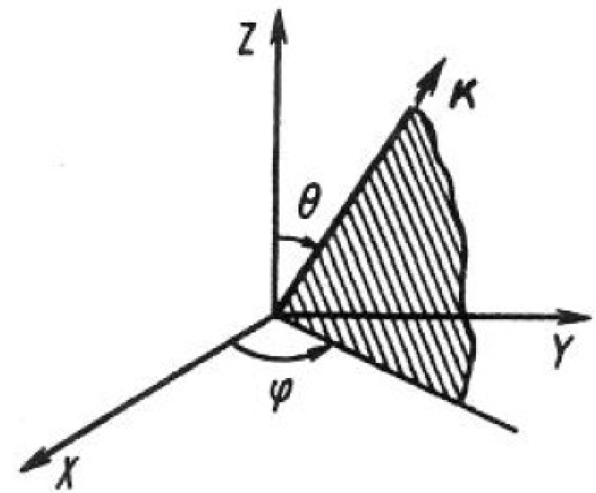




Design of the two-wavelength optical cross-correlator: choice of the crystal

The refractive index of the extraordinary wave is a function of the polar angle Θ between the axis Z and the vector *k*

$$n^e(\Theta) = n_0 \sqrt{\frac{1 + \tan^2(\Theta)}{1 + (n_o/n_e)^2 \tan^2(\Theta)}}$$

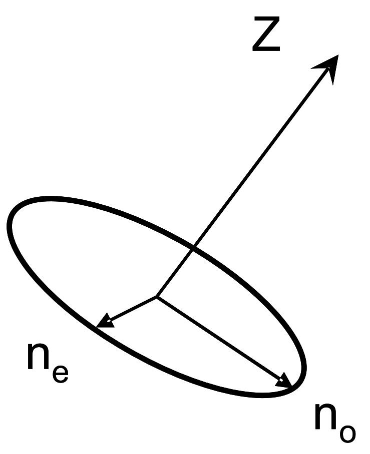


Sellmeier equations for β-BaB_2O_4 (BBO)

K. Kato IEEE-QE, vol.22, No7, pp.1013-1014 (1986)

$$n_o^2 = 2.7359 + \frac{0.01878}{\lambda^2 - 0.01822} - 0.01354\lambda^2$$

$$n_e^2 = 2.3753 + \frac{0.01224}{\lambda^2 - 0.01667} - 0.01516\lambda^2$$



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 $\vec{P}_{NL}(\vec{r},t) = \chi^{(2)}\vec{E}^2(\vec{r},t)$ $\qquad \chi_{ijk} = 2d_{ijk} = 2d_{i(9-j-k)}$ $\quad i,j,k \in \begin{bmatrix} X & Y & Z \\ \text{١} & \text{٢} & \text{٣} \end{bmatrix}$

The field is a superposition of three interacting waves:

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

Assume slowly varying amplitudes → truncated equations:

$$\hat{M}_1 A_1 = j\sigma_1 A_3 A_2^* \exp(j\Delta kz),$$

$$\hat{M}_2 A_2 = j\sigma_2 A_3 A_1^* \exp(j\Delta kz),$$

$$\hat{M}_3 A_3 = j\sigma_3 A_1 A_2 \exp(-j\Delta kz).$$

where $\sigma_\xi, \Delta k, \hat{M}_\xi \rightarrow$

Calculation of the nonlinear conversion efficiency

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

- σ - non-linear coupling coefficients ← $\begin{cases} \sigma_{1,2} = 4\pi k_{1,2} d_{eff} / n_{1,2}^2 \\ \sigma_3 = 2\pi k_3 d_{eff} / n_3^2 \end{cases}$
- Δk – wave mismatch (spatial, thermal self-focusing, non-linear absorption, etc.)
- ρ - walk-off angle
- u_g – group velocity
- g – group velocity dispersion (GVD)
- δ - linear absorption
- Q – nonlinear (e.g. two-photon) absorption

Non-linear conversion effective lengths L_{eff}

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

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

$$L_a = d_0 / \rho$$

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

$$L_{diff} = k d_0^2$$

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

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

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

$$L_{dis} = \tau^2 / g(\lambda, \Theta)$$

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

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