



Generation of broadband near-infrared pulses from multipass optical parametric amplification

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Abstract

Here amplification of near-IR pulses with central wavelength $1.6\ \mu\text{m}$ and bandwidth around $1000\ \text{nm}$ through optimized 3 stages of optical parametric amplification in BBO crystals is presented. After the second stage those pulses were compressed to almost transform limit duration, resulting $7.6\ \text{fs}$ which corresponds to a little bit more than one optical cycle.

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1 Theory

The interaction of an optical wave with matter is expressed by polarization \mathbf{P} . It is a vector field and describes response of a medium to an incident field. In the linear optics approximation which is valid for weak applied electric field the polarization is aligned with and proportional to it

$$\mathbf{P} = \chi \mathbf{E} \quad (1)$$

where χ is the dielectric susceptibility, \mathbf{E} is the electric field of the wave.

As field grows, the relation (1) is not satisfied. If $|\mathbf{E}|$ is not too large we can represent χ as a Taylor series, then the polarization becomes

$$\mathbf{P} = \chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E} \mathbf{E} + \chi^{(3)} \mathbf{E} \mathbf{E} \mathbf{E} + \dots \quad (2)$$

where the first term is linear and the others are nonlinear components of the polarization. It should be noted that $\chi^{(1)}$, $\chi^{(2)}$, \dots are tensors of the second, third and so on ranks respectively. The even terms are existing only in anisotropic non-centrosymmetric crystals. Indeed, if a medium is isotropic, or has a center of symmetry, then when the direction of the applied electric field \mathbf{E} changes the polarization \mathbf{P} should change sign. To satisfy this requirement, even terms in the expression (2) should be absent, which corresponds to $\chi^{(2)} = 0$.

In general, the interaction by n -order nonlinear polarization will lead to $(n+1)$ -wave mixing. Let's consider an input field is made up by two monochromatic plane wave interacting with medium which possess only second-order nonlinearity

$$E(z, t) = \frac{1}{2} E_1 e^{i(\omega_1 t - k_1 z)} + \frac{1}{2} E_2 e^{i(\omega_2 t - k_2 z)} + \text{c.c.} \quad (3)$$

Substituting this expression in $\mathbf{P}^{(2)}$ we obtain

$$\begin{aligned} \mathbf{P}^{(2)} = \chi^{(2)} E^2(z, t) = \frac{\chi^{(2)}}{4} \Big\{ & E_1^2 e^{i2(\omega_1 t - k_1 z)} + E_2^2 e^{i2(\omega_2 t - k_2 z)} + 2E_1 E_2 e^{i[(\omega_1 + \omega_2)t - (k_1 + k_2)z]} \\ & + 2E_1 E_2^* e^{i[(\omega_1 - \omega_2)t - (k_1 - k_2)z]} + |E_1|^2 + |E_2|^2 + \text{c.c.} \Big\} \quad (4) \end{aligned}$$

As you can see it contains different components with frequencies $2\omega_1$, $2\omega_2$, $\omega_1 - \omega_2$, $\omega_1 + \omega_2$ and 0. These three-wave mixing processes correspond to the nonlinear effects known as second-harmonic generation (SHG) of the respective fields, sum-frequency generation

(SFG), difference-frequency generation (DFG) and optical rectification respectively.

The optical parametric amplification (OPA) is based on difference-frequency generation. The main idea of this process is a strong field with frequency ω_p , named *pump* amplify a weak field with the required frequency ω_s , named *signal* ($\omega_p > \omega_s$). To satisfy the energy conservation (5) another field with frequency ω_i , named *idler*, should be generated

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i \quad (5)$$

But it is not enough to effective DFG. This process becomes more effective in the case if incoming wave from part of a nonlinear space has the same phase as a wave produced by this part. The intensity of DFG increases by several orders of magnitude through its accumulation occurs over the entire length of the nonlinear medium. Such situation is realized if momentum conservation or *phase-matching condition* holds

$$\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i \quad (6)$$

It is the most important condition for nonlinear phenomena.

We can rewrite relation (6) in terms wavelength and refractive index

$$\frac{2\pi}{\lambda_p}n_p = \frac{2\pi}{\lambda_s}n_s + \frac{2\pi}{\lambda_i}n_i \quad (7)$$

In materials with normal dispersion the refractive index decreases with the wavelength, that is $n_p > n_s > n_i$ for $\lambda_p < \lambda_s < \lambda_i$. In this case phase-matching condition implies that

$$0 < \frac{1}{\lambda_p}(n_p - n_s) = \frac{1}{\lambda_i}(n_i - n_s) < 0 \quad (8)$$

This relation proves that it is impossible to satisfy (8) in materials with normal dispersion.

However phase-matching condition can be satisfied in a birefringent crystals, where the refractive index depends on the polarization and direction of the light that passes through. Typically a crystal has three axes which has one, two or three different refractive indexes. In the case of uniaxial crystals two equal indexes are called ordinary (n_o), the other one is called extraordinary (n_e). If $n_e < n_o$ the crystal is called negative, if $n_e > n_o$ is called positive. It means that we can choose direction of light propagation to fulfill (8). In this case the angle between optical axis of crystal and interacting wave

vectors is called *the phase-matching angle*.

Depending on the propagation direction of the three waves involved in a second order nonlinear process, we can define two types of phase-matching configurations:

- Type I, when the two beams with lower frequencies are linearly polarized on parallel directions. The two possibility are $o + o \rightarrow e$ and $e + e \rightarrow o$, where o means parallel to the ordinary axis, and e means parallel to extraordinary axis
- Type II, when the two beams with lower frequencies are linearly polarized on perpendicular directions. The four possibility are $o + e \rightarrow e$, $e + o \rightarrow e$, $e + o \rightarrow o$ and $o + e \rightarrow o$.

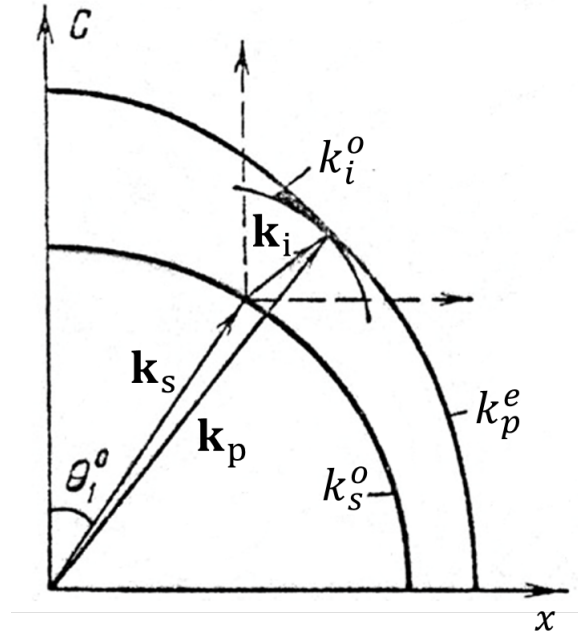


Figure 2: The illustration of type 1 phase-matching condition in birefringent crystal. C is optical axis.

2 Experimental part

2.1 Optical parametric amplification

The main facility is a Kerr-lens mode-locked Ti:Sa Laser, which produces 150 fs pulses with 800 nm central wavelength, about 10 mJ energy, 1 kHz of repetition rate. In the entrance of the device there is a beam splitter with 70% of reflectance: 7 mJ goes to the third stage of OPA directly, a little part goes to the first two stages, another part is sent to individual OPA to produce carrier-envelope-phase (CEP) stable idler pulse with 1020 nm wavelength. This pulse is focused on glass of 3 mm thickness by 125 mm focal length lens. Here white light generation (WLG), also known as supercontinuum generation process occurs, which holds when all of nonlinear processes act together upon a pump beam, dramatically enhancing spectral broadening. After that white pulses are focused on 1.5 mm of barium borate (BBO) crystal. Further we will call them seed. Simultaneously a tiny part of the pump about 40 μJ is focused in the same crystal leading to overlapping with seed in the crystal both in time and in space, resulting in the first stage of optical parametric amplification, which is schematically illustrated on Fig. 3. Depending on the angle between pump pulses and the optical axis of the crystal, and on the temporal overlapping between pump and seed pulses, it is possible to amplify different wavelengths of the seed pulses. In the crystal first type ($o + o \rightarrow e$) of nonlinear processes occurs, pump is incident at the angle of 19.8° to optical axis. We obtained amplified pulses with 1.5 μJ of energy from first stage with central wavelength 1.6 μm and bandwidth from 1.2 μm to 2.2 μm . This spectrum is illustrated in Fig. 4.

The second stage of OPA amplifies signal pulses generated in the first stage making use of 700 μJ of the pump through focusing them on BBO of 1.5 mm thickness. On output after this stage we obtain 60 μJ in signal wave, its spectrum is shown on Fig. 5.

The main aim of my task was optimization of the third stage of OPA. To achieve optimal amplification I tried different thickness of BBO crystal, changed angle between pump pulses and the optical axis of crystal, altered delay between pump and signal, varied their radii by introducing a telescope and played with pump energy. All of my actions led to the optimal parameters of the 3 stage: 3 mm thickness of BBO, 7 mJ of energy in the pump pulses, 13 mm radius of the signal and 10 mm of the pump.

It resulted in 850 μJ energy of broadband near-infrared pulse with 1.6 μm central wavelength. Its spectrum starts on 1.2 μm and ends with 2.3 μm is pretty smooth that

corresponds to good fulfillment of the phase-matching condition (Fig. 6).

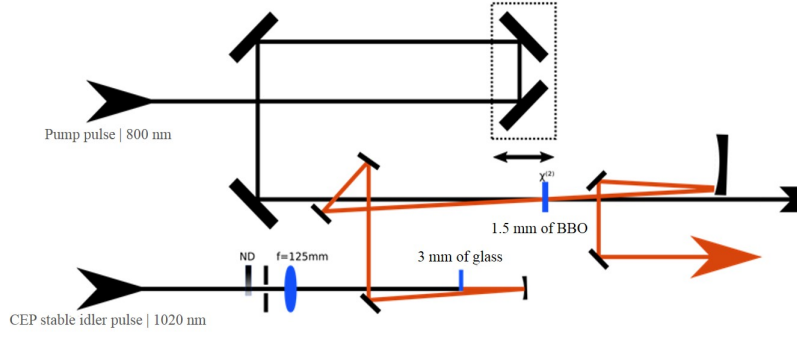


Figure 3: The schematic illustration of pulse propagation in the first OPA

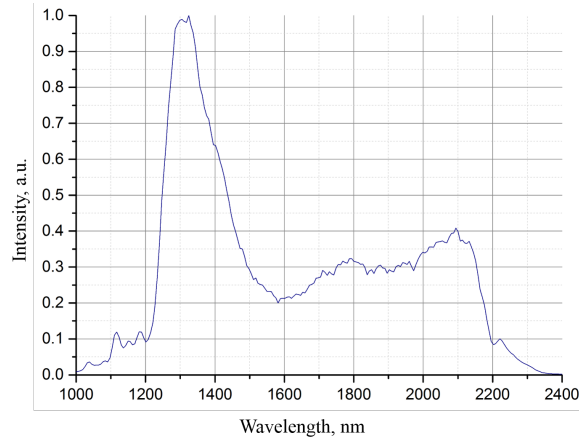


Figure 4: Spectrum of the signal after the first stage of OPA.

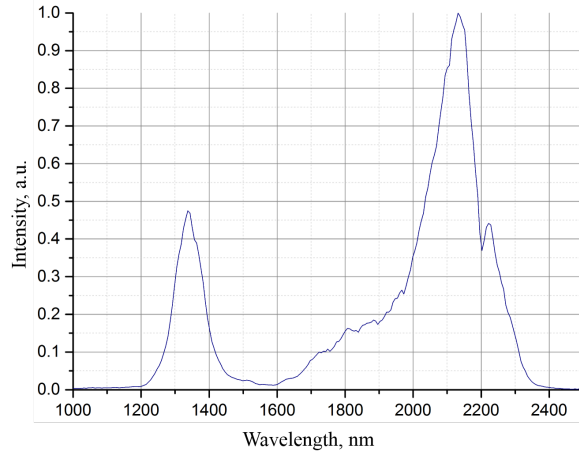


Figure 5: Spectrum of the signal after the second stage of OPA.

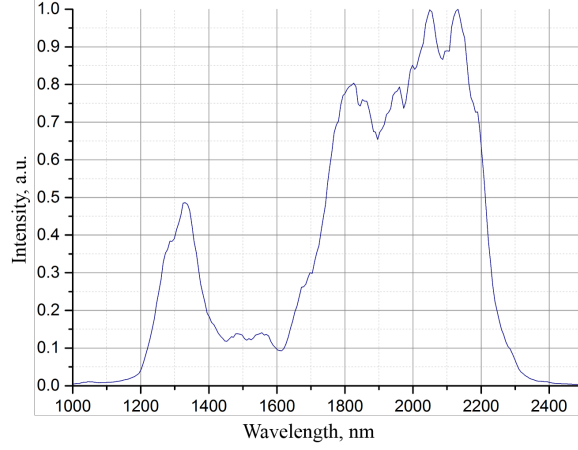


Figure 6: Spectrum of the signal after the third stage of OPA.

2.2 Characterization of the signal pulse

The pulse duration was measured after second stage by two-dimensional spectral shearing interferometry (2DSI) by introducing chirp-compensation stages.

Two Dimensional Shearing Interferometry is unique among pulse measurement techniques in that it unambiguously measures the spectral phase of a pulse by directly interfering neighbouring frequencies. An interesting characteristic of this technique is the excellent immunity from intensity noise and phase-matching bandwidth limitations, given that the spectral phase information is retrieved from spectral fringes. This measurement method is also more advisable respect to other shearing interferometry techniques, such as spectral phase interferometry for direct electric-field reconstruction (SPIDER), because it is delay-free. The drawback to be paid is that 2DSI is not a single shot measurement as SPIDER is.

The 2DSI method, as any other shearing methods, is based on nonlinear interaction between two monochromatic beams, slightly separated in frequency by Ω , and the pulse under test.

We can envisage this process as two independent nonlinear interactions (SFG or, as in our case, DFG) between the investigated pulse and the two monochromatic beams. The results are two pulses, whose band are widely overlapped due to the smallness of compared with the bandwidth. Those two pulses interfere together, and each spectral component is modulated by the phase difference between the two interfering components. This modulating phase difference reproduces the one between two frequencies, separated by Ω , of the investigated pulse, that generates the same sum (or difference) frequency.

Propagation pulses through developed by Giulio Rossi set-up for 2DSI schematically is shown on Fig. 7.

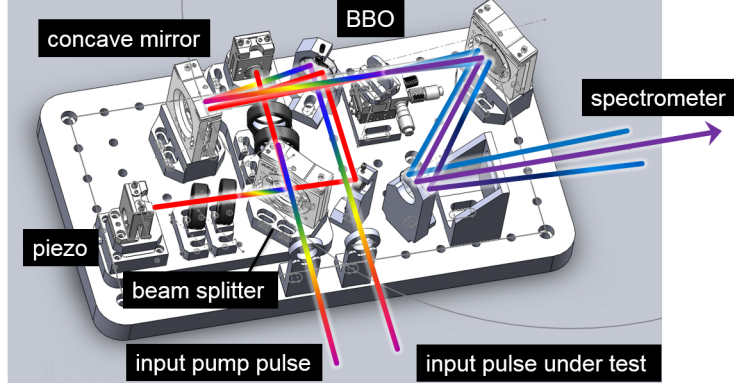


Figure 7: Schematic propagation pulses through set-up for 2DSI.

In order to observe the spectral phase difference between the two pulse components at a given frequency in a robust way, of one of the two monochromatic beams is thus scanned, in time, over a few optical cycles. The phase scan is typically done by vibrating one of the mirrors in the Michelson interferometer (Fig. 7) using a piezoelectric device. This results in a phase term, that is added to the up-converted (or down-converted) pulse. The spectrum of the signal is then recorded as a function of the phase, yielding a 2-D intensity function. For our case it is represented in Fig. 8.

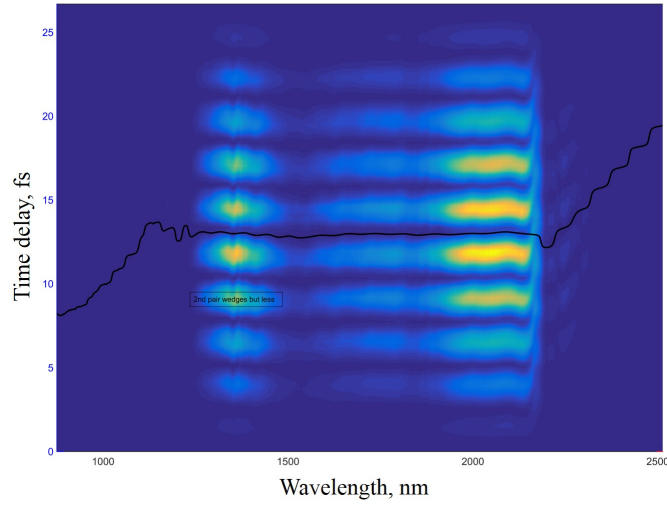


Figure 8: 2DSI trace from pulse after the second stage of OPA. The black line shows extracted group delay.

As you can see in Fig. 8, the line shows group delay is almost flat. It means that

all colors of signal wave propagates with the same speed which in turn indicates on good optimization of chirp-compensation stages. This stage consists from 2 compressors created by two chirped mirrors and ZnSe wedges possessing huge positive group velocity dispersion. The pulse duration retrieved from data in Fig. 8 was 7.6 fs that is very close to transform limit duration (Fig. 9)

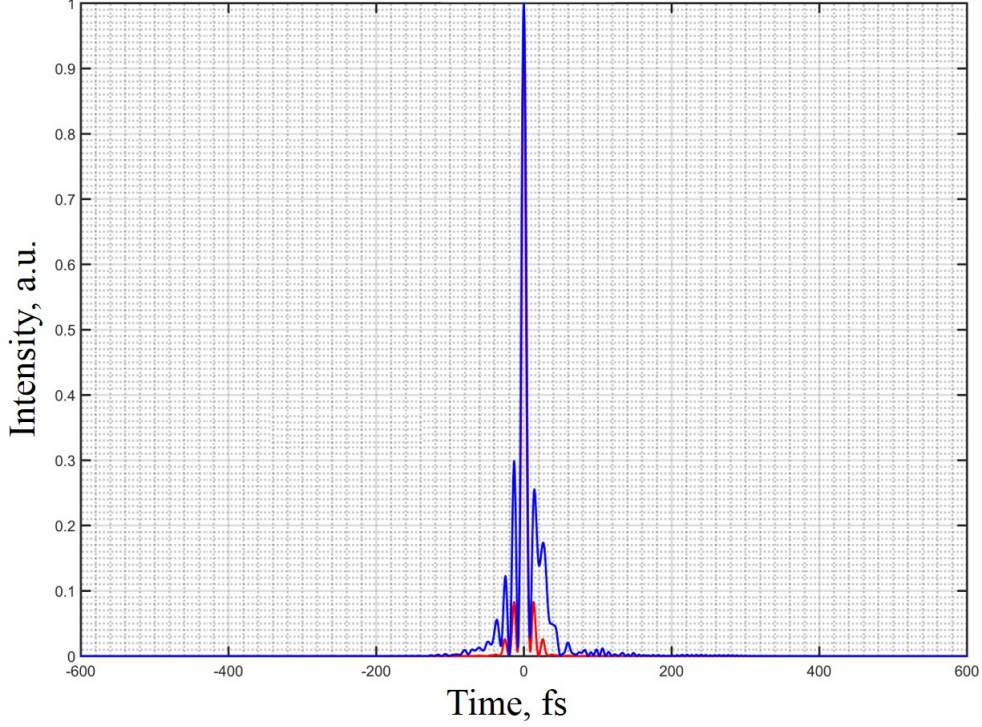


Figure 9: The signal pulse in time domain retrieved from 2DSI. The red line shows transform limit duration for current bandwidth of the spectrum.

3 Summary

We have demonstrated amplification of broadband near-IR pulses through multipass configuration of carefully optimized OPA. It allowed us to obtain 840 μJ energy of the signal after third stage starting with 1.5 μJ after first stage. We could provide broadband phase-matching condition for OPAs near zero group velocity dispersion due to aligning the chirp-compensation stages that resulted in 7.6 fs pulse duration.

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