Balanced optical cross-correlator for timing jitter compensation

September 11, 2014

Abstract

In this report I will briefly talk about the motivations behind the need to build new ultrashort laser source, the most important one is that in this way we will able to probe a new range of phenomena with dynamics that were unaccessible before. I will also give an overview of the field of non linear waveform synthesis and describe the source which is being built by the Ultrafast Optics and X-rays group here at CFEL, DESY. This is needed to introduce the project I have worked on, the balanced optical cross correlator (BOC), a setup which is used to compensate for time jitters between pulses on the attosecond scale. It was conceived for synchronization of free electron laser and then also adopted in waveform synthesizers where there is the need to precisely synchronize pulses together.

Contents

1 Introduction

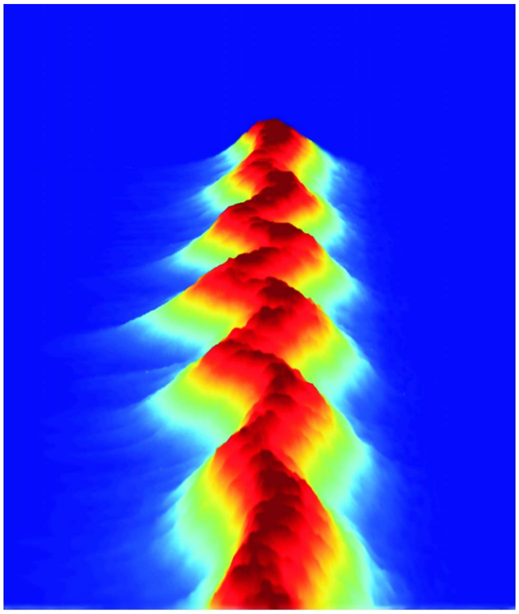
In modern research in laser physics one of our persistent goals is the generation of shorter and shorter light pulses. In fact, the duration of a pulse tells us what is the time scale we are able to probe in our experiments and so it determines which phenomena we can investigate. Being able to produce bursts of light with a smaller duration than that of the dynamics of the phenomenon studied is one of the most important tasks when studying the evolution of systems.

Fundamentally, the properties we are interested in when talking about ultrashort pulses is their bandwidth (by Fourier, the broader the bandwidth the shorter the time duration) and their chirp, which is the relative arrival time of different frequency components of the pulse; controlling these parameter properly grants that the pulse would be as short as possible (Transform-Limited pulse width).

Lately, with the “shortening” of the duration of light pulses, which has already reached the single optical cycle and even less, it has become important to have control over othe details of the pulse like the carrier wave and the pulse envelope. The generation of pulses with pre-determined electric field, which is what we are interested in doing to shorten the duration of the pulse, requires us, for example, to be able to manipulate the phase of the carrier wave with respect of the envelope (carrier-envelop phase, CEP). This can be done nowadays and it is the key to an optical waveform generator, a device which can generate a prescribed optical waveform i.e. pulses with user-designed electromagnetic field.

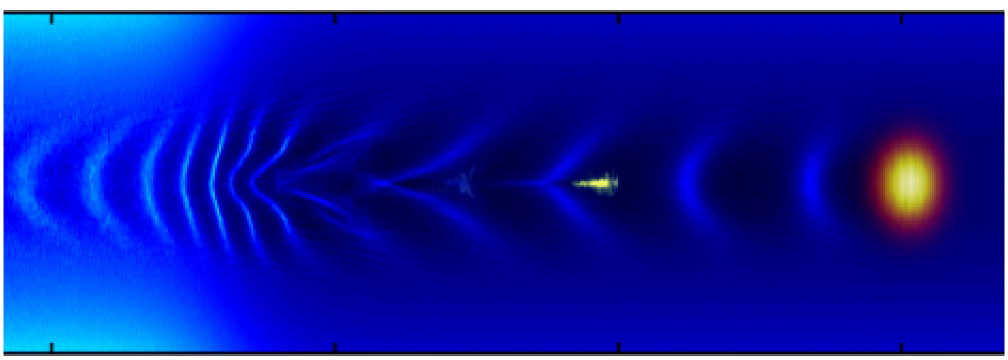
The generation of ultrashort CEP-controlled laser pulses allows us to probe a whole new set of phenomena in light-matter interaction that were unaccessible before. The field of “waveform non-linear optics” gives us the opportunity to study the effects of extremely short pulses with custom designed electric field in different situations. The most important applications regard high harmonic generation (generation of isolated XUV pulses), this would open a broad range of possibilities in exploring ultrafast phenomena like electron dynamics inside atoms and molecules.

Figure 1: Isolated attosecond pulse (from: http://www.fisi.polimi.it/en/research/research_structures/activities/54137)



Furthermore, another application could be the acceleration of electron through relativistic laser-plasma interaction (laser wakefield electron acceleration) that would enable us to build the next generation of accelerators for experimental particle physics.

Figure 2: Electron bunch in wakefield acceleration (from: https://www2.physics.ox.ac.uk/research/plasma-accelerators)



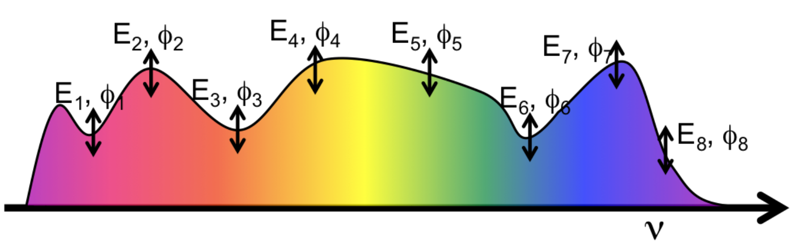
Other applications can also be found in various different fields, like the generation of attosecond electron wavepacket fot time-resolved electron microscopy , or like the control of electric currents in semiconductors and insulators on the sub-cycle scale which could lead to an extension of the signal processing capabilities of electronic devices (to PHz range).

2 Waveform synthesis

One interesting way of producing ultra short light pulses is the coherent combination of different pulses with longer duration but different bandwidth. This is truly possible, even if it is counter-intuitive, and it can be explained by means of Fourier transform or through wave interference. From the wave description, we can interpret the phenomena as the result of constructive and destructive interference between waves with different frequencies. The final result is that the constructive interaction of the different light pulses reduces to a shorter time interval and produces a shorter pulse than its parent pulses. Form the Fourier transform point of view, every time event has its dual in the frequency domain; so we can transform any signal $E(t)$ to its spectrum $E(\omega)$ by means of Fourier transform, which decompose any signal in a series of sinusoidal waves at different frequencies, each with a particular weight and phase. The time duration of the signal depends on the total bandwidth of the interacting waves and on the relative phase between the combined waves.

The requirements to obtain ultra short pulses as coherent superposition of several longer light pulses with different bandwidth are mainly that the sub-bands of the parent pulses have to span over a wide spectral region, in this way the synthesized pulse will be broadband, and that the spectral phase of each sub-pulse must be correctly stitched to one another, which requires phase manipulation techniques.

Figure 3: Sub-cycle tailoring of $E(t)$



One last aspect we must care about is the synchronization of the different light pulses, to overcome this problem a module that compensate for relative delay is needed. The solution to this matter is the Balanced Optical Cross-correlator (BOC), a system which measures the relative delay between the pulses that must be synthesized and compensate for it acting on different delay lines.

2.1 Waveform synthesizer

The waveform synthesizer is an ultrashort laser source that can perform waveform synthesis, it is composed by three different channels, each one covers a different region of the spectrum: the infrared (IR) channel amplifies pulses with wavelength from 1100nm to 2100nm, the near-infrared (NIR) channel that goes from 650nm to 1000nm and the visible (VIS) channel that includes wavelength from 450nm to 700nm. A Ti:Sapphire laser together with a commercial single pass legend amplifier and a singlepass Cryo amplifier, which consists of a Ti:Sa crystal cryogenically cooled with liquid helium, generate 20mJ pulses 150fs long with a repetition rate of 1kHz. Each pulse is then split several times, one part is used to generate a passively CEP (carrier envelop phase) stabilized withe light, and the rest is used as pump for the optical parametric amplifiers (OPA) of the different stages of the three channels. The CEP stable white light is generated from a two stage OPA that uses part of the $800nm$ starting pulse. Every pulse generated by the oscillator though has a different phase ϕ from the other ones, so they are not CEP stable. In the two stages the pulses produce white light while travelling in a sapphire crystal and then they will have a phase $\phi + const$; the part of the white pulse with wavelength close to $1.3\mu m$ is used in a non linear process with the same $800nm$, phase ϕ pulse which generated it. By difference frequency generation (DFG) it is possible to obtain a pulse at $2.1\mu m$ with always the same constant phase (the two initial phases ϕ cancel each other and we are left with a constant). By the end of these processes we are left with $40\mu J$ of energy in the CEP stable $2.1\mu m$ pulse, of which we then take the second harmonic that is later used to produce white light in a sapphire plate that is now CEP stable. The white light pulse is then split in three parts, to seed the different channels, with dicroic mirrors that first separate the visible and the near infrared part of the spectrum of the white light from the infrared part and then the visible from the near infrared. The result of this are three CEP stable pulses in different region of the spectrum, the three channels, which get amplified in three stages by OPAs and eventually coherently combined back together to generate a 2-octave spanning pulse which, in time, means ultrashort. The syntesis is done with dicroic mirrors, which succesively combine the VIS with the NIR and the two with the IR. The leakege of the mirrors is fed to the BOC for timing jitter compensation, it is important indeed that the pulses' delay is stabilized within a fraction of the wavelength to have coherent syntesis of the beams. The scheme of the synthesizer can be seen in fig. 4.

Figure 4: Scheme of the waveform synthesizer being constucted in CFEL

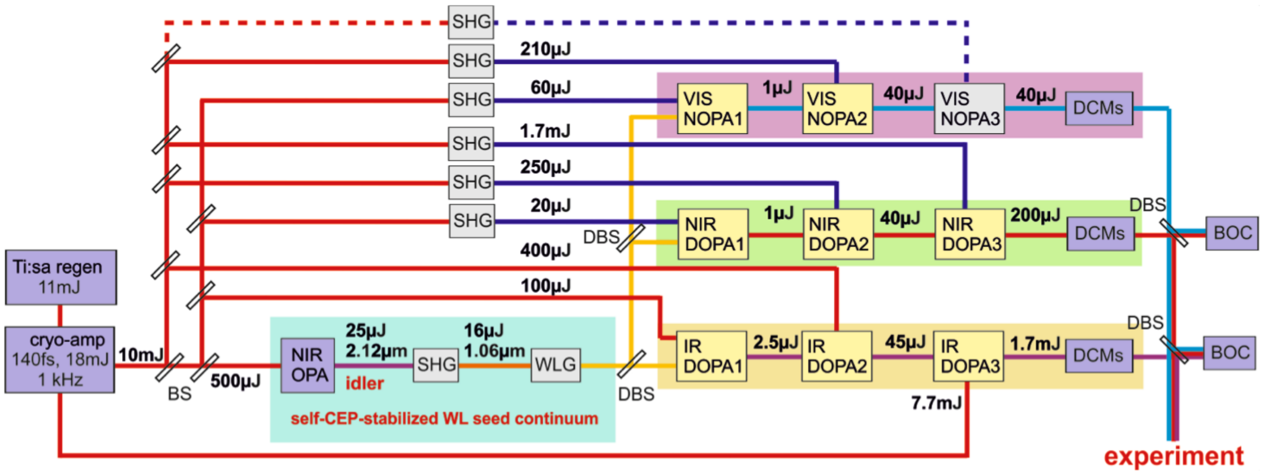
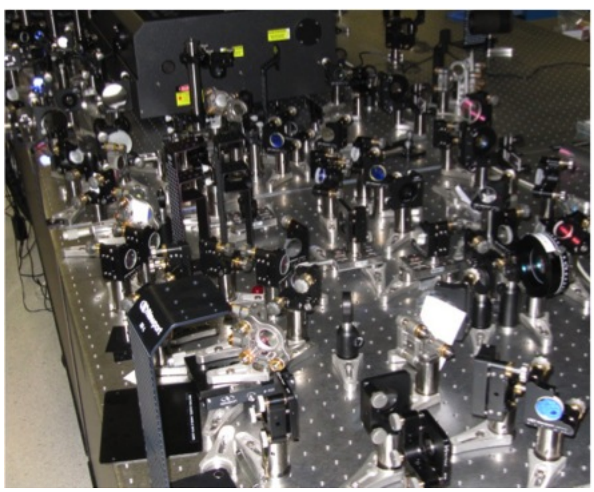


Figure 5: First and second stage of the experimental setup

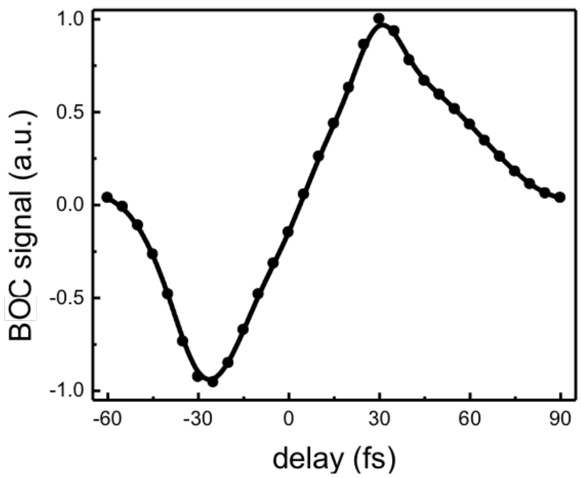


3 Balanced optical cross-correlator

The balanced optical cross-correlator (BOC) is the part of the set up that is in charge of the control of relative delay between the pulses that need to be synthesized. In facts, the parent pulses (that might be derived from a common source as in the synthesizer) follow different paths from the point where they are generated to the point where they are combined and they are subject to different linear and non linear processes that enable us to manipulate the properties of the pulse. This means that they are subject to different environmental instabilities such as temperature changes or vibration of mechanical components which can give a time dependent variation of the path length that corresponds to a varying relative delay between the pulses. So, as a first step to fight instabilities in the experimental setup one should try to stabilise as much as possible the environmental conditions in the laboratory (temperature, humidity, air fluctuations) and be careful about the interferometric stability of all optomechanical components, because when dealing with ultra short light pulses even changes at the micrometer scale matter.

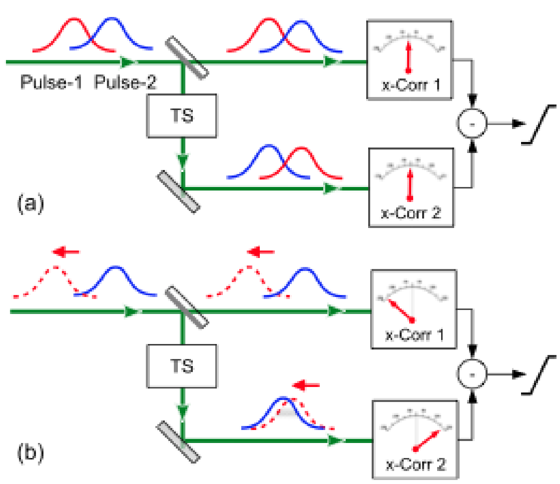
When nothing else can be done in controlling the environmental changes one can implement the BOC in his setup and this will enable him to actively compensate for possible instabilities. The BOC works by comparing two signals, whose amplitudes are proportional to the overlap between the pulses, coming from the correlator. The signals from the correlator correspond to a measure of the delay between the pulses in two opposite cases: for the combined beam and for the combined beam where the pulses' position are exchanged. When the two signals are not balanced, which means their difference is not zero, the correlator generates an output signal which is linearly proportional to the relative delay between the pulses. Although the output signal is linear only in a small region in the vicinity of the zero point, which means that the BOC works only when the pulses are separated by a certain amount of time, it is possible to coarsly scan the delay between the pulses until the right amount of delay is found and then finely tune the residual time jitter with the BOC. So, eventually the linear part of the output of the BOC can be used as a feedback to modify the path length of one of the pulses with a controlled delay line to compensate for the time jitter measured.

Figure 6: BOC output signal



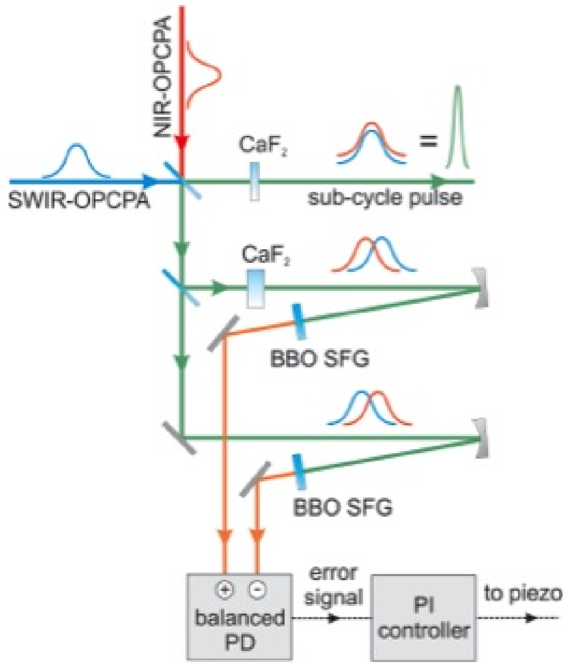
We will now consider one possible general scheme for the BOC and then our particular case in details. In the general scheme in fig. 7 the two pulses, pulse 1 and pulse 2, are combined and the combined beam is split into two replicas. One of the two replicas goes through a time swap module which exchanges the position of the pulses, so that in one arm pulse 1 arrives before pulse 2 and in the other arm pulse 2 arrives before pulse 1. In each arm the replicas are then sent in a crystal were they produce non-linear effects (SHG, SFG), the pulse coming out of the crystal as a result of the non-linear interaction is used to produce a cross correlation signal. In fact, the intensity generated in this non-linear process is proportional to the temporal overlap between the pulses, so it can be used as a measure of the overlap. Close to the "zero delay" point, the output of the comparison between the correlators is linear and so it is possible to use this signal to correctly compensate for any relative delay between the pulses, in case the output of the BOC is not zero, by acting on a delay line in one of the pulse's path.

Figure 7: General scheme of the BOC



In our set-up in fig. 8 the BOC is used to compensate possible timing jitters between the channels to combine. One BOC adjusts the delay between the VIS and NIR channels and a second BOC controls the delay between NIR+VIS and the IR. To make the BOC work, the leakages from the dicroic mirrors that combine the beams is used. The two replicas from each leakage are generated with a beamsplitter and each one goes into one of the arm of the correlator. Since the pulses combined have different spectra, the time swap is done by using a material of the right thickness which only introduces linear dispersion. With negatively chirped pulses, the propagation through a plate of CaF_2 with thickness d adds the right amount of dispersion needed to exchange the position of the pulses in time. In each arm the pulses are then sent into a nonlinear crystal, a $2mm$ thick BBO, where sum frequency signal is generated and then measured with a photodiode. A photodiode is a p-n junction, when a photon of sufficient energy strikes the diode, it creates an electron-hole pair. If the absorption occurs in the junction's depletion region, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The output signal, the difference between the two correlation signals produced by the photodiodes, goes to a PID filter which controls the delay line, a piezo actuator, to compensate for the time jitter measured by changing the delay in one of the combined pulses' paths.

Figure 8: BOC scheme for NIR and IR channel



4 Bibliography

1. S.-W. Huang et al., Nature Photonics 5, 475 (2011)
2. C. Manzoni et al., Opt. Lett. 37, 1880 (2012)
3. T. R. Schibli et al., Opt. Lett. 28, 947 (2003) (original demonstration)