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MASTER THESIS WORK

Measurement of the carrier-envelope phase stability of a novel mid-infrared source

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Measurement of the carrier-envelope phase stability of a novel mid-infrared source

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Abstract. The control and stability of the carrier-envelope phase of few-cycle pulses are crucial issues in attoscience. This project reports on a novel few-cycle mid-infrared source based on optical parametric chirped pulse amplification with $100\,kHz$ repetition rate at a wavelength of $3.2\,\mu m$ and a pulse duration of $67\,fs$. Due to the design of the source it is supposed to be intrinsically passively carrier-envelope phase stable. This assumption is proved experimentally with a new scheme to access the information about the carrier-envelope phase. Compared to the f–$2f$ scheme, which is widely used, this new scheme has the advantage of monitoring the carrier-envelope phase without using the main signal of the source.

Keywords: Attoscience, optical parametric chirped pulse amplification, carrier-envelope phase, mid-infrared source

1. Introduction

The focus of the thesis is the apparatus to characterize the carrier-envelope phase (CEP) stability of a new mid-infrared source. The key features of this source are: Mid-infrared wavelengths, ultra-short pulses, high repetition rate and CEP stability.

1.1. Mid-infrared wavelengths and ultra-short pulses

Using an ultrafast source, which means pulse durations in the range of tenths of femtoseconds, opened new possibilities in the strong field physics as well as in classical experiments. A short pulse duration is accompanied by a broad bandwidth of the spectrum due the Fourier relation between time and frequency. A broad bandwidth centered in the mid-infrared is very useful for spectroscopy, as it coincides with the vibrational transitions of important molecules. The range of applications is large, for example breath monitoring for detecting cancer [1], identification of bio-marker molecules [2] and the detection of explosives.

Additionally, high harmonic generation(HHG) with mid-infrared pulses provide an ionization process which is clearly in the tunneling regime and make the modeling much closer to reality, because it's not an intermediate process between tunneling and multiphoton absorption, as in the near-infrared range [3].

1.2. High repetition rates

Most experiments involving a low cross-section interaction require a high number of shots to be achieved. A high repetition rate system affords to reduce the requirement on the long term stability of the system as the signal to noise ratio(S/N) is favored.

1.3. CEP stability

A few-cycle pulse can be represented as

$$E(t) = E_0(t)\,cos(\omega t + \phi_{ce}) \tag{1}$$

Here E_0(t) is the slow varying envelope of the pulse and the last part of the equation is the fast varying carrier. The envelope $E_0(t)$ can be expressed as $E_0(t) = A_0\,cos^2(\frac{\pi t}{\tau})$ with $t \in [-\frac{\tau}{2}, \frac{\tau}{2}]$. The carrier envelope phase is the difference in phase of highest peak of the electric field versus the peak of the envelope. The difference in phase between carrier and envelope is described by ϕ_{ce}. If the CEP is stable, then ϕ_{ce} is constant from shot to shot.

The different positions between carrier and envelope are caused by dispersion, through difference of group velocity and phase velocity and by nonlinear effects [4]. Usually each pulse of a laser has slightly different CEP because it changes each round trip in the cavity through distortions. Figure 1 illustrates a few-cycle pulse with different CEPs. CEP stability is essential for many experiments, for example the measurement of double-ionization [6]. The stability of the CEP is also very important for the generation of single attosecond pulses. Furthermore the performance for HHG is better with longer wavelengths, because the generated wavelength is proportional to the inverse of the squared wavelength of the femtosecond pulse [3]. The main goal of the thesis is to measure the CEP stability of this novel mid-infrared source.

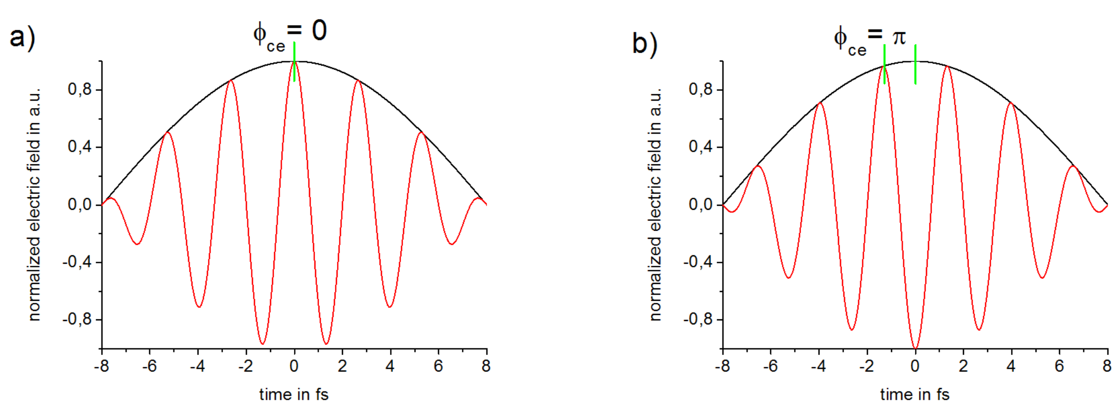

Figure 1. The figures a) and b) illustrate the effect of a carrier envelope phase on a few-cycle pulse. The black line shows the envelope and the red line the carrier.

2. The mid-infrared source

First a CEP stable pulse in the mid-infrared is generated with difference frequency generation (DFG). After the DFG the mid-infrared pulse is stretched and then amplified in optical parametric amplification stages (optical parametric chirped pulse amplification). Finally the down-chirped mid-infrared pulse is compressed to a pulse duration close to the Fourier-transform limit.

2.1. The difference frequency generation

The DFG has three advantages. First it provides access to the wavelengths in the infrared. Second a CEP stable pulse is achieved, as explained below. And finally the DFG provides a broad bandwidth to support short pulses. The source for the DFG is a fiber laser system(Toptica FFS) which has two outputs and both have their origin in the same oscillator. After amplification and compression, both outputs deliver a pulse with energy of $2.4\,nJ$ and a pulse duration of $75\,fs$ at a central frequency of $1.55\,\mu m$ and $100\,MHz$ repetition rate. One of the outputs is sent through a highly nonlinear fiber (HNLF),which spreads the wavelengths from $1\,\mu m$ to $2.3\,\mu m$. The spectrum between $1\,\mu m$ and $1.150\,\mu m$ from the stretched pulse is compressed again to obtain a pulse duration of $45\,fs$ and a pulse energy of $0.17\,nJ$. The difference frequency of the two phase-coherent pulses is generated in a periodically poled lithium niobate (PPNL) crystal resulting in an idler beam in the mid-infrared which is centered at $3.2\,\mu m$ with a power of $1.5\,mW$ at $100\,MHz$ and a bandwidth of $400\,nm$.
The CEP stability of the idler is achieved by considering the following facts. The phases of the pulse with two arms of the fiber laser can be described as $\psi_1 = \phi_1 + \phi_{ce_{osc}}(t)$ and $\psi_2 = \phi_2 + \phi_{ce_{osc}}(t)$ with ϕ_1 and ϕ_2 as constants and $\phi_{ce_{osc}}(t)$ is the non-constant carrier-envelope phase from the original pulse in the oscillator which is the source for both arms. The phase ψ_i for the idler generated in the DFG is

$$\psi_i = -\frac{\pi}{2} + \psi_1 - \psi_2 = -\frac{\pi}{2} + \phi_1 + \phi_{ce_{osc}}(t) - (\phi_2 + \phi_{ce_{osc}}(t)) \tag{2}$$

The resulting phase of this idler is therefore

$$\psi_i = -\frac{\pi}{2} + \phi_1 - \phi_2 \tag{3}$$

In equation 3 all remaining parts of the phase are constants, hence the CEP of the idler is constant and this source is passively CEP stable.

2.2. Amplification of the idler

The idler pulse of the DFG is first stretched in a $5\,cm$ long piece of Sapphire which is negatively dispersive. Thus blue and red components of the beam travel with different phase velocities and the idler pulse gets stretched in time. After this, the idler is amplified in three successive optical parametric amplifier (OPA) stages. Like the DFG, the optical parametric amplification is a three-wave-mixing process. In the crystal the idler∗ beam overlaps with a strong pump beam, which has a shorter wavelength than the idler beam. In the three-wave-mixing photons from the pump are converted into idler photons. This process is called parametric amplification. At the same time a signal beam is created with a photon energy which is the difference between the photon energy of the idler and photon energy of the pump.

Moreover the phase of the idler is not affected by this process, as it is described in the following phase equations:

$\psi_p = const$, $\psi_s = -\frac{\pi}{2} + \phi_p - \phi_i$, $\psi_i = -\frac{\pi}{2} + \phi_p - \phi_s$

With ψ_p,ψ_s and ψ_i the phases of pump, signal and idler

The pump for the OPA stages is a Nd:YVO_4 laser (HyperRapid from Lumera Laser GmbH). The main characteristics are a central wavelength at $1.064\,\mu m$, repetition rate of $100\,kHz$ at an average power of $40\,W$ and pulse duration of $8\,ps$. Important for the OPA operation is the good beam profile of the pump, which has a $M^2 \approx 1.2$ for the used laser and the power stability which has pulse to pulse fluctuations $< 0.4\%$ and $< 0.1\%$ RMS over 15 hours [5].

For the first stage a pump power of $2.1\,W$ is used and leads to a gain-factor of 8x10^3 for the seed (which is the idler wave of the DFG). After the first stage the seed pulse has a bandwidth of $200\,nm$ and a pulse energy of $80\,nJ$.

The pump power for the second stage is $5.1\,W$ which leads to a further pulse energy amplification to $1.2\,\mu J$ with a bandwidth of $250\,nm$ which corresponds to a gain factor of 40.

At the last stage the pump power is $20\,W$. The result is an amplified idler beam with a maximum pulse energy of $10\,\mu J$. If the setup is optimized for a large bandwidth instead of high pulse energies then the bandwidth of the amplified mid-infrared beam is $350\,nm$ FWHM with a pulse energy of $7.5\,\mu J$ at $100\,kHz$. The gain factor for the third stage is 10.

For the amplification the idler and pump must overlap temporally and spatially very well to get a high gain. Spatial overlap is achieved by focusing both beams in the crystal. Temporal overlap is achieved by delay lines and electronical synchronization that adjusts the length of the cavity of the pump laser to match it to a multiple of the repetition rate of fiber laser (A solution from Menlo Systems GmbH).

Using OPA instead of storage-gain media has several advantages. First, there is no heat deposition in the amplifiers because the amplification is a parametric process in which only the waves interact with each other. There is no gain medium, like in normal amplifiers, which needs to be cooled. Usually the heat removal in storage-gain media limits the repetition rate. Second, a large bandwidth can be amplified in OPA , which is very important to generate short pulses. Usually phase-match conditions are only given for a single wavelength λ_0. Although there is a phase-mismatch for other wavelengths a certain bandwidth around the center wavelength λ_0 is also amplified which is the bandwidth acceptance angle. The bandwidth acceptance angle gives information

∗ in contradiction to the usual nomenclature, the amplified beam in the OPA will be called idler, because it is the idler signal of the DFG

how much bandwidth is amplified and is usually characterized as the full-width-half-maximum (FWHM) of the gain profile.
The most important advantage of this OPA is that the CEP of the amplified beam stays constant in time.

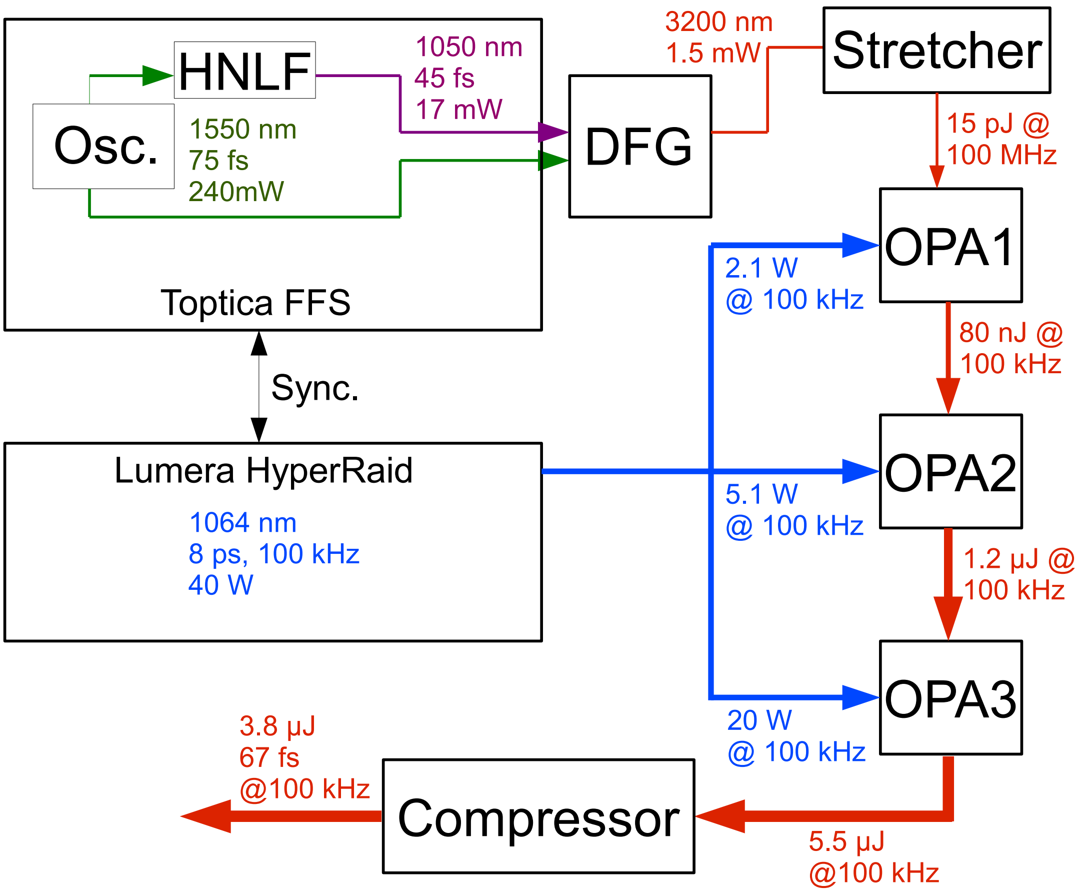

Figure 2. The complete OPCPA system.(Osc. = Oscillator, PCF = photonic crystal fiber, HNLF = highly nonlinear fiber)

2.3. Compression

Typically for an OPCPA system the amplified pulsed must be compressed because the temporal duration of the pulse is long after several stages of stretching and amplifying. This is reached with a Martinez-type stretcher/compressor and a deformable mirror in the Fourier plane. The deformable mirror optimizes the spectral phase shape and therefore the pulse duration is minimized, close to the Fourier-transform limit.
The deformable mirror is controlled by a computer with a genetic algorithm and a feedback loop to find an optimal shape of the mirror.

3. Measurement of the carrier envelope phase stability

The relative and measurement of the carrier-envelope phase is possible with different schemes. For this work two different setups were used to access the information about the CEP stability. The first one is the so called $f-2f$ method, which is usually used and the second one describes a new, self developed scheme, which exploits the nature of the optical parametric amplification to measure the CEP.

3.1. The $f-2f$ method

The f–$2f$ method is based on spectral interferometry [8]. A white light supercontinuum interferes with a a second-harmonic signal which is generated from a certain bandwidth of the supercontinuum itself.

That means that from a supercontinuum, which is generated by HNLF, the blue components interfere with the the second harmonic of the red components of the same supercontinuum. Both signals are intrinsic delayed in time due to the nature of dispersion and the different phase velocities. Taking again the expression for a few-cycle pulse (equation 1) then the detected signal with a spectrometer is given by [8]

$$I(\omega) = I_{sc}(\omega) + I_{sh}(\omega) + 2\sqrt{(I_{sc}(\omega) \cdot I_{sh}(\omega))}\cos(\omega\tau_d + \phi_{ce} + \frac{\pi}{2}) \tag{4}$$

with ϕ_{ce} as the CEP and τ as the temporally delayed between blue component(I_{sc}) and the SHG of the red component(I_{sh}). The observed spectrum on a spectrometer is superposed by fringes. The frequency of these fringes is given by the time delay τ_d and the position of the fringes by the CEP. Thus, if the CEP changes then moving fringes are observed on the spectrometer.

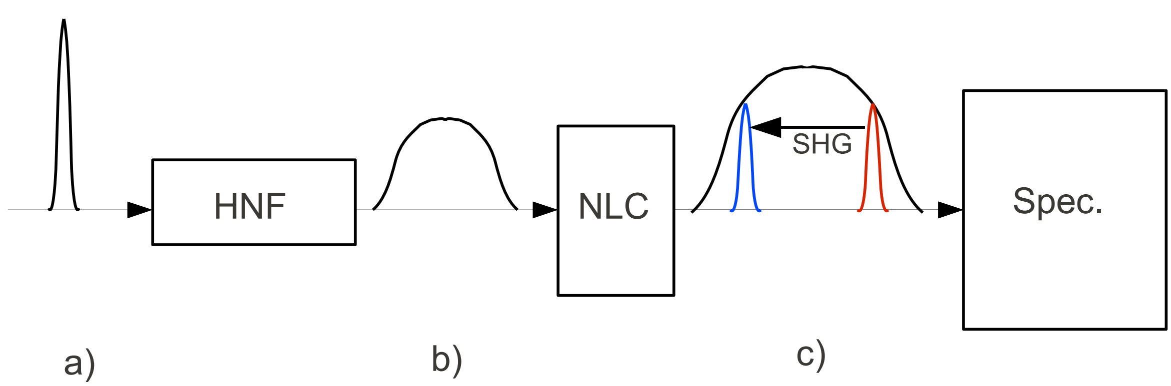

Figure 3. The basic setup for a $f-2f$ measurement of the CEP.
a) The input few-cycle pulse is send through a highly nonlinear fiber (HNF). b) The generated white light supercontinuum is send through a nonlinear crystal(NLC) to generate the second harmonic. c) The second harmonic of the red component interferes with the blue component of the supercontinuum on a spectrometer (Spec.).

The implementation of the f–$2f$ setup for the OPCPA system needs some modifications, because optics and measurement devices for a wavelength of $3.2\,\mu m$ are rare or not available. Figure 4 shows the setup for the CEP measurement. First the second harmonic of the $3.2\,\mu m$ beam is generated in Silver Thiogallate (AgGaS2) crystal. The SHG only doubles the phase, which is constant in time. Therefore it doesn't affect a relative measurement. After the second harmonic is splitted into two beams with a polarizing beam splitter (PBS) and a half-wave plate to control the ratio. One beam is going through a photonic crystal fiber (PCF) to generate a white light supercontinuum. The other beam is sent through a β-barium borate (BBO) to generate again a second harmonic, which is therefore the 4th harmonic of the initial beam with $3.2\,\mu m$ and carries four times the phase of this initial beam. Both beams are overlapped on a spectrometer (Ocean Optics HR 4000). In order to observe the fringes, like described above, there must be a temporal delay $\tau_d \neq 0$ between the two beams to achieve the spectral interferometry. On the other side there is an upper limit for τ_d, because the visibility of fringes with high frequency is limited by the reduction of the spectrometer ($R = 0.2\,nm$). Figure 5a) shows the two spectra after the PCF, respectively the BBO crystal. Approximately a bandwidth of $20\,nm$ spectrally overlap. To resolve four fringes, which are easy to observe in this bandwidth, a time delay of $\tau_d \approx 200\,fs$ is necessary. Figure 5b) illustrates this issue for different values of the CEP and τ_d for a normalized spectrum.

3.2. New scheme to access the CEP

This scheme uses the fact that after the amplification in the OPAs not only the idler ($3.2\,\mu m$) is left, there is also a residual pump beam and the signal beam ($1.595\,\mu m$) left as pictured in figure 6. Usually both are not used. Considering the phase of both carefully the result is following.
The signal beam results from the DFG of the idler beam and pump beam. Therefore the phase of the signal is

$$\phi_s = -\frac{\pi}{2} + \phi_p - \phi_i \tag{5}$$

The goal is to make a beating between the signal beam and pump beam. The electric field of the beating can be expressed as

$$E_b(t) = A \cdot cos(\omega_b \cdot t + \phi_b) \tag{6}$$

where ω_b is the beating frequency and ϕ_b the phase of the beating signal.
The phase of the beating phase is determined by

$$\phi_b = \phi_p - \phi_s = \phi_b - (\phi_p - \phi_i - \frac{\pi}{2}) = \phi_i + \frac{\pi}{2} \tag{7}$$

We can see that the beating signal of idler and pump gives directly the information about the CEP.
It must be considered that both beams must spectrally overlap for a beating signal. This is achieved by broadening the signal in a photonic crystal fiber (PCF) to generate

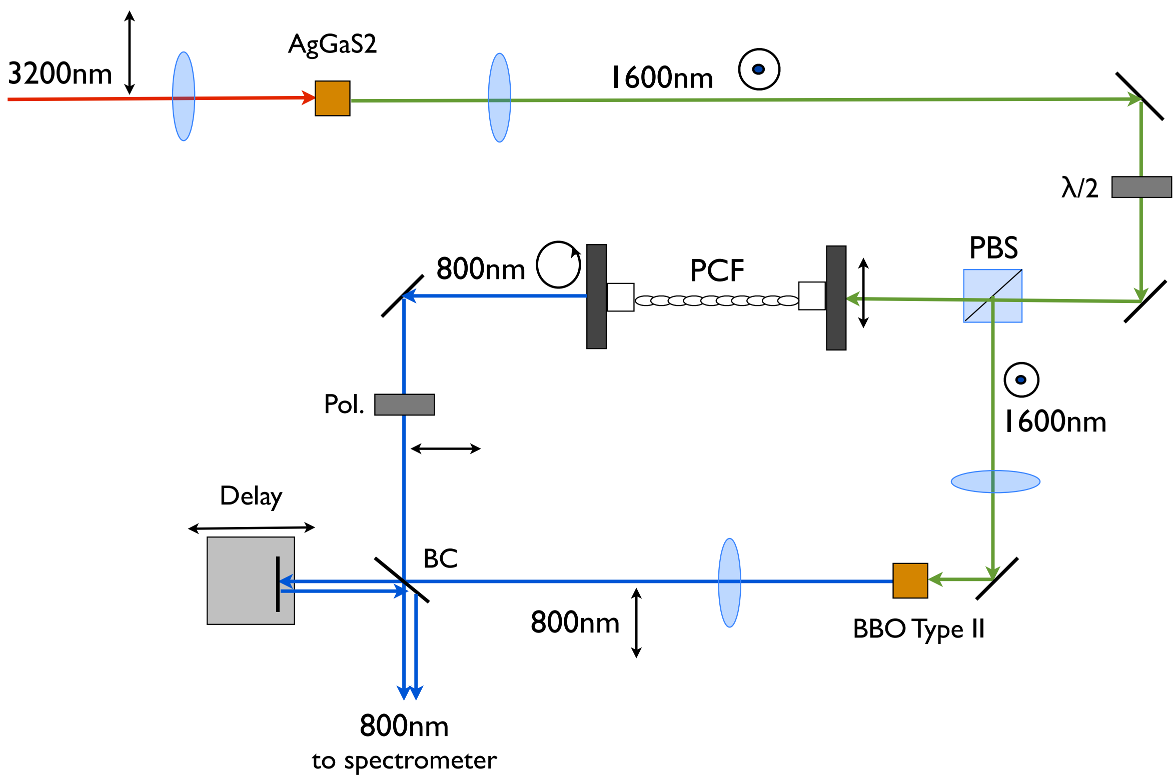

Figure 4. Complete scheme for measuring the CEP with the $f-2f$ method. (PBS = polarizing beam splitter, Pol. = polarizer, PCF = photonic crystal fiber)

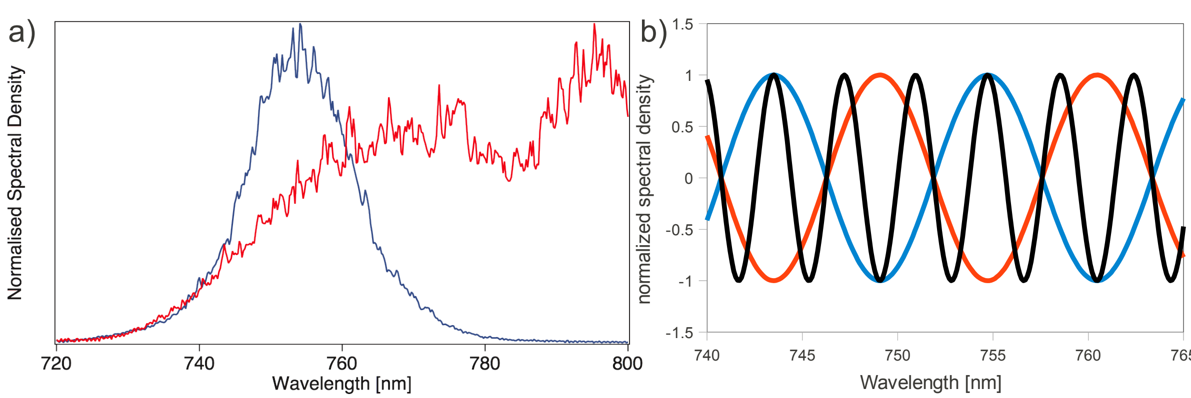

Figure 5. a) Spectrum of the white light super continuum(red) and the 4th harmonic(blue). b) Illustration of the fringes in the bandwidth of interest for different values of the CEP and τ_d. Blue line: $\phi_{CE} = \pi$, $\tau_d = 200\,fs$, red line: $\phi_{CE} = 0$,$\tau_d = 200\,fs$, black line: $\phi_{CE} = 0$,$\tau_d = 0.5\,ps$

a supercontinuum.
The beating signal is detected by an avalanche photodiode, which is connected to a Radio frequency analyzer (RFA). A relative change of the CEP can be easily observed

on the RFA. The bandwidth of the signal on the RFA gives information about the bandwidth of frequency of the beated signal, which is determined by the beam with the lower bandwidth. This is the pump beam with approximately $\Delta\lambda = 0.2\,nm$. And the CEP is represented by the amplitude of the signal detected on the RFA.

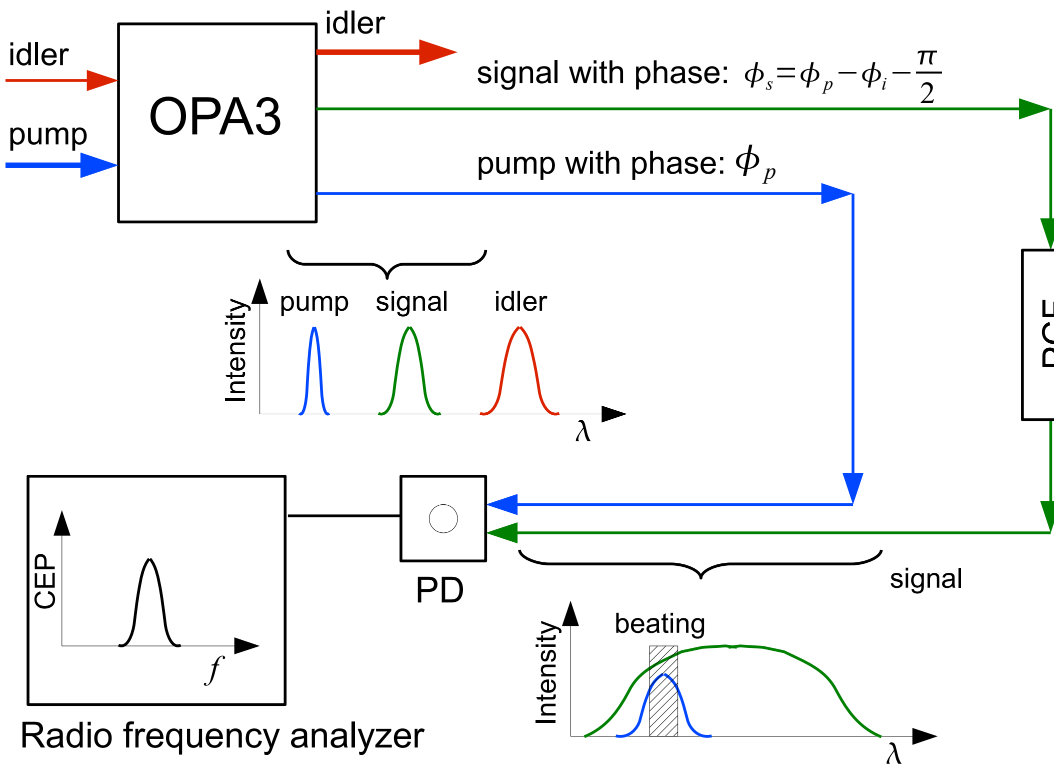

Figure 6. Complete scheme for measuring the CEP with the new scheme. (PD = Photodiode, PCF = photonic crystal fiber)

4. Conclusion

Two different setups to measure the carrier-envelope phase stability have been proposed. Both setups were implemented and built in the lab, but until the presentation of this project no measurement of the CEP stability was accomplished yet. The measurements are still being performed, due to time constraints and unexpected delays with equipment. Additionally there are difficulties with the experimental realization. The main problem with the $f-2f$ method is to find the right time delay τ_d. The time delay must be set with great precision to achieve a slow frequency of the fringes, because only $\approx 20\,nm$ are overlapping which corresponds to $100\,points$ on the spectrometer. The difficulties with the new scheme result from the fact, that the residual pump and the signal overlap after the third OPA. The pump is ≈ 40 times stronger than the signal beam. They have to be separated, because only the signal beam has to be sent through the PCF. This is done by using filters and mirrors with special coatings. Although appropriate optics elements are used the power of the signal drops about 75%. This low power accompanied by a long pulse duration of picoseconds, because the signal beam is not compressed, makes it difficult to couple the light into the PCF and observe the broadening of the bandwidth. A problem for both methods is that the OPCPA system is very sensitive to the pointing of the beams, which affects the stability of the output power. The beam pointing can be easily disturbed by air streams and vibrations. The generation of a supercontinuum in the PCF usually only adds a constant phase, which doesn't disturb the stability of the CEP in time. In the case the intensity is not constant, then the added phase is also not constant in time, because it depends directly on the intensity. Thus, it is probable that the PCF introduces a CEP instability which would result in a decrease of visibility in the fringes observed in the spectrometer. Considering the high repetition rate ($100\,kHz$) and the integration time of the spectrometer($4\,ms$), then great care should be taken in boxing every part of the system and avoid any possible vibration to be able to observe the fringes.

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