Spectral Phase Measurement Using Phase Conjugated Spectral Interferometry

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Abstract

In this project we studied a new method for ultrafast measurements. We tried to improve the method of Spectral Phase Interferometry, by finding an alternative for the reliance of the method on an external pulse. Instead of an external pulse, we used a phase conjugate replica of the unknown pulse we'd like to measure. Theoretical justification is presented.

Experimental achievements are presented too. Unfortunately we didn't achieve the main goal of reconstructing an electric field of a pulse, and the causes are presented too.

Introduction

Ultrashort Pulses Measurement

In optics, an ultrashort pulse of light is an electromagnetic pulse whose time of duration is of the order of femtosecond (10^{-15} second). Such pulses have a broadband optical spectrum ($\Delta\lambda\sim100$nm), and can be created by mode locked oscillators. The short duration of these pulses makes the idea of measuring ultrashort events possible. Furthermore they are characterized by a high peak intensity that usually leads to nonlinear interactions in various materials, including air. These features make ultrashort pulses important for scientific research and technological development.

At any given time, waves and pulses are characterized by amplitude and phase. Since the periods of optical frequencies are orders of magnitude shorter than any modern detector's integration time, optical oscillations (phase) are impossible to measure directly. The only information which can be directly measured is the average intensity. Therefore, measurements of the electric field require indirect measurements from whom the electric field can be reconstructed. We will focus on a method which enables measuring a single pulse- Spectral Phase Interferometry for Direct Electric field Reconstruction (SPIDER).

Spectral Phase Interferometry

Assuming two time- delayed pulses are measured by a spectrometer. One of the pulses is the one we would like to measure; the other one is a known reference pulse. The spectrum measured by the spectrum would be the spectral interference pattern from the pulses:

$$E(t), E_{ref}(t+\tau) \xrightarrow{F.T} E(\omega), E_{ref}(\omega)e^{i\omega\tau} \rightarrow |E(\omega)|e^{i\phi(\omega)}, |E_{ref}(\omega)|e^{i(\phi_{ref}(\omega)+\omega\tau)}$$

$$I_{spec}(\omega) = \left|E(\omega) + E_{ref}(\omega)e^{i\omega\tau}\right|^2 = |E(\omega)|^2 + \left|E_{ref}(\omega)e^{i\omega\tau}\right|^2 + 2\,\mathrm{Re}\left(E(\omega)E_{ref}^{*}(\omega)e^{-i\omega\tau}\right) =$$

$$\Rightarrow I_{spec}(\omega) = I(\omega) + I_{ref}(\omega) + 2\left|E(\omega)E_{ref}(\omega)\right|\cos\left(\underbrace{\phi(\omega) - \phi_{ref}(\omega)}_{\Delta\phi(\omega)} - \omega\tau\right)$$

Assuming the time delay satisfies ωτ>>ΔΦ, but it's still short enough so the pulses overlap and interfere, it's possible to find the phase difference out of the interference pattern. Given the spectrum and phase of the reference pulse, we can find the spectrum and phase of the unknown pulse, and reconstruct the electric field.

Phase Conjugation

Using nonlinear optical processes, it is possible to exactly reverse the propagation direction and phase variation of a beam of light. The reversed beam is called a conjugate beam, and thus the technique is known as optical phase conjugation (PC).

Common way of producing optical PC is to use a four- wave mixing technique [1], which is presented in Figure 1Figure 1: PC schema. Given two counter- propagating beams A_1, A_2, known as pump beams, and A_3, known as signal beam, the process will produce A_4- the conjugate beam:

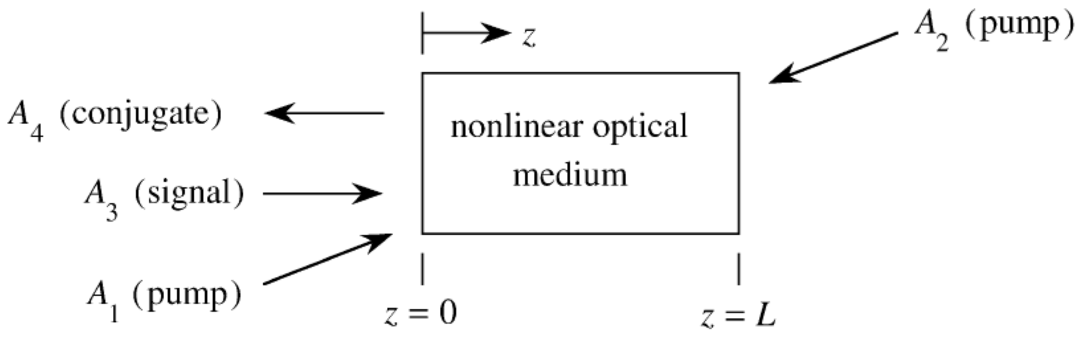

Figure 1: PC schema

The obtained expression for the conjugate beam is:

$$A_4 = \frac{i\omega L}{2nc}\chi^{(3)} A_1 A_2 A_3^*$$

And A_3, A_4 are counter- propagating, ω is the frequency, L is the interaction length, c is the speed of light and n is the refractive index of the medium.

One can interpret this nonlinear optical interaction as being analogous to a real- time holographic process. In this case (which is common while using photorefractive materials), the interacting beams simultaneously interact in a nonlinear optical material to form a dynamic hologram (two of the three input beams), or real- time diffraction pattern, in the material. The third incident beam diffracts off this dynamic hologram, and, in the process, reads out the phase conjugate wave.

The Photorefractive Effect

The photorefractive effect is a nonlinear optical effect seen in certain materials that respond to light by altering their refractive index. The photorefractive effect occurs in several stages, as explained in Figure 2. First of all, a photorefractive material is illuminated by coherent beams of light. Interference between the beams results in a pattern of dark and light fringes throughout the material. In regions where a bright fringe is present, electrons can absorb and be excited from the valence band to the conduction band. These electrons diffuse throughout the crystal, and form a pattern of charge distribution fringes. The charge distribution causes electric field, which causes the refractive index of the crystal to change, via the electro- optic effect. This causes a spatially varying refractive index grating to occur throughout the crystal. Now, the refractive index grating can diffract light shone into the crystal, with the resulting diffraction pattern recreating the original pattern of light stored in the crystal.

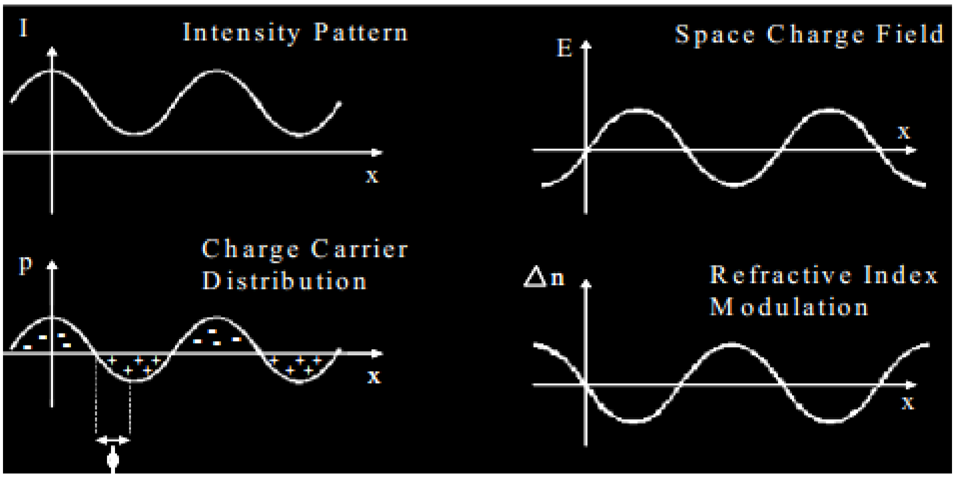

Figure 2: Photorefractive Effect

Theoretical Concept

One of the main problems of pulse measurements, using spectral interferometry (SI) methods, is the need for a known reference pulse, which should be similar (in terms of pulse duration) to the unknown pulse. But in order to know the exact spectral phase of the reference pulse, it should be measured using another reference pulse, which should be measured using another reference pulse etc.

We'll try to use unknown pulse for both purposes: to be measured and to be a reference pulse as well. In this configuration, the spectrum which would be measured:

$$I_{spec}(\omega) = I(\omega) + I_{ref}(\omega) + 2\left|E(\omega)E_{ref}(\omega)\right|\cos\left(\underbrace{\phi(\omega) - \phi_{ref}(\omega)}_{\Delta\phi(\omega)} - \omega\tau\right)$$

$$\xrightarrow{E=E_{ref}} I_{spec}(\omega) = I(\omega) + I(\omega) + 2\left|E(\omega)E(\omega)\right|\cos\left(\underbrace{\phi(\omega) - \phi(\omega)}_{\Delta\phi(\omega)} - \omega\tau\right) =$$

$$= 2I(\omega)\left[1 + \cos(\omega\tau)\right] = 4I(\omega)\cos^2\left(\frac{\omega\tau}{2}\right)$$

Note that the entire information about the phase was lost, so this configuration doesn't solve the problem.

Therefore we'll try another configuration, in which the reference pulse isn't the pulse itself, but its phase conjugate:

$$\xrightarrow{E_{ref}=E^*} I_{spec}(\omega) = I(\omega) + I(\omega) + 2\left|E(\omega)E^*(\omega)\right|\cos\left(\underbrace{\phi(\omega) - \left(-\phi(\omega)\right)}_{\Delta\phi(\omega)} - \omega\tau\right) =$$

$$= 2I(\omega)\left[1 + \cos\left(2\phi(\omega) - \omega\tau\right)\right] = 4I(\omega)\cos^2\left(\phi(\omega) - \frac{\omega\tau}{2}\right)$$

This way, the spectrum contains the information about both, intensity and phase, and the pulse's electric field can be reconstructed.

Experiments

Phase Conjugation – CW

In order to study the phenomenon of PC, we began working with a frequency- doubled CW Nd:YAG laser (532nm). Since our original goal was to work with pulses and we preferred to avoid temporal pulses matching, and used the Feinberg's Cat Conjugator configuration [1], with $BaTiO_3$ crystal, as shown in Figure 3:

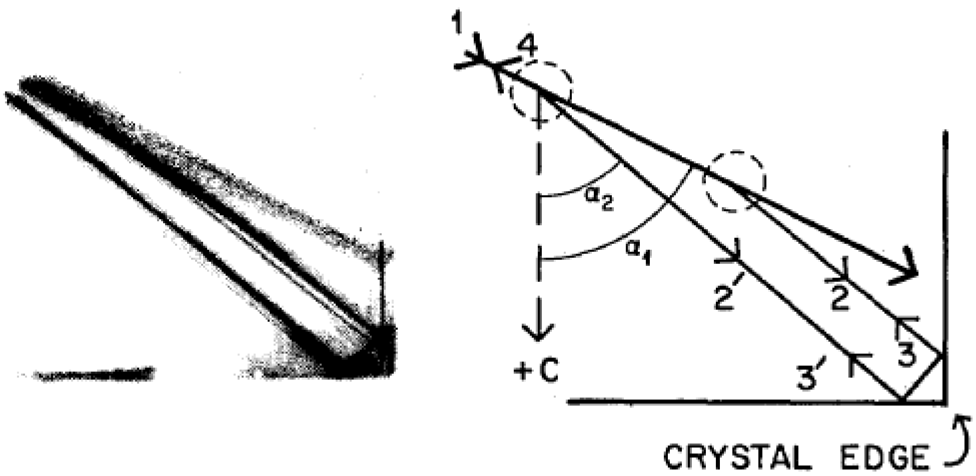

Figure 3: Feinberg's Cat Conjugator

The incident beam (1) enters the crystal from top left. Beam 2 splits off (due to fanning) and is internally reflected twice near the crystal edge and becomes beam 3', which then intersects beam 1 slightly upstream. Beam 2' has also split off from beam 1 and travels around the loop in the opposite direction. Beams 1-3 generate beam 4 by four- waves mixing in the interaction region circled in the right, as do beams 1'-3' in the interaction region circled by the left. Beams 1, 3, 3' are considered as pump beams, and beams 2, 2' are the signal beams. Beam 4 is the phase conjugate replica of beam 1, and it leaves the crystal exactly back along the direction of the incident beam.

For capturing the PC beam we used the experimental setup [3] shown in Figure 4:

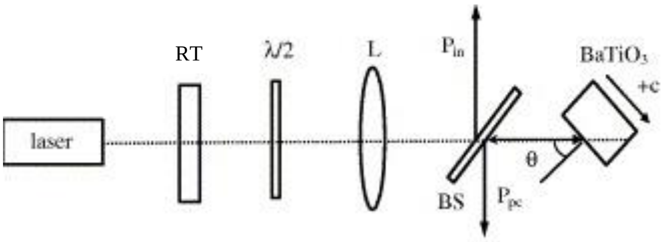

Figure 4: Experimental Setup

We imaged the resolution target twice: using a conventional mirror, using PC mirror. Afterwards we repeated the experiment but this time we placed a phase distorter between the mirror and the beam splitter. We expect that in the PC case (Figure 5), the phase distortion of the PC beam will cancel the phase distortion of the original beam, and we'll get a sharper and clearer image than in the case of conventional mirror (Figure 6), which will be doubly- distorted.

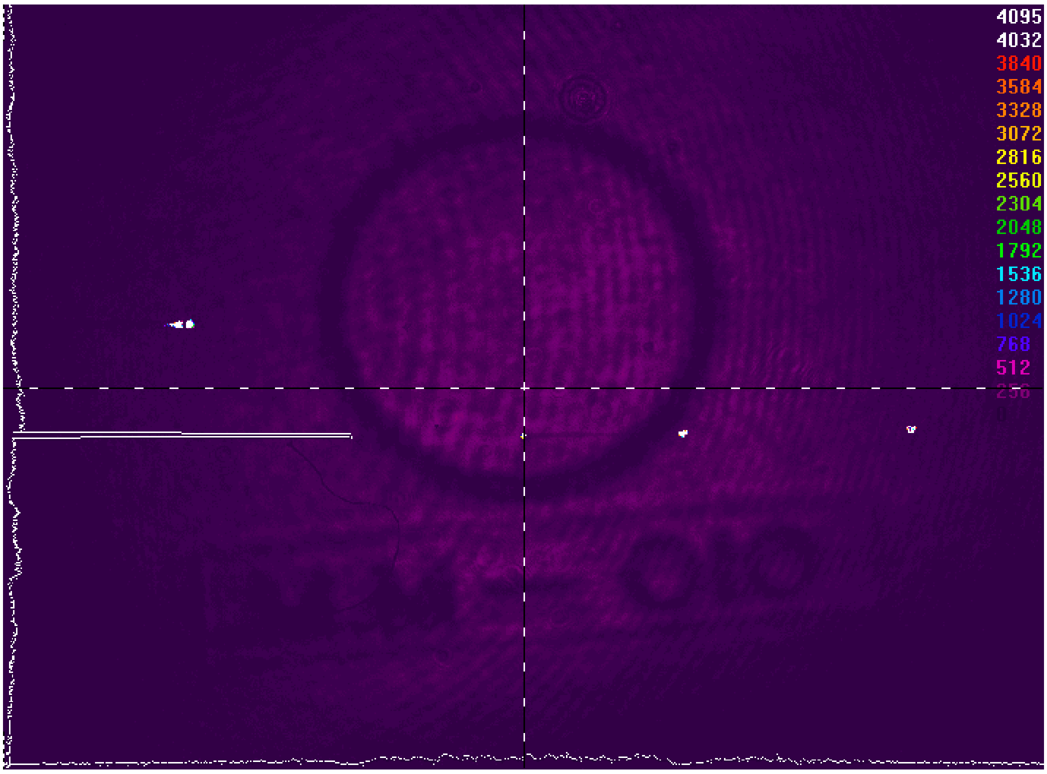

Figure 5: Phase Conjugate Mirror

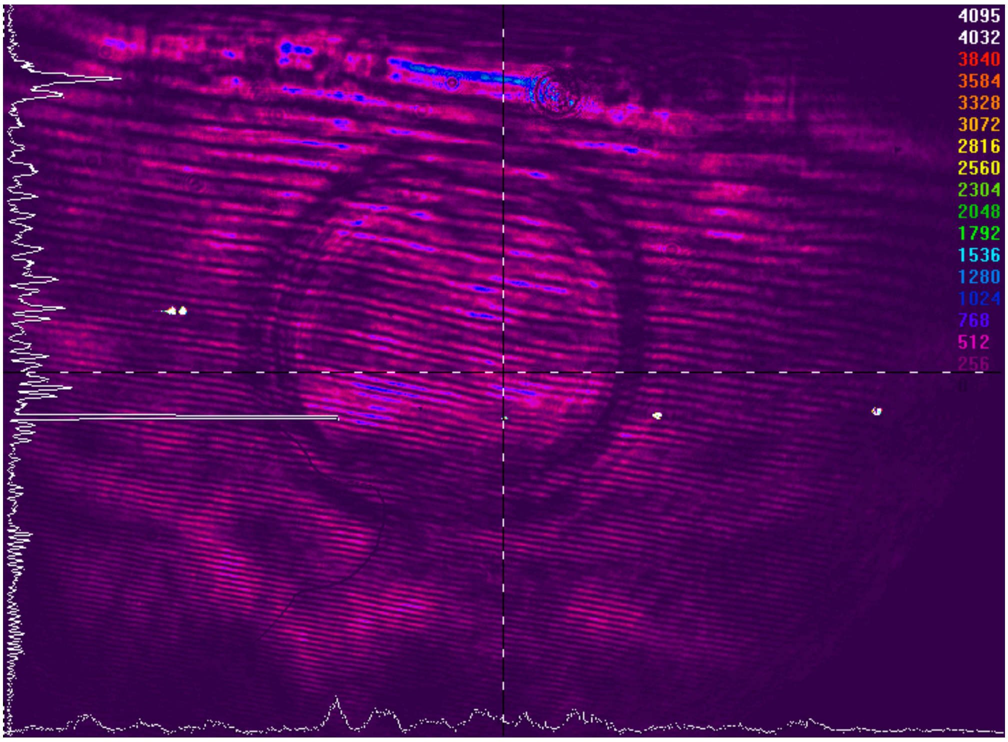

Figure 6: Conventional Mirror

As we expected, much more and finer details are visible when using the crystal. These results confirm that phase conjugate beam was really produced.

Similar results were obtained for the same setup, but using a CW Ti:Sapphire laser (~800nm).

Spectral Phase Interferometry

In order to check the algorithm for finding the phase out of the spectrum, we placed a piece of glass in an arm of Michelson Interferometer, and found the phase difference due to dispersion in glass. As expected, the dispersion was parabolic.

Phase Conjugation – Pulses

We worked with an OPO pumped by a passively mode- locked Ti:Sapphire oscillator, with pulse width of 130 fs, and repetition rate of 100MHz. The central wavelength of the output pulse was about 532nm.

Unfortunately we haven't succeeded producing significant PC pulse power yet.

Spectral Phase Interferometry – PC

Since we never got a good PC pulses, we couldn't measure anything.

Discussion

We have proved the theoretical concept of phase reconstruction via PC SI, and have successfully found phase difference due to dispersion in glass. Moreover, we have successfully produced PC of CW beams. Unfortunately we haven't succeeded producing significant PC pulse power yet. The PC pulse power hasn't been high enough for being separated from the noise, and producing an accurate SI results. We found out that the problems we're having are caused by the laser instability and insufficient spatial coherence, therefore further work should focus on improving the spatial and temporal quality of the pulses.

Moreover, even if high quality PC pulses will be produced, it won't assure reconstruction of the pulse. As illustrated with CW in Figure 3, PC beams are generated in interaction region which are located inside the crystal. In the process of PC pulse generation, PC is generated for every wavelength separately. Since the process is nonlinear, in order to generate PC for the entire pulse spectrum, the interaction regions of different wavelength must not overlap. If the PC of every wavelength is generated in a different location inside the crystal, they aren't generated simultaneously, and will leave the crystal at different times. If so, unknown spectral phase is added during the process, and the PC pulse won't be exactly a replica of the original pulse, i.e. we'll measure a phase, but not necessarily the phase of the original pulse.

Bibliography

[1] J. Feinberg, "Self- pumped, continous- wave phase conjugator using internal reflection," *Optics Letters,* vol. 7, no. 10, p. 486, 1982.

[2] R. W. Boyd, Nonlinear Optics.

[3] H.-. F. Yau, P.-. J. Wang, E.-. Y. Pan and J. Chen, "Self- pumped phase conjugation with femtosecond pulses by use of BaTiO3," *Optics Letters,* vol. 21, no. 15, p. 1168, 1996.