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Femtosecond Laser Pluses: Concept and Measurement Technique

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Abstract: *Since the birth of the laser, nearly 40 years ago, scientists have been continually interested in generation of ultrafast laser pulses in the picoseconds and femtosecond time domain. The recent development of all-solid state femtosecond lasers, tunable in the visible and near-infrared spectral regions, has already shown an impact on spectroscopic investigations in different areas in physics, chemistry and biology. This study gives a brief introduction into the world of femtosecond laser pulses and the most frequently used techniques to measure such ultra short pulses. The advent of femtosecond lasers has spawned whole new fields of scientific investigation.*

Keywords: Ultrafast Laser, Femtosecond, Infrared, Frequently, Investigations

I. INTRODUCTION

Femtosecond pulses are formed by the superposition of a high number of resonator modes. This technique allows the generation of light signals on much shorter time scales than electrical switches can react (~ nanoseconds, 1ns = 10^{-9} s) the higher the number of locked modes the shorter the pulse. The physical limit of the pulse length is given by the duration of a single optical cycle i.e. the wavelength of the laser Ultra-short-pulse lasers are the most important experimental tools for investigating fast evolving atomic and molecular dynamics in physics, chemistry and biology. Our understanding of the relaxation of elementary excitations in condensed matter carrier dynamics in ultrafast semiconductor devices or the temporal evolution of chemical reactions has been dominantly formed by experiments performed with Pico second (1ps =10^{-12} s) and femtosecond (1 fs = 10^{-15} s) optical pulses.

Moreover with the availability of high-power ultra-short pulses down to 10 fs in duration from solid state laser a system using the chirped-pulse amplification concept has opened up entirely new regimes of light-matter interactions. For instance when a high-power femtosecond pulse is focused into gas electrons will be accelerated in the laser field resulting in a vast number of fascinating new physical phenomena including x-ray generation. On the other hand femtosecond laser micromachining has excited vivid attention in various industrial fields and in medicine owing to the advantages of ultra-short laser pulses compared to long-pulse treatment. These are mainly the reduction of the laser flounce needed to induce ablation and the improvement of the contour sharpness of the laser-generated structures.

However the high peak intensities and the broad bandwidth of the laser pulses provided by short-pulse systems raise special sometimes counteracting requirements for optical materials applied for radiation protection. i.e. the nominal optical density of a filter has to be maintained for a wide range of fluences and pulse durations while out of the absorption bandwidth the filter should be as transparent as possible Since the birth of the laser nearly 40 years ago scientists have been continually interested in generation of ultrafast laser pulses in the picoseconds and femtosecond time domain. The recent development of all-solid state femtosecond lasers tunable in the visible and near-infrared spectral regions has already shown an impact on spectroscopic investigations in different areas in physics, chemistry and biology. This study gives a brief introduction into the world of femtosecond laser pulses and the most frequently used techniques to measure such ultra-short pulses.

II. METHODOLOGY

The monochromaticity combined with choice of wavelength can enhance the processing efficiency and the possibility of selective material processing. The spatial coherence can enhance the high energy density (J/cm2) of processing beam via focusing of laser light and the collimation can initiate the noncontact material processing. With these unique properties laser opens up possibilities of new processing techniques that are difficult to achieve by conventional material processing methods.

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The new processing techniques include laser drilling on thin and brittle material laser scribing on thin film with low adhesion layers fabrication of nano-scale surface structure, fabrication of three dimensional (3D) structures inside a semi-transparent material etc. In this series of studies laser-processing techniques are applied to photovoltaic (PV) semiconducting materials (crystalline and multi crystalline silicon and copper-indium-gallium-selenide) and dielectric transparent materials (lithium niobate and fused silica). LSFL is generated by interference between irradiating laser pulses and surface electromagnetic wave (SEW). On the other hand HSFL may be generated by the effect of second harmonic generation (SHG), specific types of Plasmon and/or self-organization. We fabricated HSFL on lithium niobate (LN) wafer surface by femtosecond laser for applying to two-dimensional photonic crystal. LN is human-made dielectric material that has electro-optical, acoustic-optical, nonlinear optical, ferroelectric, photo-elastic and photo-refractive properties.

III. Measurement Technique for Femtosecond Laser Pluses

For energy power spectrum and spatial beam measurements of ultra-short laser pulses standard laser diagnostic techniques are employed. For a measurement of the pulse duration or more interesting of the time dependent amplitude and phase of an ultra-short laser pulse dedicated methods were developed and described in several textbooks and references therein (Trebino, 2000). Here the basic ideas and underlying concepts are highlighted. As the time and frequency domain are related by the Fourier transformation it should be sufficient to measure amplitude and phase in only one of the domains. Let's first shortly reflect on the frequency domain. All spectrometers no matter whether diffraction-gratings or Fourier-transform devices measure a quantity that is proportional to the spectral intensity and therefore the phase information is lost.

On the other hand direct electronic techniques for temporal pulse width measurements consisting of fast photodiodes and high bandwidth (sampling) oscilloscopes are limited to the several Pico second regimes. Fast photodiodes are therefore not suited to record the temporal profile of an ultra-short laser pulse. Often they are employed to check on the mode locked operation of an ultrafast oscillator or in order to derive synchronization signals for amplification set ups or synchronized experiments. The only detector that reaches a time resolution bellow one picoseconds is the streak camera However a characterization of ultra-short pulses with respect to amplitude and phase requires optical correlation techniques especially methods that operate in the time-frequency domain. The latter techniques will be described in more detail.

The commercial femtosecond laser system (Spectra Physics) consists of a Titanium-Sapphire oscillator (Mai-Tai) which seeds a chirped regenerated amplifier (Spitfire Pro). The repetition rate of the system was either set to 1 kHz providing an output power of 2.2 mJ or at 5 kHz with an output power of 440 μJ. For most experiments a central wavelength of 800 nm was selected. Only for one measurement on Camphor it was changed to 760 nm in order to generate light at 380 nm. The fundamental laser pulse has a bandwidth of approximate 8 nm and the shortest pulse obtainable is about 150 fs

3.1 Streak Camera

The basic principle of a streak camera is depicted in Fig. 7. The ultrafast optical signal I (t) to be analyzed is focused on a photocathode where the signal is converted almost instantaneously into a number of electrons. The electrons then pass through a horizontal pair of accelerating electrodes and hit a phosphor screen after passing an electron multiplier (MCP=Multi Channel Plate). The screen is then imaged with the help of a highly sensitive camera (not shown). The temporal resolution relies on the concept of transferring a temporal profile into a spatial profile. This is done by passing the electron pulse between a pair of vertical sweep electrodes. High voltage is applied to the sweep electrodes at a timing synchronized to the incident light. During this high speed sweep the electrons arriving at different times are deflected at different angles and consequently hit the MCP at different vertical directions. In this manner the vertical position on the phosphor screen serves as a time axis. The brightness of the signal is proportional to the intensity profile of the incident ultra-short optical signal. The horizontal direction of the image corresponds to the horizontal location of the incident light. For example if the streak camera is used in combination with a polychromator the time variation of the incident light with respect to wavelength can be measured. Time resolved spectroscopy is therefore one of the application areas of these devices. Commercial devices (Hamamatsu Photonics K.K., 1999) are quoted with a temporal resolution <200 fs. Using different photocathode materials a spectral response can be achieved from 115 nm up to 1600 nm. X-ray streak cameras with a temporal resolution of 1.5 ps are quoted as well.

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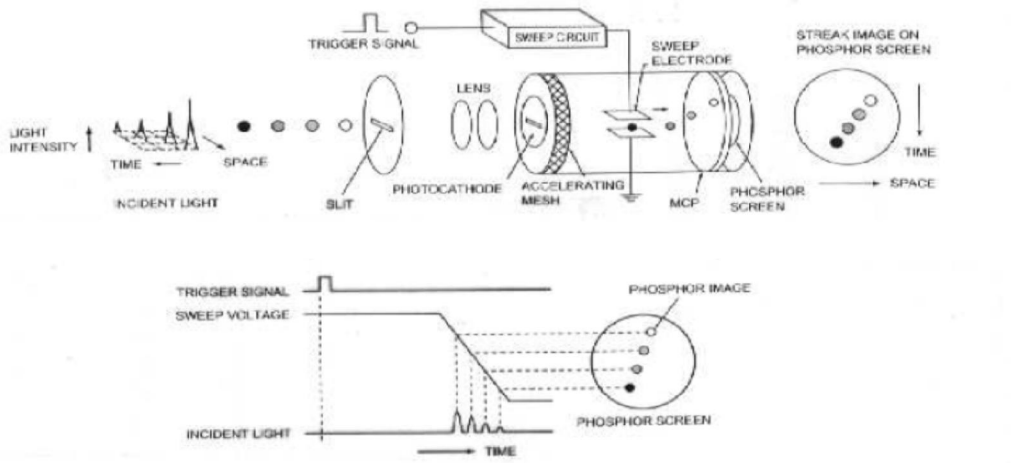

Figure 1: Working principle (top) and timing (bottom) of a streak camera (taken from: (Hamamatsu Photonics K.K., 1999). The spatial coordinate might be a wavelength coordinate after having dispersed the ultra-short optical signal with the help of a polychromator.

3.2 Time Frequency Methods

As described above the interferometric autocorrelation even together with the independently measured spectrum give not sufficient information to characterize arbitrary shaped ultra-short laser pulses with respect to their temporal amplitude *A(t)* or temporal intensity *I(t)* and the temporal phase function *a(t)* or their frequency domain counterparts. Techniques have emerged that operate not in the time or frequency domain but in the "joint time-frequency" domain involving both temporal resolution and frequency resolution simultaneously and being able to completely determine the pulse shape (Trebino, 2000). For illustration purposes we start with an example from music in order to describe a line of music we use notes. The frequency is indicated by the pitch of the note and the duration of the note indicates how long the frequency has to be held. The sheet of music will tell us in what order the notes have to be played and additional information like "piano" and "forte" is given to indicate the intensity to be played.

3.3 Sonogram Based Methods

Recording the sonogram involves that the frequency spectrum is sliced and the arrival time of the frequency components is measured. Experimentally this can be achieved for example by cross correlation of a pulse with a frequency – filtered replica of the pulse in an instantaneous nonlinear medium (see Fig. 2).

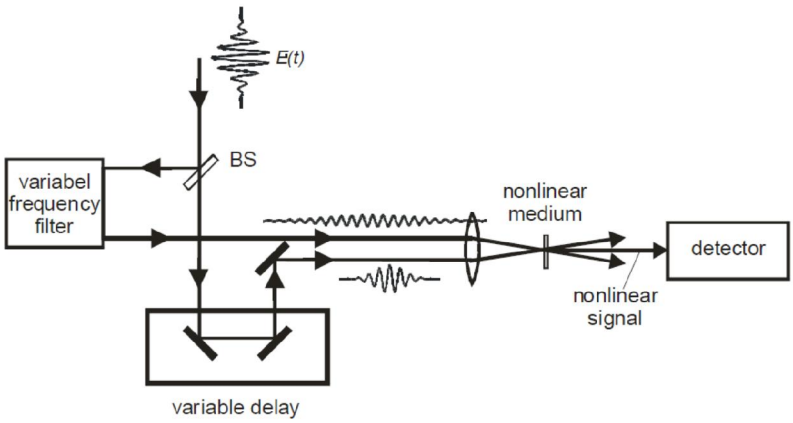

Figure 2: Schematic of a FDPM (Frequency-Domain-Phase-Measurement) or STRUT (Spectrally and Temporally Resolved Up conversion Technique) apparatus.

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The corresponding technique is known as Frequency-Domain-Phase-Measurement (FDPM) and described in. The method gives information on the group delay and integration can be performed that gives the spectral phase function without any iterative algorithm. An experimental realization has been termed STRUT (Spectrally and Temporally Resolved Up conversion Technique) and exists also in a single shot version (Rhee *et al.*, 2006). As the sonogram and the spectrogram are mathematically equivalent FROG retrieval algorithms (being in principle somewhat slower) can also be used in this approach (Rhee *et al.*, 1996).

From a practical point of view the method is experimentally more involved than a FROG set up and it is less sensitive because energy is lost at the filter before the nonlinear medium. In the SHG version, the STRUT apparatus and the FROG apparatus are identical when removing the frequency filter and using a spectrometer as the detector in Fig. 2.

IV. Result and Discussion

The experiments in this study will be performed using femtosecond laser pulses at different wavelengths. In this study we will be analyzed some of the basic linear and nonlinear physics that governs how femtosecond laser pulses behave in transparent materials. A femtosecond pulse with only moderate energy can have an extremely high peak power and peak intensity. When materials are subjected to these high powers and intensities, the material response becomes highly nonlinear. We will discussed the state-of-the-art in ultra short-pulse laser systems, and briefly describe the lasers used in the experiments. Femtosecond laser pulses can be generated directly from a wide variety of lasers with wavelengths ranging from the ultraviolet to the infrared. This range is greatly extended by the use of nonlinear frequency conversion techniques. Continuous tuning is achieved for example via optical parametric oscillators followed by (cascaded) sum- and difference frequency mixing. Tuning of amplified femtosecond laser systems is achieved via optical parametric amplifiers. The generation of a white light continuum is also a standard technique to generate new wavelengths. With high power femtosecond laser systems the x-ray region can be reached by focusing the radiation into a solid state material or via high harmonic generation whereas the latter technique also opens the door to the auto second regime. The THz spectral region can be accessed via femtosecond lasers as well.

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