Characterization of complex ultrashort laser pulses for single shot THz diagnostic

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Abstract

This report introduces a possibility of single shot THz diagnostic by the use of echelon mirror.

Observation of ultrashort laser pulses measuring techniques such as FROG and GRENOUILLE is presented including its setups and installation and use of GRENOUILLE device.

Obtained calculated and experimental results are compared and explained.

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Contents

1. Introduction

1.1. THz radiation at FLASH 1

Terahertz radiation consists of electromagnetic waves within the band of frequencies from 0.3 to 10 terahertz (THz). One terahertz is 10^{12} Hz. Wavelengths of radiation in the terahertz band correspondingly range from 30 to 1000 µm.

Terahertz radiation can penetrate thin layers of materials but is blocked by thicker objects. THz beams transmitted through materials can be used for material characterization, layer inspection, and as an alternative to X-rays for producing high resolution images of the interior of solid objects.

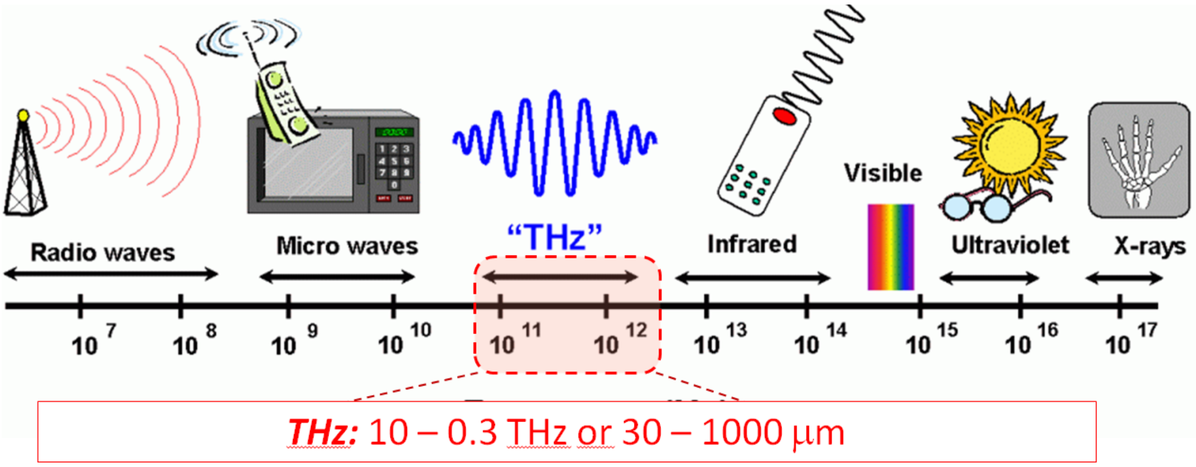

Fig. 1. Terahertz waves lie at the far end of the infrared band, just before the start of the microwave band.

The THz undulator beamline (BL3) at FLASH 1 (see Fig. 2) has been designed to provide coherent femtosecond (fs) – picosecond (ps) THz pulses for pump-and-probe experiments with the fs VUV pulses from FLASH. First light has been delivered into the FLASH experimental hall 'Albert Einstein' in November 2007. The THz pulses are generated by a purpose built undulator implemented in series to the VUV undulators. The design of the beamline allows to overlap a VUV pulse and a THz pulse generated by the same electron bunch at the end of BL3. The pulses should therefore be naturally synchronized. The expected pulse energies lie within the microjoule regime.

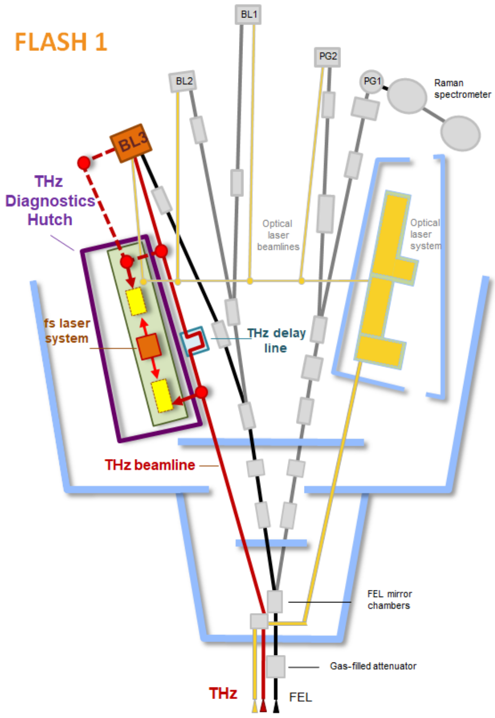

Fig. 2. THz Diagnostic Hutch on the BeamLine 3 at FLASH 1 Experimental Hall.

THz radiation with the following parameters is available for pump-and-probe experiments at BL3:

- tunable: 10 - 300 µm; up to 100 µJ/pulse; ~10% bandwidth,
- broadband at 200 µm; up to 10µJ/pulse; ~100% bandwidth
- synchronized and phase stable to X-ray pulses (down to 5 fs)
- delivered to the experiment via vacuum beamline as:
- ultra--high vacuum (~10^{-8} mbar), shorter delay between THz and X--ray (~4 m path difference), can accommodate up to 0.3 m wide setup;
- high vacuum (pressure ~10^{-6} mbar), longer delay between THz and X--ray (~7 m path difference); can accommodate up to 2 m wide setup

1.2. Single shot THz diagnostic

Let's consider THz profile presented on Fig. 3. In order to diagnose such profile, it should be scanned by a sequence of ultrashort laser pulses. Currently, only multi shot diagnostic is available.

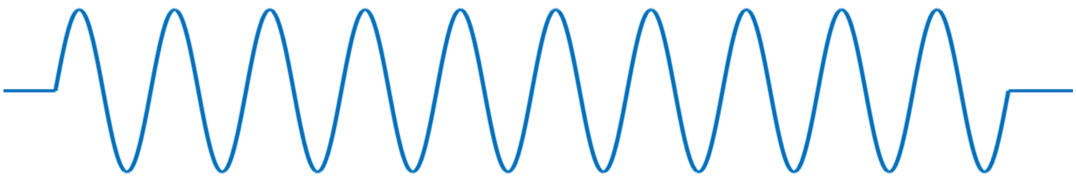

Fig. 3. THz profile that must be diagnosed

But there is a way to obtain train of pulses (see Fig. 4) with certain delay between each of them to make single shot THz diagnostic possible. It can be done using echelon mirror.

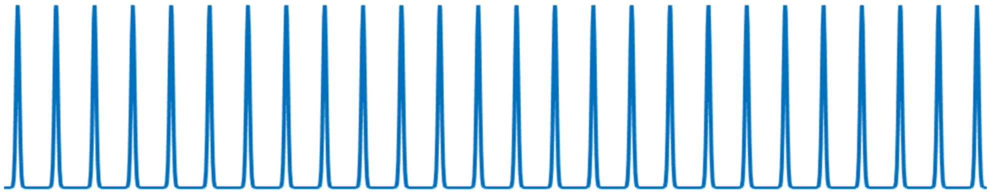

Fig. 4. Train of pulses required for single shot THZ diagnostic

1.3. Echelon mirror

Echelon mirror (Fig. 5 a) has special stepped structure on its front surface (see Fig. 5 b). When such mirror is illuminated with light it creates multiple pulses with specific delay. The delay is defined by the height of step and is about 50 fs in this case.

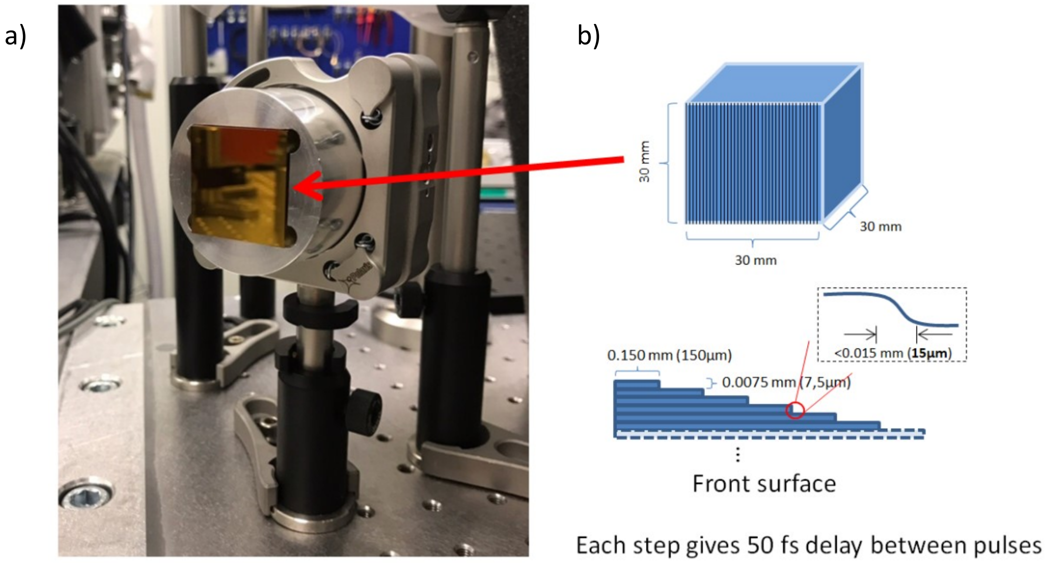

Fig. 5. a) Echelon mirror; b) Front surface structure of echelon mirror.

1.4. Research motivation

The motivation of this research is to test the echelon mirror and prove its efficiency. It is required to check the ability of echelon mirror to generate multiple pulses with expected delay and obtain the look of this pulse train. Confirmation of mentioned features would allow possibility of echelon mirror usage for single shot THz diagnostic.

In order to measure complex ultrashort laser pulse such as a pulse train special measurement techniques are used. It is discussed in chapters 2 and 3.

2. FROG

2.1. Working principle

One of the most developed ultrashort laser pulse measuring techniques is FROG - Frequency-Resolved Optical Gating – was proposed by Rick Trebino in 1990s. Operating in hybrid time-frequency domain, FROG measures complete intensity and phase of the pulse vs. time and frequency.

In its simplest form, FROG is any autocorrelation-type measurement in which the autocorrelator signal beam is spectrally resolved. Instead of measuring the autocorrelator signal energy vs. delay, which yields an autocorrelation, FROG involves measuring the signal spectrum vs. delay. Then a pulse-retrieval algorithm is used to retrieve the pulse from the spectrally resolved autocorrelation. Thus FROG can measure the complete intensity and phase vs. time and frequency.

There are several different beam geometries for FROG. The most common and the most sensitive FROG beam geometry is second-harmonic-generation (SHG) FROG. The SHG FROG beam geometry is shown in Fig. 6. Basic idea is to measure pulse with itself. Therefore the pulse is split into two, one is delayed with respect to the other, and both separated beams are overlapped in a SHG crystal. After that spectrometer measures pulse spectrum vs. delay.

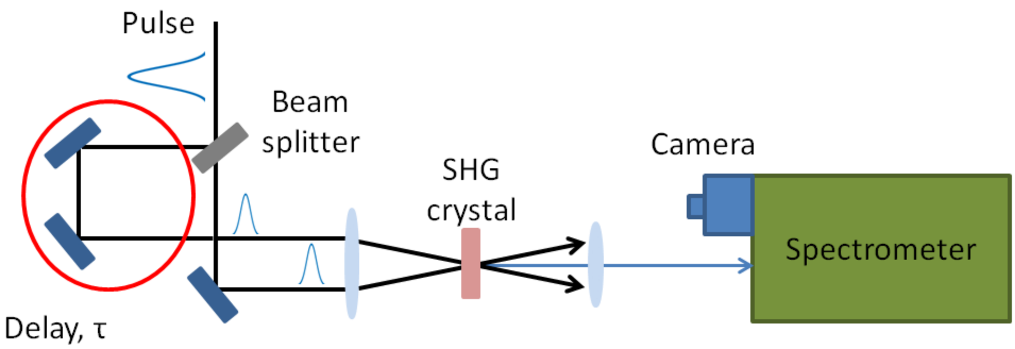

Fig. 6. Principal scheme of SHG FROG.

The main advantage of SHG FROG is sensitivity: it involves only second-order nonlinearity, while some other FROG variations use third-order optical nonlinearities, which are much weaker. As a result, for a given amount of input pulse energy, SHG FROG will yield more signal pulse energy. SHG FROG is commonly used to measure unamplified pulses directly from a Ti:Sapphire oscillator, and it can measure pulses as weak as about 1 pJ; it is only slightly less sensitive than an autocorrelator.

The main disadvantages of SHG FROG are that it has a somewhat unintuitive trace that is symmetrical with respect to delay, and, as a result, it has an ambiguity in the direction of time.

FROG is very accurate. In practice, FROG has been shown to work very well in the IR, visible, and UV. Work is underway to extend FROG to other wavelength ranges, such as the x-ray. It has been used to measure pulses from a few fs to many ps in length. It has measured pulses from fJ to mJ in energy. And it can measure simple near-transform-limited pulses to extremely complex. It can use nearly any fast nonlinear-optical process that might be available. FROG has proven to be a marvellously general technique that works. If an autocorrelator can be constructed to measure a given pulse, then making a FROG is straightforward since measuring the spectrum of it is usually easy.

2.2. FROG setup

FROG experimental setup is presented on Fig. 7. First, laser beam is guided to the beam splitter. After that one of the separated beams is delayed and then both beams are focused with a parabolic mirror into the BBO crystal. On the next step there are 3 beams: 2 fundamental and 1 second harmonic. The pinhole filters fundamental beams since they are directed at an angle. Finally, second harmonic beam pass into the spectrometer where its spectrum is measured vs. delay time.

This technique provides a multi shot measurement, so the delay should be varied manually using the delay stage.

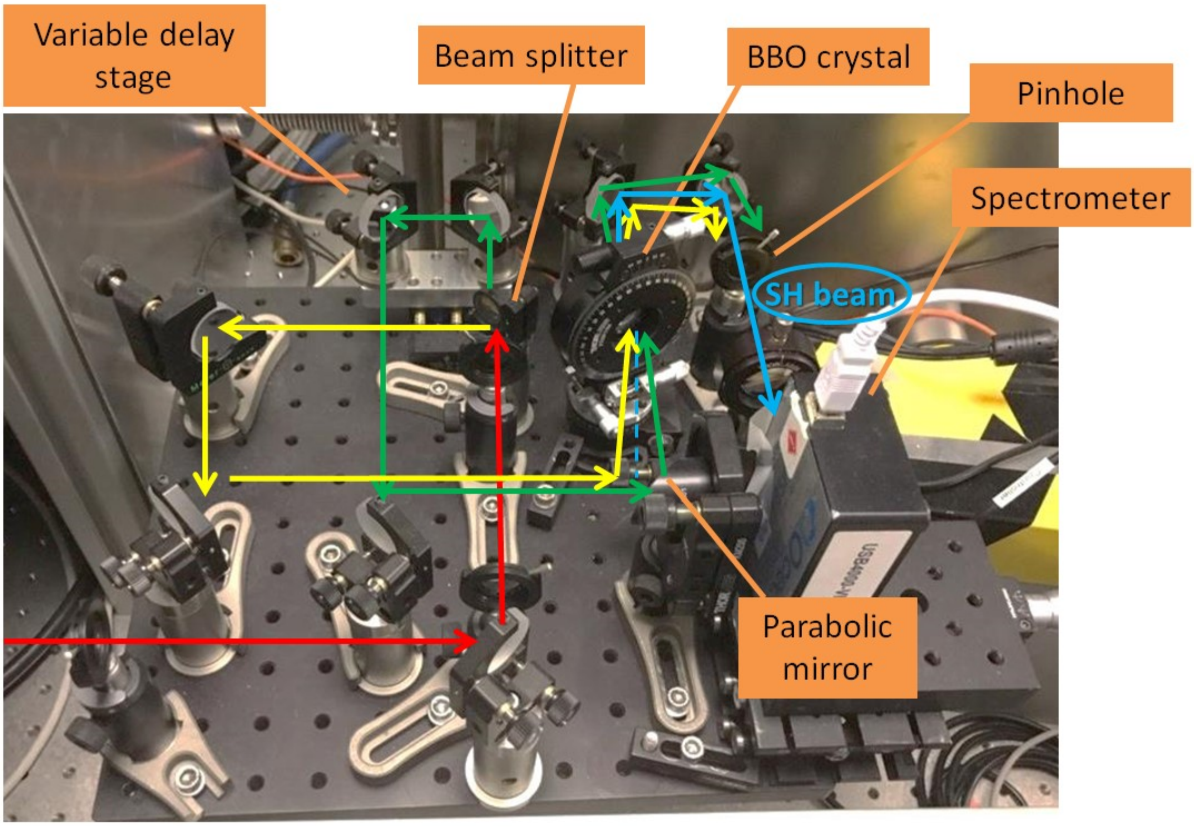

Fig. 7. FROG experimental setup.

3. GRENOUILLE

3.1. Working principle

There is an improvement of FROG – GRENOUILLE (GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields). This device gives a single shot pulse measurement. Moreover it is more compact, what accomplished the following way.

Firstly, the beam splitter, delay line, and beam combining optics are replaced by a single simple element, a Fresnel biprism. Secondly, the thin SHG crystal is replaced by a thick SHG crystal, which not only gives considerably more signal (signal strength scales as the approximate square of the thickness), but also simultaneously replaces the spectrometer (see Fig. 8).

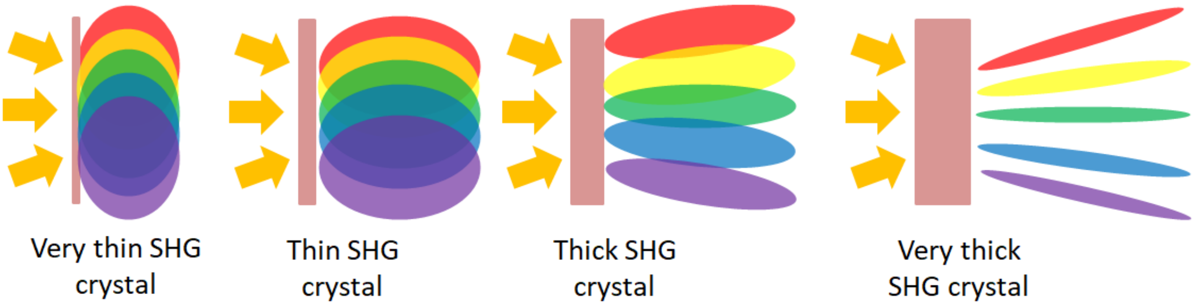

Fig. 8. Illustration of thin and thick SHG crystals illuminated by converging broadband light.

To understand working principle of GRENOUILLE let's consider the Fresnel biprism first. It is a prism with an apex angle close to 180˚. When a Fresnel biprism is illuminated with a wide beam, it splits the beam into two beams and crosses them at an angle. Crossing beams at an angle is exactly what is required in conventional single-shot autocorrelator and FROG beam geometries, in which the relative beam delay is mapped onto horizontal position at the crystal. But, unlike conventional single-shot geometries, beams that are split and crossed by a Fresnel biprism are automatically aligned in space and in time. Then the crystal is imaged onto a camera, where the signal is detected vs. delay.

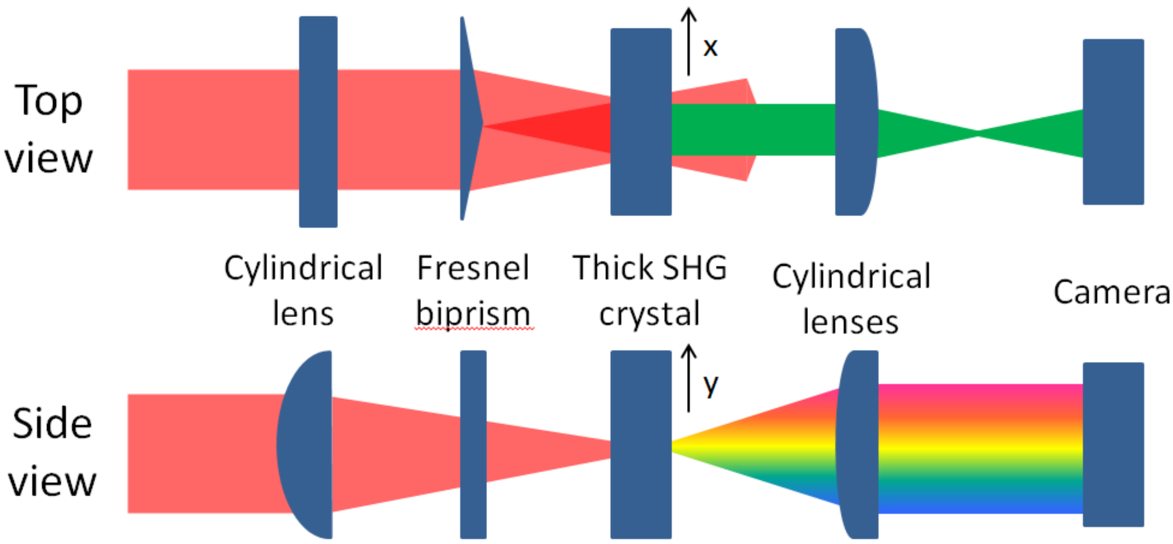

Fig. 9. Side and top views of the GRENOUILLE beam geometry.

FROG also spectrally resolves a pulse that has been timegated by itself. GRENOUILLE combines both of these operations in a single thick SHG crystal. As usual, the SHG crystal performs the self-gating process: the two pulses cross in the crystal with variable delay. But, in addition, the thick crystal has a relatively small phase-matching bandwidth, so the phasematched wavelength produced by it varies with angle (See Fig. 9). Thus, the thick crystal also acts as a spectrometer.

The device is completed by additional cylindrical lenses. The first cylindrical lens must focus the beam into the thick crystal tightly enough to yield a range of crystal incidence (and hence exit) angles large enough to include the entire spectrum of the pulse. After the crystal, a cylindrical lens then maps the crystal exit angle onto position at the camera, with wavelength a near-linear function of (vertical) position.

GRENOUILLE has many advantages. It has few elements and is more compact. It operates single-shot and is considerably sensitive. Furthermore, since GRENOUILLE produces (in real-time, directly on a camera) traces identical to those of SHG FROG, it yields the full pulse intensity and phase (except the direction of time). But the most important is that GRENOUILLE is extremely simple to set up and align.

3.2. Experimental setup with GRENOUILLE

Experimental setup with GRENOUILLE device is presented on Fig. 10.

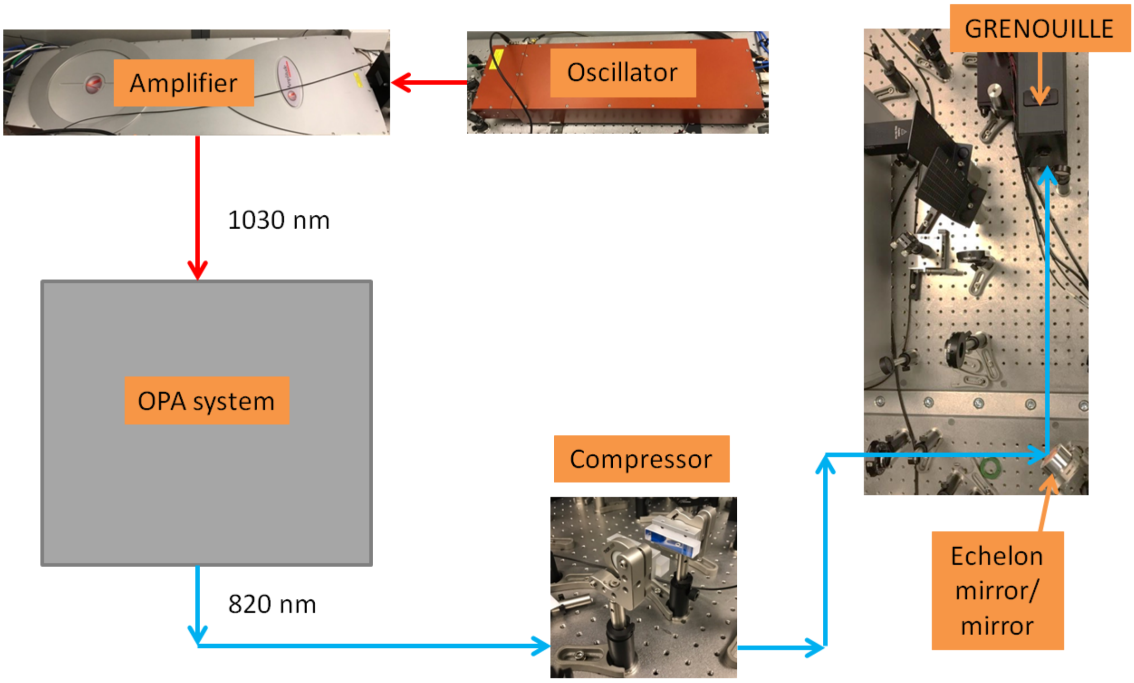

Fig. 10. Experimental setup with GRENOUILLE device.

Beginning in the Yb oscillator and amplifier beam is guided to the OPA system, which transforms 1030 nm wavelength light to 820 nm light.

After that beam goes to the compressive system of mirrors, then to the mirror/echelon mirror and finally to the GRENOUILLE device, where single shot measurement can be made.

3.3. Installation and use of GRENOUILLE

- **Installation of QuickFrog program**
  From the Windows Start button, select Programs -> Femtosoft Technologies -> QuickFrog. Double-click the QuickFrogInstaller program. Follow the steps in the QuickFrog installation program to install the QuickFrog software onto the computer.
- **Installation of the camera drivers**
  The IDS uEye USB Camera is recommended. The uEye drivers should be installed manually. A compatible version of the uEye drivers can be found in the IDS directory. Note that installer must be run before plugging the USB camera into the computer. Start the uEye installation by double-clicking the installer file. On the next stages select “Install driver”. As Setup Type choose “USB” option. Follow the prompts in the installer to complete the installation. This will install the drivers for the IDS uEye USB cameras.
- **Connecting the IDS uEye USB Camera**
  Once the QuickFrog software is installed, the uEye camera can be connected to any free USB port on the computer. Fig. 11 shows the connections for the USB cameras.

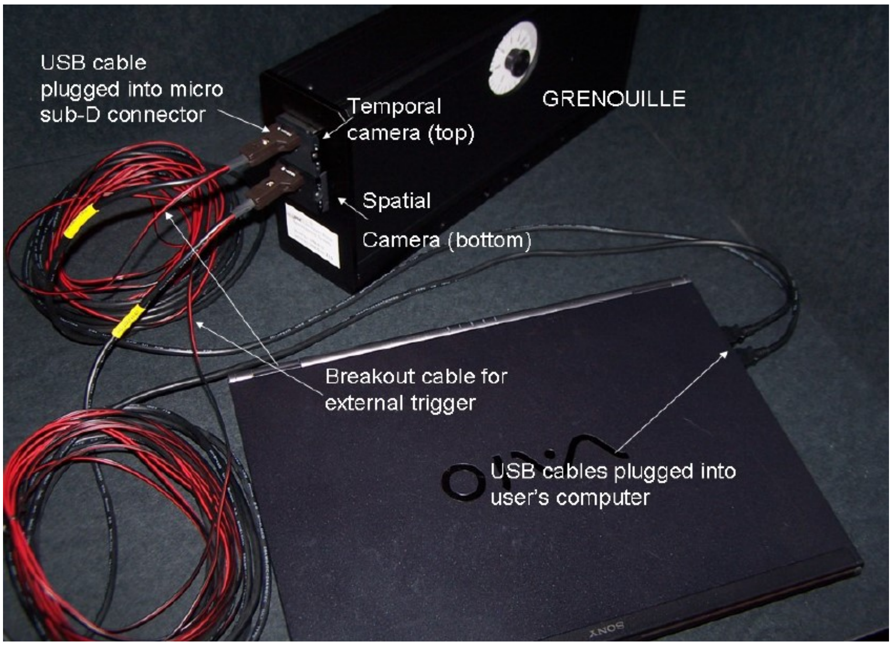

Fig. 11. Connections for the USB cameras.

For a two-camera GRENOUILLE system, be sure to connect only the Temporal Camera (Signal Camera) at this time. The Spatial Camera (Alignment Camera) can be connected after the driver installation completes. Otherwise, QuickFrog might mix up the two cameras. If this happens, activate the Configuration -> Camera Calibrations dialog in QuickFrog and switch the two data source numbers (exchange 1 with 2 and vice versa).

Windows should detect the new hardware, and the New Hardware Wizard will appear. Follow the instructions to finish the uEye driver installation.

- **Camera Should be Working**
  Check the light on the back of the uEye camera. It should now be green. (The light is red when the drivers are not installed).
- **Two Camera GRENOUILLE Systems**
  For a two-camera GRENOUILLE system now is the time to connect the Space camera. Now the uEye camera is ready to go! Start QuickFrog and begin!
- **QuickFrog Software Setup**
  During the first QuickFrog run, before the program starts a dialog will appear asking which GRENOUILLE device is being used:

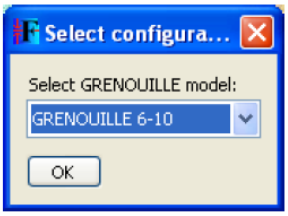

Fig. 12. Selecting of configuration dialog.

This dialog will not appear a second time. This option can be changed in the Configuration -> Camera Calibrations menu selection.

- **Alignment of the GRENOUILLE**
  GRENOUILLE software has two working regimes: space and time modes. Space mode is used to do the beam alignment. Click the Align button to superimpose a crosshair. Follow the procedure in the GRENOUILLE manual to align the optics of the device. The beam has to be aligned through the system directly to the centre of spatial camera. Iris can be closed to make sure that the beam is in the right position.

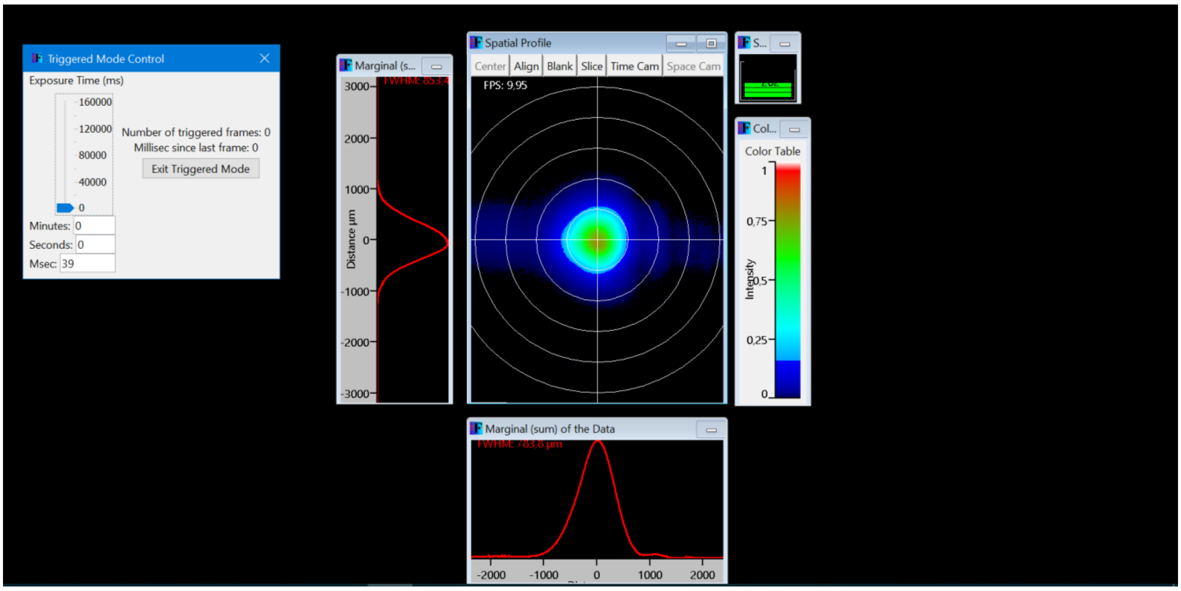

Fig. 13. Space mode of GRENOUILLE software. The beam is in the right position (centre) of spatial camera.

- **Adjusting of Light Levels**

The intensity of the incoming light should be adjusted so that the saturation indicator in the Control Panel window is lighting up all three green bars, but not reaching, or just barely reaching, the yellow bar.

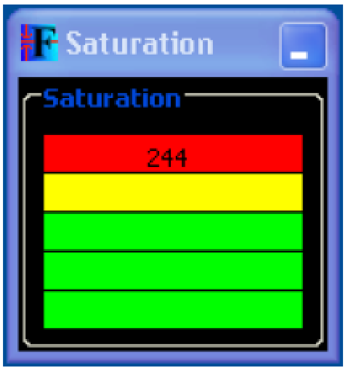

Fig. 14. Adjusting of Light Levels.

- **Setting of Centre Wavelength**

After the beam is aligned system can be switched to the time mode by pressing Ctrl-T or using the menu bar. The wavelength value of the center pixel of the camera should be determined. This value can be entered into Wavelength box of the Control Panel. This value must be reset with every GRENOUILLE wavelength settings tuning.

- **Measurements obtaining**

In time regime single shot pulse measurement can be done. Measured FROG pattern can be received, and the system provides such results as retrieved FROG pattern, autocorrelation, temporal profile with phase and spectral profile with phase.

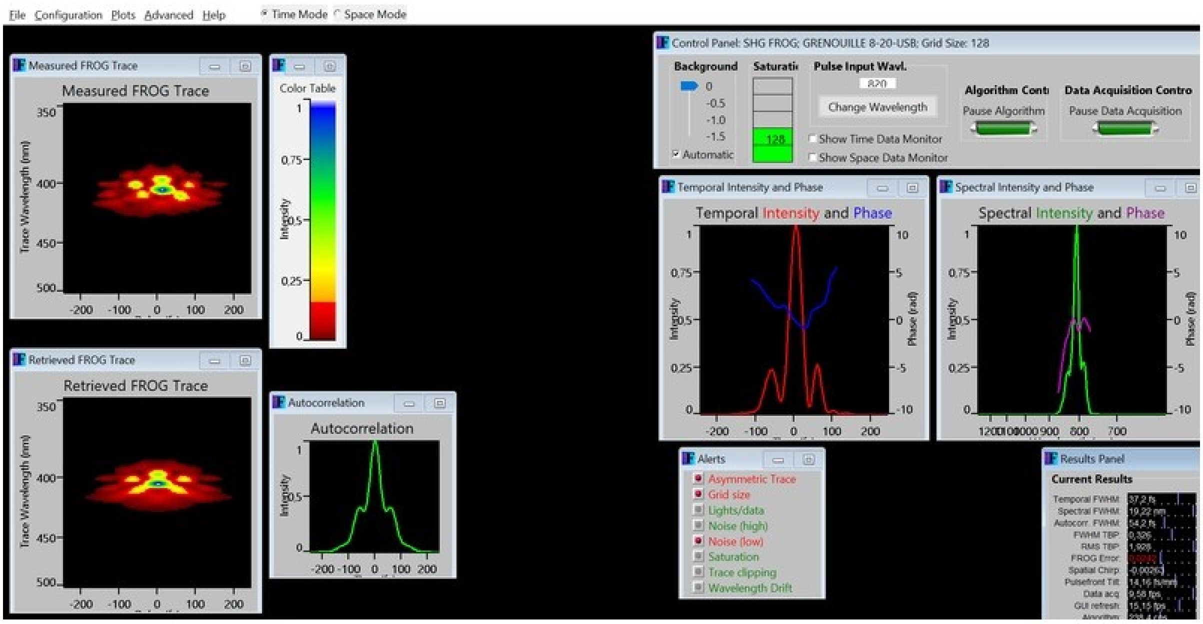

Fig. 15. Time mode of GRENOUILLE software. The system yields results in a single shot.

4. Simulations and experimental results

4.1. Simulation code

MatLab code was made to represent simulations of FROG pattern in order to explain experimental results. The code is accomplished by the following way.
For the case of ordinary mirror first step is generating single ultrashort Gaussian laser pulse:

$$E_{SP}(t) = \cos(\omega t) \cdot e^{-t^2/\sigma^2} + 0.4 \cdot \cos(\omega t) \cdot \left(e^{-(t-dt)^2/\sigma^2} + e^{-(t+dt)^2/\sigma^2}\right),$$

where dt is a time distance between main and side peaks. Pulse is not Gaussian; it has side "shoulders". It is performed by adding Gaussian envelopes of lower intensities before and after initial pulse.
In case of echelon mirror on the first stage train of pulses is developed. Each next pulse is injected at the certain time after the previous one. The algorithm is repeated until obtaining a required number of pulses in train:

$$E_{MP}(t) = \sum_{n=0}^{N-1} \cos(\omega t) \cdot e^{-(t-n\cdot\Delta t)^2/\sigma^2} \cdot e^{-(t-t_0)^2/\sigma_e^2},$$

where N is number of pulses in train, $t_0$is the centre of envelope of a pulse train, Δt is a delay between pulses in one pulse train.
Delayed single pulse and delayed train of pulses are generated the following way:

$$E_{SP}^{del}(t) = \cos(\omega(t - t_i^{del})) \cdot \left[e^{-(t-t_i^{del})^2/\sigma^2} + 0.4 \cdot \left(e^{-\left(t-dt-t_i^{del}\right)^2/\sigma^2} + e^{-\left(t+dt-t_i^{del}\right)^2/\sigma^2}\right)\right],$$

$$E_{MP}^{del}(t) = \sum_{n=0}^{N-1} \cos\left(\omega(t - t_i^{del})\right) \cdot e^{-\left(t-n\cdot\Delta t-t_i^{del}\right)^2/\sigma^2} \cdot e^{-\left(t-t_0-t_i^{del}\right)^2/\sigma_e^2},$$

where t_i^{del} is i-th array element of delay range.
For each time in the whole delay range original pulse/train of pulses is multiplied by delayed one and Fourier transform of this composition is made. Every result is written into matrix, which present FROG pattern when plotted.

4.2. Results with ordinary mirror

Results of this subchapter are comparison of simulations and FROG and GRENOUILLE patterns for a compressed pulse.

On Fig. 16a pulse is compressed but not chirped. It can be seen that it is not a Gaussian profile – it has "shoulders" in time domain as well as in frequency domain (see Fig. 16 b,c). On the pattern there are main intensive peak and side peaks as well. These side peaks come from the interference of the pulse "shoulders". 3 peaks of different intensities in time domain and also in frequency domain can be observed on the pattern.

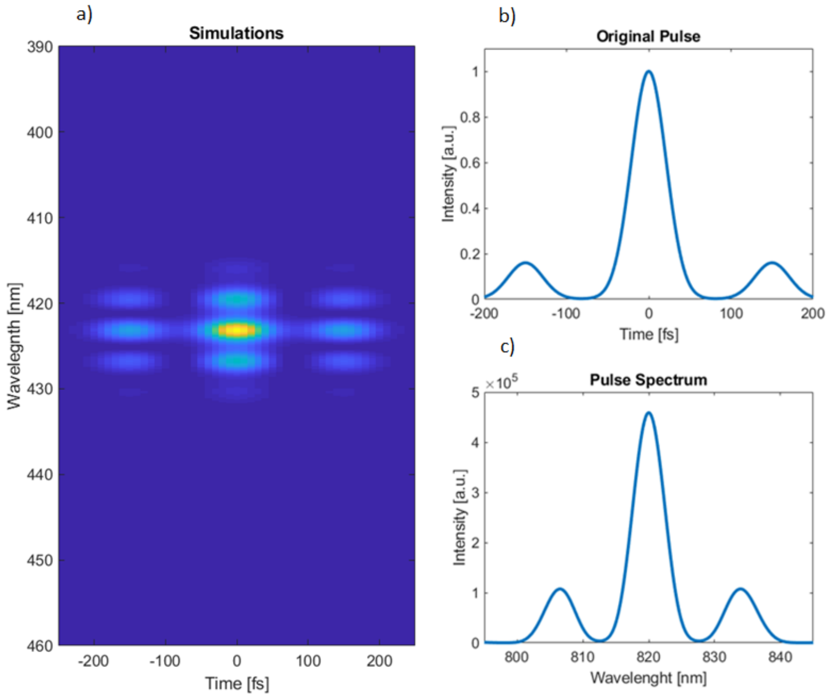

Fig. 16. a) Calculated FROG pattern; b) Original pulse in time domain; c) Pulse spectrum in frequency domain

For GRENOUILLE pattern on Fig. 17a pulse is compressed and chirped. GRENOUILLE device measures phase and temporal profile (see Fig. 17b), which looks quite similar to calculated original pulse. Since in this case the pulse is chirped complexly, side peaks are shifted in spectrum.

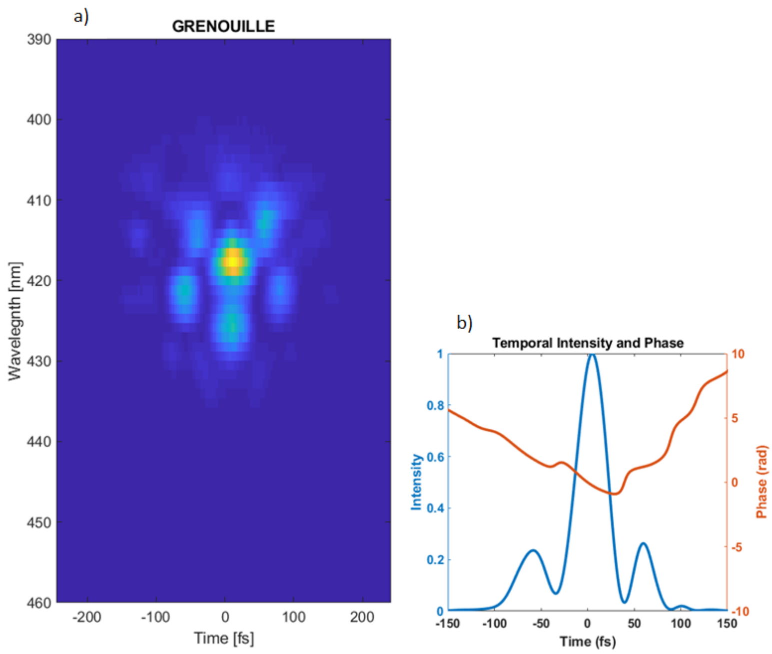

Fig. 17. a) GRENOUILLE pattern; b) Retrieved temporal profile and phase.

For FROG pattern (Fig. N a) pulse is compressed a little more, so there are no side peaks can be seen. Pulse autocorrelation is presented on Fig. 18b.

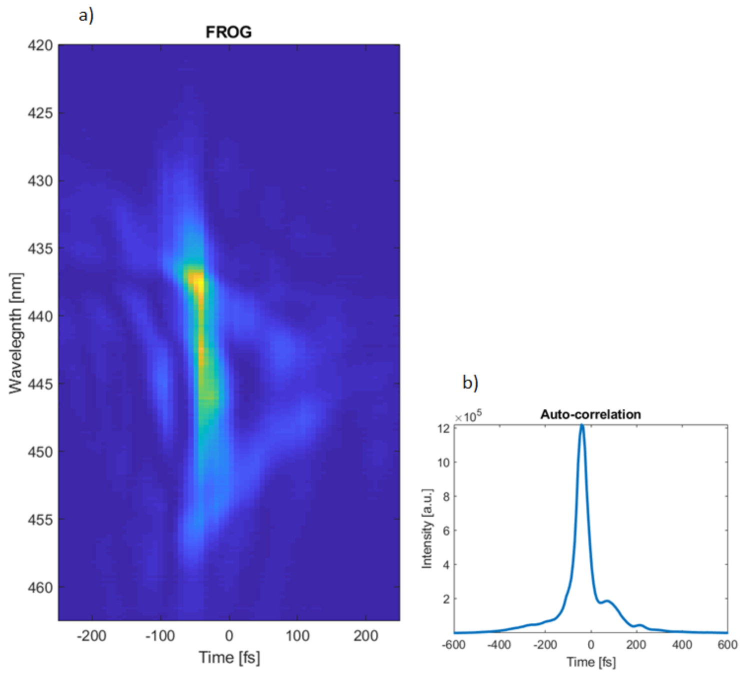

Fig. 18. a) FROG pattern; b) Autocorrelation.

4.3. Results with echelon mirror

Results of this subchapter are comparison of simulations and FROG and GRENOUILLE patterns for a pulse train, generated after illumination of echelon mirror with light.

Calculated original pulse is a train of pulses with certain delay in time domain (see Fig. 19b). Analogous peaks can be seen in time domain on the simulated FROG pattern on Fig. 19a. Since peaks of original pulse interfere, there are several peaks of different intensity in spectrum on Fig. 19c, what can also be observed in frequency domain on the pattern.

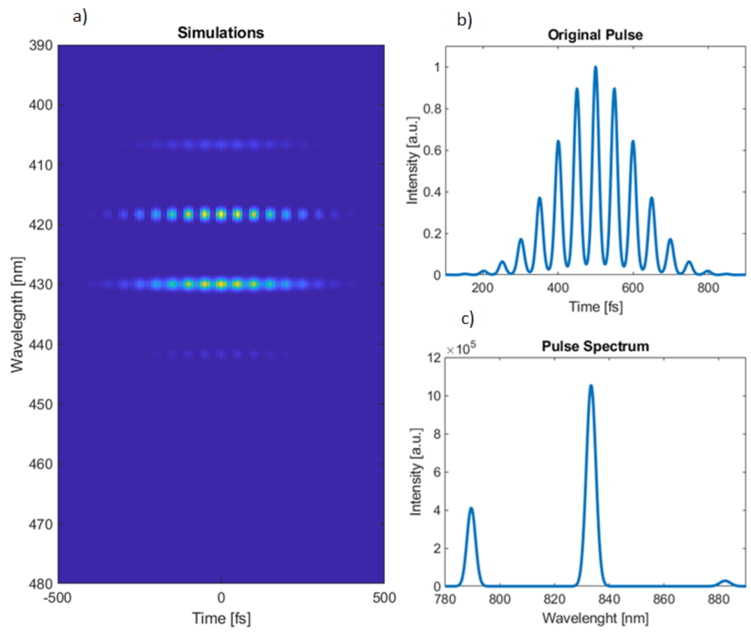

Fig. 19. a) Calculated FROG pattern; b) Original pulse in time domain; c) Pulse spectrum in frequency domain

GRENOUILLE and FROG patterns (Fig. 20a, 21a) present essentially the same results. There are train of pulses in time domain and several peaks in frequency domain. There is also the measurement from autocorrelator (Fig. 21b) and temporal profiles from GRENOUILLE measurement (Fig. 20b,c). Profile presented on Fig. N b might seem not very accurate and do not similar to calculation profile. The reason for that could be the inability of system to reduce errors in such short time (during single shot). However, for the next measurement retrieved temporal profile is almost identical to the calculated one (see Fig. 20c).

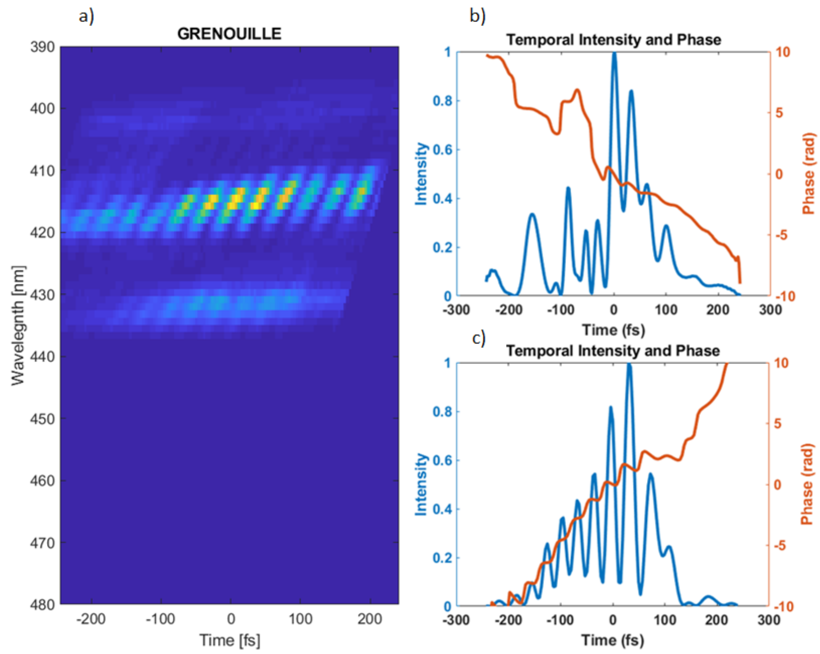

Fig. 20. a) GRENOUILLE pattern; b) Retrieved temporal profile and phase in one moment of time; c) Retrieved temporal profile and phase in another moment of time.

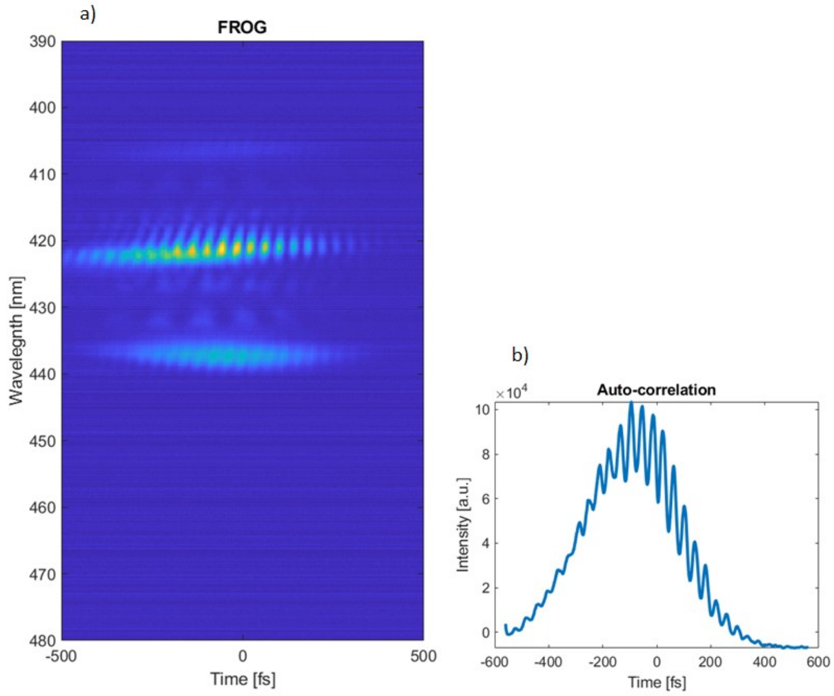

Fig. 21. a) FROG pattern; b) Autocorrelation.

5. Conclusions

5.1. Conclusion 1

- The train of pulses generated after illuminating echelon mirror with light is measured using special technique FROG and device GRENOUILLE;
- MatLab code is developed, and calculated FROG pattern is in agreement with experimental results;
- Multiple pulses are generated by echelon mirror indeed;
- Since echelon mirror works, it can be implemented for single shot THz diagnostic.

5.2. Conclusion 2

GRENOUILLE device was put into use for the first time. Several benefits of this device were detected:

- Single shot
- Compact and portable
- Easy to align
- Receiving immediate results
- Results similar to FROG
- GRENOUILLE is effective and quick, thus it is a great replacement of FROG.

6. References

1. *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulse.* Trebino , Rick

2. *Single-shot terahertz time-domain spectroscopy in pulsed high magnetic fields.* G. Timothy Noe II, Ikufumi Katayama, et. al.