Designing the femtosecond optical oscilloscope

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Abstract. We present the results of our recent experimental and numerical studies on femtosecond pulse spectrotemporal imaging in a similariton-induced temporal lens aimed to designing a femtosecond optical oscilloscope [1]. We have studied nonlinear and dispersive peculiarities of modern high-tech materials, such as photonic crystal fibers, hollow-core fibers etc, to use them in the scheme, and to provide compactness and reliability of the device. The use of hollow-core fibers, as a dispersive medium instead of a pair of prisms or gratings, is of special importance for constructing the industrial tool. Additionally, we are experimenting on the method of dispersive Fourier transformation, using the effect of chromo-modal dispersion in multimode fibers [2], to provide real-time performance of the device.

1. Introduction
The urgent problem of signal characterization in femtosecond time scale involves the powerful arsenal of modern laser physics, using methods of nonlinear and adaptive optics, Fourier optics and holography, spectral interferometry, etc. The most popular and commercialized method of ultrafast signal analysis are FROG and its modifications [3], which provide accurate determination of the pulse temporal profile and phase by recording high-resolution spectrograms, which are later decoded by iterative algorithms for spectral phase retrieving. Other popular technique are spectral interferometry (SI) [4] and its developments (SPIDER [5], SPIRIT [6] and SORBETS [7]), which allow to reconstruct the phase without iterative procedures. Another pulse characterization technique is MIIIPS [8], which uses adaptive compensation of phase up to transform-limited pulse shaping with use of feedback from second harmonic generation (SHG) process for carefully determining spectral phase. All of methods described above are measuring spectral phase, putting it on the spectrum and reconstructing pulse shape.

The pulse direct measurement demands transferring of temporal information to the space or frequency domain, or to the time domain, with a scale measurable achievable by electronic oscilloscopes. The recent implementation of such method allows pulse direct measurement without additional retrieval procedures, and designing of a silicon-chip-based ultrafast oscilloscope with a \textasciitilde 200 fs resolution [15]. In view of higher temporal resolution, our method of spectro-temporal imaging through temporal lensing seems to be more promising, as it is principally limited by nonlinear response time of silica [9-14]. Here we report our current studies on R&D of commercial version of femtosecond optical oscilloscope, which grants direct measurement of femtosecond waveform, with resolution exceeding the resolution of silicon-chip-based ultrafast oscilloscope by an order of magnitude.
2. Principles
We convert the temporal modulation (information) of optical signal into spectral domain (fig. 1), and image it by optical spectrum analyzer [16]. Thus, our time-to-frequency Fourier converter (time lens), upgrades spectrometer into a femtosecond oscilloscope. Our setup consists of dispersive and nonlinear arms, and a nonlinear crystal where the pulses from both arms interact. The Signal $\tilde{A}(\omega)$ gains parabolic phase (linear chirp) in a dispersive delay line (DDL). The output of DDL is described as $\tilde{A}_d(t) = \tilde{A}_i(\omega) \exp(i\phi_c \omega^2 / 2)$ with the given coefficient $\phi_c = -C_d \omega$ (linear chirp). In the nonlinear arm, which consists of a single mode fiber, a nonlinear-dispersive similariton is generated with known parameters, namely, highly linear chirp and wide spectrum, which means that the pulse will have flat top. As both arms have linear chirp, the pulse shapes in both arms will repeat their own spectra: $A_d(t) \propto \tilde{A}_d(\omega)$, and $A_i(t) \propto \tilde{A}_i(\omega)$ with $\omega \approx C_d t$. Both arms are participating in sum frequency generation (SFG) process in nonlinear crystal, where due to their chirp values $C_d = C_n$, and the flat top similariton spectrum in the scales of dispersive pulse spectrum, the output temporal SFG-signal profile repeats the input spectral amplitude profile: $\tilde{A}_{SFG}(t) \propto \tilde{A}_i(\omega) \times \tilde{A}_d(\omega)$. As a result, the SFG-signal spectral and input temporal amplitude profiles repeat each other: $\tilde{A}_{SFG}(\omega) \propto A(t)$, and the output spectrum displays directly the input temporal intensity profile: $S_{SFG}(\omega) = |\tilde{A}_{SFG}(\omega)|^2 \propto |A(t)|^2 = I(t)$, with the scale $\omega = Ct$. The resolution of the measurement carried out by this method is determined by the similariton spectral width. A few tens of nanometers of spectral width for the similariton secures a resolution [16] of an order of magnitude higher then the one for the silicon-chip-based ultrafast optical oscilloscope [15].

![Figure 1. Pulse spectrotomtemporal imaging.](image)

3. Experimental studies
3.1. Laboratory version of the device
In our femtosecond optical oscilloscope, the input radiation is initially split by a beam splitter into two arms, with approximately 20% and 80% power proportions, depending on the setup. The low power part passes through a dispersive delay line (DDL), which consist of a pair of prism/grating or other dispersive medium with negative dispersion. Here the pulse obtains linear negative chirp, which is easily calculated having the prism/grating configurations. The high power part passes through a standard single mode fiber, where a nonlinear-dispersive similariton is generated with positive linear chirp depending only on the fiber parameters. Both arms must be set up so that the pulses obtain equal absolute values of chirp after passing through them. One of the prisms/gratings must be on a translation stage, for further accurate equilibration of the chirp absolute values. Beams from the both arms are focused through a lens on a second harmonic crystal, such as BBO, where in the process of sum frequency generation chirps from both arms are compensating each other, resulting in spectral compression [17;18], while the temporal profile of the DDL pulse is multiplied by the flat top of the similariton signal. The resulting sum frequency signal is measured by an optical spectrum analyzer, where the image of the input signal temporal profile is depicted in the spectral domain. One or more of mirrors in the scheme must be on a translation stage, for accurate spatial delay manipulations, which allows the tuning of the central wavelength at which the sum frequency signal is generated, due to the linear chirp of the similariton.
The initial experimental scheme used a pair of prisms as a dispersive delay line and had sizes of around 3x3 m². Different shapes were given to the input pulse, afterwards the measured autocorrelation traces were compared to autocorrelations of spectrotemporal images. Figure 2(a) shows a two-peak pulse image with equal peaks, calculated autocorrelation traces are compared to measured ones (figure 2(b)), which nearly ideally repeat each other, meaning that the spectrotemporal imaging was done with extreme precision [16]. Figure 3(c) and (d) correspond to more complex pulse shape and its autocorrelation comparison to experimental one respectively. In this more complex case, the calculated autocorrelation trace had some minor deviations from measured autocorrelation curves [16]. Peaks were shaped by placing one or more ~100 μm thick plates of glass inside part of beam and changing the proportion of radiation that passes through it and the radiation that skips the plates.

![Figure 2](image1.png)

**Figure 2.** Results of spectrotemporal imaging with initial prism pair-based scheme: image of two equal peaks (a), measured and calculated autocorrelation curves (b), complex waveform spectral image (c), and its autocorrelation comparison to the measured autocorrelation trace (d).

![Figure 3](image2.png)

**Figure 3.** 23x SC in STI scheme from 11.1 nm @ 800nm central wavelength (a) down to 0.12nm @ 394nm central wavelength (b).

As the spectral compression ratio has strong impact on the resolution of the signal image, experiments towards achieving high values of compression were done. Prism pair has been used as dispersive delay line with separation of 3.5 meters. Spectral compression of 23x has been achieved through the SFG technique, with compressed spectrum from 11.1 nm at 800 nm central wavelength (figure 3(a)) down to 0.12 nm at 394 nm (figure 3(b)). This technique of spectral compression is noticeable as it is free of aberration due to parabolic phase of similariton pulse, which serves as the time lens in this technique. Moreover, as the similariton is linearly chirped, it is possible to tune the SC radiation along the similariton spectral width by simply changing the spatial delay between dispersive and nonlinear arms.

Besides the autocorrelation curve comparison to calculated curves, we have done implemented spectral interferometric technique for pulse characterization, for comparing the results with images from our optical oscilloscope [1,19]. For this technique radiation is split into two arms, one passes through single mod fiber generating similariton (figure 4(a)), the other part passes directly without being altered. Afterwards those two arms are coupled into a spectrometer where spectrum with interferential beatings is registered. Phase is retrieved from it by numerical analyse (figure 4(b)), and
is put on initial spectrum, resulting in pulse form reconstruction (figure 5(c)). Results are compared to autocorrelation measurements (figure 4(d)) and are in good agreement with them. Figure 5 represents an example of comparison of spectral interferometric and spectrotemporal imaging studies. Spectrum of input pulse is measured (figure 5(a)), and the spectral phase (figure 5(b)) is calculated from interferometric spectral beats. Afterwards the input pulse shape (figure 5(c)) is calculated and compared with results of optical oscilloscope. Results are in good agreement with each other.

Figure 4. Two peak pulse reconstruction through SI in compareison with autocorrelation measurements: spectrum of nonlinear-dispersive similariton (a), retrieved spectral phases and measured spectrum of signal pulse spectrum (b), reconstructed temporal profiles (c), measured and calculated autocorrelation traces (d). Blue and red curves correspond to different realizations, black correspond to measured signals

Figure 5. Comparison of Spectral Interferometry (red) and Femtosecond Oscilloscope (black) results: spectrum(a), spectral phase (b), and pulse(c).

3.2. Compact scheme

The next step of our research was implementation of the commercial prototype of the device which should be smaller in sizes and more user-friendly and reliable. Figure 6(a) shows our 3D blueprint of our designed commercial prototype. Passing from prism pair to grating pair and some other mechanical optimizations allowed to decrease dramatically the sizes from 3x3 m² down to 30x30 cm² (figure 6(b)), to fit the commercial demands on standard laboratory devices. Further optimizations and use of high-tech materials (e.g. photonic crystal fiber, hollow core fiber, etc.) may reduce the sizes by at least half.

Connected with a spectral analyzer this block can allow precise measurement of femtosecond signal shape and duration. Figure 7 shows screen of optical spectrum analyzer with image of input pulse intensity profile. We use spectrometer with 0.05 nm resolution. Demands on resolution depend on input spectral width and spectral compression ratio used for imaging. Figure 8 represents results achieved with the compact device. Input spectrum of two peak pulse with equal peak height are shown in figure 8(a). Holes in this case are maximally low, which corresponds to equally shaped peaks. Figure 8(b) shows the image of equal peaks from the spectrum of output signal. Figure 8(c) and figure 8(d) show input spectrum and output spectrotemporal image of unequally shaped two peaks respectively.
Moreover, this device can be used for spectral interferometric studies by simply removing the BBO crystal and coupling both arms into the spectrometer. As the spectral interferometric scheme does not include dispersive delay line for second arm, one has to numerically compensate the linear chirp given by grating pair.

3.3. All-fiber configuration
One possible upgrade of our oscilloscope is replacement of dispersive elements (prism or grating pair) with hollow core fiber (HCF). We have examined Thorlabs HC-800-B hollow core fiber, which grants negative dispersion at our wavelength. Passing to all-fiber configuration of device would decrease its size dramatically, thus making it more comfortable in use as a diagnostic tool. Figure 9 represents our initial experimental results with HCF. We have shaped two equal peaks (figure 9(a) represents its spectrum) and recovered it @400nm (figure 9(b)). Results were distorted due to high orders of dispersion in HCF fiber. One of possible solution of this problem is to reduce the length of HCF fiber used in scheme, thus reducing the higher order dispersion impact on spectral compression process.
3.4. CMD stretcher

Another attractive upgrade of the device can be the transferring of the spectral signal back to temporal domain and measurement of the signal by an electronic oscilloscope, which would make the measurements time-resolved. To transfer the spectral information to intensity profile so that it would be possibly be measured by a common ~1GHz bandwidth oscilloscope, one would have to stretch the signal pulse dramatically from few picoseconds to few nanoseconds, giving it huge amount of parabolic phase (linear chirp). Grating pair is hard to use in this case as in the scheme one grating would have to be ~30 cm in size. We have experimented with one of solutions of this problem, which was implementation of so-called chromo-modal (CMD) dispersion [2]. Initially we have experimented with shaping the laser radiation spectrum and recovering it through CMD scheme (figure 10). Figure 10(a) represents recovery of laser spectrum with CMD without shaping. Figure 10(b) show the result with two peak spectral shape. For implementation of CMD scheme after optical oscilloscope one has to use very sensitive detectors as the signal from output of optical oscilloscope is low in power and the CMD device lowers it in two orders of magnitude.
4. Conclusion
We have shown the decade evolution of spectrotemporal imaging technique, starting from huge laboratory version and ending with small and portable commercial prototype. In comparison with other commercial diagnostic tools such as FROG [3], SPIDER [5] / SPIRIT [6], SORBETS [7], and MIIPS [8], which are based on spectral phase iterative registration and further recovery of pulse temporal profile, our method provides direct imaging of input pulse temporal profile on spectrometer screen. It also has a resolution of an order of magnitude higher than other direct imaging setups such as silicon chip based ultrafast oscilloscope. We have also provided possible upgrade directions, which could be passing to real-time single pulse measurements through generating of a giant stretched spectrum and registering it by an electronic oscilloscope. Another possible upgrade of device can be passing to all-fiber scheme, which will reduce the sizes of device by several times.

References
[1] Zeytunyan A, Muradyan A, Yesayan G, Mouradian L, Louradour F and Barthélémy A 2011 Optics Communications 284 3742–47
[2] Diebold E D et al 2011 Optics Express 19 23817
[3] Kane D J and Trebino R 1993 Opt. Lett. 18 823–25
[4] Akturk S, Kimmel M, O’Shea P and Trebino R 2003 Optics Express 11 68–78
[5] Piasecki J, Colombeau B, Vampouille M, Froehly C and Arnaud J A 1980 Appl. Opt. 19 3749
[6] Reynaud F, Salin F and Barthélémy A 1989 Opt. Lett. 14 275–7
[7] Iaconis C and Walmsley I A 1998 Opt. Lett. 23 792–4
[8] Messager V, Louradour F, Froehly C and Barthélémy A 2003 Opt. Lett. 28 743–5
[9] Mouradian L Kh, Louradour F, Messager V, Barthélémy A and Froehly C 2000 IEEE J. Quantum Electron. 36 795–801
[10] Mouradian L Kh, Zohrabian A V, Froehly C, Louradour F and Barthélémy A 1998 A in Conf. Lasers and Electro-Optics (CLEO/Europe), OSA Tech. Digest Series CMA5
[11] Mouradian L Kh, Louradour F, Froehly C and Barthélémy A 1998 in Nonlinear Guided Waves and Their Applications, OSA Tech. Digest Series 5 NFC4
[12] Mouradian L Kh, Zohrabayn A V, Ninoyan V J, Kutuzian A A, Froehly C, Louradour F and Barthélémy A 1998 Proc. SPIE 3418 78–85
[13] Zohrabayan A V, Kutuzian A A, Ninoyan V Zh and Mouradian L Kh 1997 AIP Conf. Proc. 406 395–401
[14] Markaryan N L and Muradyan L Kh 1995 Quantum Electron. 25 668–70
[15] Foster M A, Salem R, Geraghty D F, Turner-Foster A C, Lipson M and Gaeta A L 2008 Nature 456 81–4
[16] Mansuryan T, Zeytunyan A, Kalashyan M, Yesayan G, Mouradian L, Louradour F and Barthélémy A 2008 J. Opt. Soc. Am. B 25 A101
[17] Muradyan L Kh, Markaryan N L, Papazyan T A and Ohanyan A A 1990 CLEO Tech. Digest CTUH32 120-1 Sov. J. Quantum Electron. 21, 783–785 (1991).
[18] Oberthaler M and Hopfle R A 1993 Appl. Phys. Lett. 63 1017–9
[19] Mouradian L, Zeytunyan A and Yesayan G 2012 Interferometry - Research and Applications in Science and Technology chapter V Similariton-based spectral interferometry for signal analysis on femtosecond time scale ed. Dr Ivan Padron (InTech) pp. 99–124