MEFISTO: Measuring the Electric Field of Ultrashort Pulses by Interferometric Spectral Trace Observation

Ivan Amat-Roldán, Iain G. Cormack, and Pablo Loza-Alvarez
ICFO - Institut de Ciències Fotòniques, Jordi Girona, 29, Nexus II, 08034, Barcelona, Spain.
Ivan.amat@icfo.es

David Artigas
Department of Signal Theory and Communications, Universitat Politècnica de Catalunya,
Campus Nord, 08034 Barcelona, Spain.

Abstract: An analytical way to completely characterize ultrashort pulses is presented. This methodology is based on Fourier analysis of the frequency components of spectrally resolved interferometric autocorrelations. Experimental results are compared with the conventional SHG-FROG technique.

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The problem of how to extract the phase information of an ultrashort pulse when only its spectral intensity can be experimentally measured has resulted in concerted effort. There are a number of techniques that circumvent this problem, each of them possessing their own distinct advantages and disadvantages. These techniques can, in general, be divided into two main categories; time-frequency [1, 2] and interferometric [3, 4]. A Time-Frequency representation of a pulse generally allows far superior analysis making it possible to immediately detect systematic errors. These techniques, however, rely on the acquisition of many data points as well as an iterative retrieval algorithm [5] in order to recover the pulse information. In contrast, interferometric techniques [3, 4], can offer direct phase measurement without the need of retrieval algorithms or the collection of large data sets. As a consequence, pulse characterization can easily be carried out in real time [6]. Interferometric techniques however do not possess stringent error checking capability and they normally rely on a pulse-specific optical arrangement.

In this paper we will describe a new and important general methodology that allows the phase an unknown pulse to be analytically obtained. As a consequence, an iterative retrieval algorithm is not required. Furthermore, this novel method helps to bring together time-frequency and interferometric techniques while at the same time maintaining the robust error checking capability of the time-frequency approaches and discarding some of their negative attributes. Our methodology only requires a simple collinear autocorrelator whose output is spectrally resolved as a function of delay [7]. The experimental setup is shown in Fig. 1. This method is referred to us as Measurement of Electric Field by Interferometric Spectral Trace Observation (MEFISTO)

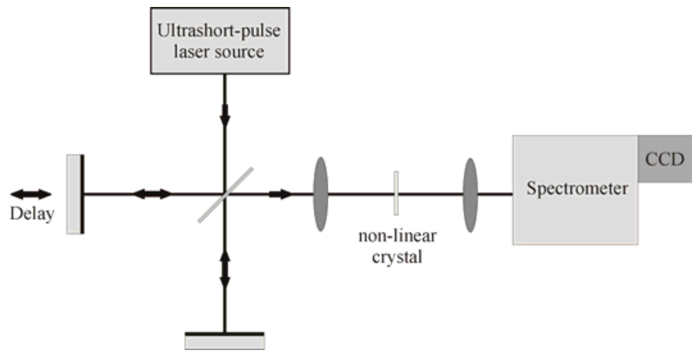

Fig. 1. Schematic of the experimental setup used for MEFISTO.

To start with our analysis, consider a pulse interacting collinearly within a nonlinear crystal, after passing through an autocorrelator. The second harmonic generated signal is then directed to a spectrograph to obtain an interferometric trace in terms of the time-delay τ and the frequency f. An experimental example of such a trace can be seen in Fig. 2(a). The resulting trace can be mathematically described as [7]:

$$I^{SHG}(f,\tau) = \left| F_t\left\{ \left(E(t)\exp[i2\pi f_0 t] + E(t-\tau)\exp[i2\pi f_0 (t-\tau)] \right)^2 \right\} \right|^2 \qquad (1)$$

Here $E(t)$ is the slowly varying amplitude of the complex electric field centred at the frequency f_0. The Fourier transform with respect to the variable t is indicated by F_t. The main difference with SHG-FROG is that all the cross-terms in (1) are retained and, as we will show below, with the new information carried on these terms it will be possible to analytically obtain $E(t)$.

In order to do this, we first calculate the Fourier transform of equation (1) in the τ axis, i.e., $Y^{SHG}(f,\kappa) = F_\tau\{I^{SHG}(f,\tau)\}$. The resulting expression consist of 5 main spectral components (see Fig. 2(b)) at frequencies DC, $\pm f_0$ and $\pm 2f_0$. Since the interferometric trace (Fig. 2(a)) is symmetric and real, the negative spectral components are real and equal to the positive ones (see Fig. 2(b)). Therefore, to analyze the information enclosed in the transformed trace, we only need to focus on the positive frequency components. Each of these terms carry information of the pulse phase and intensity and their use will depend on the particular experimental conditions[8].

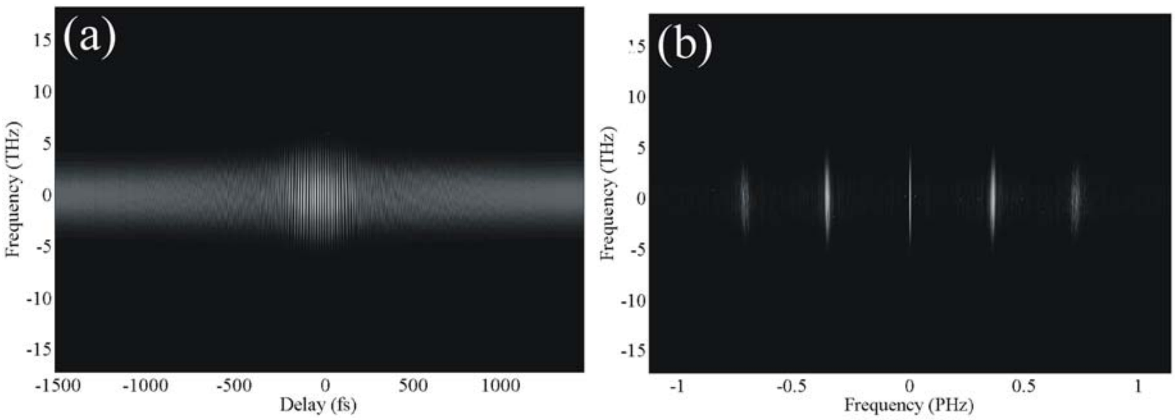

Fig. 2. a) Frequency resolved collinear autocorrelation. b) Same trace in the Fourier domain showing its Fourier components at frequencies DC, $\pm f_0$ and $\pm 2f_0$. (For clarity, intensity scale is not linear).

Here we analyze the case of the spectral components of $Y^{SHG}(f,\kappa)$ near $\kappa \approx f_0$. In such a situation, after some algebra, we can write this spectral component as,

$$Y^{SHG}_{\kappa\approx f_0}(f,\kappa) = 4U_{SHG}(f)U(f+f_0-\kappa)U(\kappa-f_0)\,\cos[\phi_{SHG}(f)-\phi(f+f_0-\kappa)-\phi(\kappa-f_0)] \quad (2)$$

where we write the complex electric field amplitude in polar form, i.e., $E(f) = U(f)\exp(i\phi(f))$ and the second harmonic field is defined as $E_{SHG}(f) = \int_{-\infty}^{\infty} df' E(f')E(f-f')$. Under typical lab conditions, the amplitude of the fundamental pulses, $U(f)$, and of the corresponding second harmonic, $U_{SHG}(f)$ are known. Therefore, the only unknowns in equation (2) are the phase of the fundamental and second harmonic pulse, i.e., $\phi(f)$ and $\phi_{SHG}(f)$. Once the phases are known, the pulses are completely characterized. This can be successfully achieved by taking two different slices in the transformed space of the interferometric trace, e.g., at $\kappa = f_0$ and $\kappa = f_0 - \Delta f$. Then from (2) by subtracting equations the two expression obtained for the two slices, we obtain

$$\Delta\phi(f) = \phi(f+\Delta f) - \phi(f) = \cos^{-1}[\Omega(f,\kappa = f_0)] - \cos^{-1}[\Omega(f,\kappa = f_0 - \Delta f)] + \phi(0) - \phi(-\Delta f) \quad (3)$$

where we have defined, $\Omega(f,\kappa) = \dfrac{Y^{SHG}(f,\kappa)}{4U_{SHG}(f)U(f+f_0-\kappa)U(\kappa-f_0)}$. Note that all the functions in the parameter $\Omega(f,\kappa)$ can be experimentally obtained. Therefore, this equation allows to characterize an ultrashort pulse by determining the phase of $E(f)$, taking an arbitrary origin $\phi(0)$ and varying f.

To show the validity of the MEFISTO methodology, we experimentally obtain the spectral phase of pulses originating from a Kerr-lens mode-locked Ti:Sapphire laser. The laser had a central wavelength of 800 nm and a repetition rate of 76 MHz. The laser beam was focused into a type I BBO crystal through an autocorrelator. The SHG signal was sent to a spectrometer and detected by a CCD linear array. The obtained frequency resolved interferometric autocorrelation trace is the one shown in Fig 2(a). We then analytically extracted the spectral phase of our pulse using equations (3). To demonstrate the effectiveness of MEFISTO, we used the same experimental data to analytically characterize the pulse and then compared them with a standard SHG-FROG retrieval. The SHG-FROG trace was obtained using the CFROG technique [7]. Marginal analysis was also carried out to ensure that errors were not present within the trace and here it should be emphasised that MEFISTO can use the same stringent marginal checks. The obtained results are outlined in Fig. 3(a) where the spectral intensity and phase of the pulse obtained from both techniques are compared. We can see that although the methodologies used to obtain the pulse characteristics were completely different, the intensity and phase are very similar. As a further comparison we also calculated the interferometric autocorrelation from the pulses obtained from both methods.

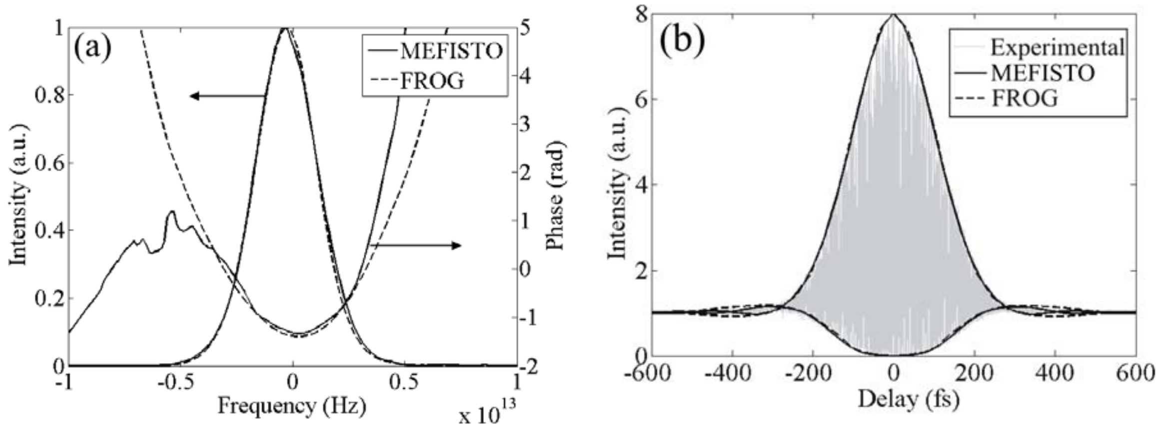

Fig. 3. a) Spectra and phases of the pulse obtained using MEFISTO (solid lines) and a standard SHG-FROG procedure (dashed lines) and b) Numerical interferometric autocorrelations obtained from MEFISTO (solid line) and the SHG-FROG technique (dashed line) compared with experimental measurements (in light gray).

In conclusion, in this work we have outlined a new procedure based on a simple collinear autocorrelator that allows the complex amplitude of ultrashort pulses to be analytically deduced. The technique relies on Fourier analysis after obtaining a spectrally resolved interferometric autocorrelation trace. The MEFISTO methodology has the crucial advantage over SHG-FROG in that it enables the simple extraction of pulse information without the need of an iterative retrieval algorithm. Furthermore, it still maintains the powerful error checking capabilities that are associated with time-frequency techniques. We have experimentally demonstrated the effectiveness of the new procedure by comparing results with the more traditional characterisation technique of SHG-FROG using an identical optical arrangement. This setup is extremely flexible and simple, allowing a large number of different applications to be carried out [9]. The MEFISTO technique also compares extremely favourably to interferometric techniques such as SPIDER where complex pre-chirping and pulse manipulation is required for specific pulses in order to avoid experimental errors being introduced.

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