Complex-field measurement of ultrafast dynamic optical waveforms based on real-time spectral interferometry

Mohammad H. Asghari*, Yongwoo Park and José Azaña

Institut National de la Recherche Scientifique – Energie, Matériaux et Télécommunications (INRS-EMT), Montreal, Québec, H5A 1K6 Canada,
*asghari@emt.inrs.ca

Abstract: Several methods are now available for single-shot measurement of the complex field (amplitude and phase profiles) of optical waveforms with resolutions down to the sub-picosecond range. As a main critical limitation, all these techniques exhibit measurement update rates typically slower than a few Hz. It would be very challenging to directly upgrade the update rate of any of these available methods beyond a few kHz. By combining spectral interferometry with dispersion-induced real-time optical Fourier transformation, here we demonstrate single-shot complex-field measurements of optical waveforms with a resolution of ~400 fs over a record length as long as ~350 ps, corresponding to a large record-length-to-resolution ratio of ~900. This performance is achieved at a measurement update rate of ~17 MHz, i.e. at least one thousand times faster than with any previous single-shot complex-field THz-bandwidth optical signal characterization method.

©2010 Optical Society of America

OCIS codes: (320.7100) Ultrafast measurements; (120.3180) Interferometry; (200.4740) Optical processing;

References and links

1. Introduction

Future progress in a wide range of fields [1-8] essentially depend on the development of improved temporal waveform measurement methods, capable of providing the stringent performance that is required to capture ultrafast phenomena, i.e. with resolutions down to the sub-picosecond range, in an entirely dynamic fashion, i.e. as these phenomena evolve at ultrahigh speeds. The capability of performing such advanced measurements is important for applications in which random (non-repetitive), rapidly-changing ultrafast waveforms need to be fully characterized and evaluated. These include real-time monitoring in ultrahigh-bit-rate applications in which random (non-repetitive), rapidly-changing ultrafast waveforms need to be fully characterized and evaluated. These include real-time monitoring in ultrahigh-bit-rate optical telecommunication, computing and information processing systems [1,2,10]; testing of electronic and photonic materials, devices and sub-systems [3-6]; and observation and analysis of a large variety of ultrafast dynamic events in physics, biology, chemistry etc [7,8].

In the past decades, new and improved methods for measuring the complex-field temporal (or spectral) profile of ultrafast optical signals have been developed [1-10]. For characterization of non-repetitive events, single-shot measurement techniques are necessary [2,10-18]. A main figure-of-merit to evaluate the performance of single-shot optical signal characterization techniques is the time-bandwidth product, calculated as the ratio between the maximum duration of the waveform that can be measured (record length) and the temporal resolution (inversely proportional to the spectral bandwidth) offered by the measurement setup. Well-established non-linear optical techniques exist for ultrafast signal measurement with few-femtosecond accuracy [12,13]; linear counterparts of these techniques have been also developed with the aim of increasing the measurement sensitivity [14,15]. However, these widely used methods typically suffer from relatively short single-shot record lengths of a few tens of picoseconds. Ultrafast optical signal measurement techniques based on the time-lens concept have been explored to overcome this limitation [2,11]. In a recent state-of-the-art
demonstration, single-shot optical waveform measurements were carried out with sub-picosecond resolutions over total durations up to the sub-nanosecond range, corresponding to an estimated time-bandwidth product of ~450, using a non-linear silicon chip-based time-lens [2]. However, time-lens based methods are typically restricted to measuring the temporal amplitude profile of the optical signal under test and they do not provide any information on the signal’s phase profile. This information is essential to achieve a full (complex-field) signal characterization. Fontaine et al. [10] recently demonstrated an interferometric method that performs parallel coherent detection on spectral slices of arbitrary optical waveforms for real-time, complex-field optical waveform measurements. While it would be challenging to extend the capabilities of this method to measure optical signals with bandwidths in the THz range using present technology, this technique has enabled the measurement of waveforms with very large time-bandwidth products (320,000).

Complex-field THz-bandwidth optical signal characterization methods generally rely on spectral measurements [12-19] since direct time-domain photo-detection is severely bandwidth limited (<50 GHz). However, a critical constraint of available optical spectrometers is that they exhibit a very limited update rate (slower than a few kHz, in the best case) and consequently, they are not capable of capturing rapidly-varying optical waveforms. This limitation is more pronounced when a higher spectral resolution is needed, e.g. to achieve an increased record length (inversely proportional to the frequency resolution). Real-time optical Fourier transformation (RT-OFT) [20,21] is based on mapping the energy spectrum of a given time-limited waveform along the time domain by simple linear propagation through a highly-dispersive medium, e.g. optical fiber. This enables measuring the desired energy spectrum directly in the time domain, which translates into potential measurement update rates orders of magnitude larger than with conventional spectrometers. If the dispersive medium is properly designed, a simultaneous improvement in the spectral measurement resolution and sensitivity can be also achieved. RT-OFT has been exploited for a range of important applications, including real-time reflectometry and spectroscopy [22, 23], and analysis of rapidly-changing physical processes [7, 8]. However, as a main limitation, RT-OFT only provides information on the spectral amplitude profile of the signal under analysis, and consequently, it does not allow one to obtain a full characterization of the target signal, including information on the phase profiles. Time-domain interferometry methods based on fiber dispersion have been previously employed for complex-field optical signal and device characterization [3,4,24-26]. These previous methods are self-referenced, and thus they offer relatively limited measurement accuracy and sensitivity. In optical waveform measurement techniques that use referencing, the signal under test (SUT) is combined with a strong reference signal; this offers an additional degree of control as compared with self-referenced methods since for instance, the reference signal energy can be optimized to increase the visibility of the measured interference fringes, leading to an associated improvement in the measurement accuracy and sensitivity. As a critical associated drawback, these methods require the use of averaging of the temporal interference pattern for precise waveform recovery [25], which adversely affects their capability to perform real-time and single-shot signal measurements. A referenced single-shot scheme for real-time complex-field characterization of optical signals was demonstrated in [27] by use of heterodyning combined with time magnification, but it can only be used for characterizing optical signals with bandwidths up to a few tens of GHz.

In this manuscript, we propose and develop a simple and practical (fiber-optics) method for complex-field ultrafast optical signal characterization using a balanced Fourier-transform spectral interferometry (FTSI) scheme [15-19] combined with RT-OFT. Using this new linear approach, we demonstrate single-shot characterization of complex optical events (including accurate measurement of continuous and discrete-time phase variations), with a large time-bandwidth products (up to ~900) and average powers as low as ~26 nW, at update rate of ~17 MHz, i.e. at least thousand times faster than with spectrometer-based solutions. In a
remarkable application example, we fully characterize the dynamic ultrashort pulse response of an intensity electro-optic modulator (EOM) as its bias condition is rapidly swept at a measurement update rate of ~17 MHz.

2. Operation principle

FTSI is a simple and very sensitive linear technique for complex-field characterization of ultrafast optical signals [19]. This technique is based on measuring the spectral energy density of the interference pattern between the optical SUT and a well-characterized reference signal (ultrashort optical pulse with a spectral content extending over that of the SUT). Let us assume an optical signal defined as (analytic representation) $E(t) e^{j2\pi f_0 t}$, where $E(t)$ is the signal’s complex envelope ($t$ is the time variable), and $f_0$ is the optical carrier frequency. The FTSI method is based on measuring an interference spectral pattern (also called spectral interferogram), $SI(\omega)$, that is generated by combining a reference pulse ($R(t) e^{j2\pi f_0 t}$) and the SUT ($E(t) e^{j2\pi f_0 t}$), relatively delayed by $\tau$, e.g. using an optical coupler,

$$SI(\omega) = |R(\omega) + E(\omega) e^{-j\omega \tau}|^2 = \left| R(\omega) \right|^2 + \left| E(\omega) \right|^2 + 2 \Re \left\{ R^* (\omega) \times E(\omega) \times e^{-j\omega \tau} \right\}$$

where $\Re\{}$ means the real part, $j=\sqrt{-1}$, $\omega=2\pi f$ and $f$ is the base-band frequency variable. Since the information on the complex-field of SUT, $E(\omega)$, is embedded in the interference part of $SI(\omega)$ (i.e. $SI_I(\omega)$ in Eq. (1)), this part should be isolated from the background signal, $SI_B(\omega)$, in the spectral interferogram. For this purpose, the reference signal is suitably delayed with respect to the SUT using an optical delay line ($\tau$) in such a way that the interference part can
be isolated from the background signal in the time domain, i.e. after taking the inverse Fourier transform of the spectral interferogram in Eq. (1). Moreover, a time delay between the reference pulse and SUT is always needed to ensure there is no phase ambiguity in reconstruction of the SUT. In particular, the interference spectral pattern is recorded using a conventional optical spectrum analyzer (OSA). The amplitude and phase profiles of the SUT in the frequency domain can be accurately recovered from the measured spectral interferogram using the following Fourier-based procedure:

$$E(\omega) = \frac{\mathcal{F}\left[\Theta(t-\tau) \times \mathcal{F}^{-1}\left[SI(\omega)\right]\right]}{R(\omega)} e^{j\omega t}$$

(2)

where $\mathcal{F}$ is the Fourier transform and $\Theta(t-\tau)$ represents the Heaviside function that is used to single out the term centered at $\tau$ in the temporal function $\mathcal{F}^{-1}\left[SI(\omega)\right]$ (i.e. term corresponding to the interference signal). The time-domain complex-field profile of the SUT can be then numerically calculated by taking an inverse Fourier transform of $E(\omega)$. Full knowledge of the reference pulse amplitude and phase profiles is assumed. Despite all its well-proved advantages, the measurement update rate offered by this technique is severely limited by the update rate of current spectrometers. In addition, the measurable time duration of the SUT (record length) is also limited by the frequency resolution of the spectral interference measurement [16-19]. The record length could be increased by improving the resolution of the spectrometer, but this in turn would negatively affect the measurement update rate. We overcome these fundamental limitations using RT-OFT of each interference waveform induced by a simple linear propagation through a highly-dispersive fiber-optics element [20,21].

Fig. 1 illustrates the operation principle of the proposed method. Each waveform will be temporally stretched as it propagates through the dispersive element. If the dispersion characteristics of this element are properly designed, i.e. if a sufficiently large group velocity dispersion (GVD) over the entire interference signal bandwidth is induced, then each spectral interferogram will be mapped along the time domain in such a way that it can be captured in real-time using a single high-speed photo-detector connected to a commercial high-speed digitizer (e.g. real-time oscilloscope). This measurement strategy is intrinsically single-shot: As illustrated in Fig. 1, consecutive interferograms, corresponding to consecutive single SUTs, can be separately recorded and processed at fast update rates. The SUT time separation, $T$ in the figure (corresponding to a measurement update rate of $1/T$), is only limited by the total dispersion-induced temporal stretching undergone by each of the interferograms since temporal overlapping between consecutive stretched interferograms should be avoided. The optimal GVD value will be also dictated by the required resolution of the recorded stretched interferograms, which is inversely related to the measurement time window (record length): A higher GVD translates into a longer temporal stretching and an associated improved resolution in the recorded interferogram, which in turn implies an increased record length. By properly optimizing the GVD introduced by the dispersive element, according to the bandwidth of the temporal detection stage, the interferograms can be grabbed with both very high resolutions and fast update rates. Using this simple approach, we capture here the required spectral interference waveforms, each extending over an equivalent full-width spectral bandwidth of \(\sim 16\) nm (full width at half maximum (FWHM) of \(\sim 2.9\) nm), with an equivalent wavelength resolution of \(\sim 10\) pm (corresponding to a record time length of \(\sim 350\) ps) at an update rate of up to \(\sim 17\) MHz. This represents an improvement by a factor of more than 1,000 over the update rate that can be provided by any available optical spectrometer simultaneously offering the above bandwidth and resolution specifications [28]. Notice also that in our experimental setup we have incorporated a balanced temporal interleaver scheme [29] to physically suppress the DC component of the measured spectral interference pattern, which in turn has...
two additional important benefits, i.e. extending further the record time window and improving the signal to noise ratio of the spectral measurement. The employed balanced temporal interleaver scheme is described in the following Section 3 and illustrated in greater detail in Fig. 2.

3. Experiments and discussions

A detailed diagram of the used setup for the experimental demonstration of the proposed real-time complex-field ultrafast optical signal measurement is shown in Fig. 2.

A balanced spectral-interferometry scheme combined with RT-OFT was employed. The mode-locked fiber laser (MLFL) source (Pritel Inc.) generated nearly transform-limited Gaussian-like optical pulses at a repetition rate of 5 MHz (or 17 MHz, depending on the experiment), with a full-width (defined at 1% of the energy density peak) spectral bandwidth of ~16 nm (FWHM of ~2.9 nm), centered at a wavelength of ~1550 nm. We confirmed that the ultrashort pulses generated from the MLFL were nearly transform-limited through autocorrelation and spectral measurements. In particular, the measured autocorrelation of the laser pulses was nearly identical to that calculated from the measured laser spectrum assuming a uniform (flat) spectral phase profile.

The laser pulses were split using a 90:10 fiber-optic coupler; one of the resulting pulse trains was used as the optical reference source whereas the other pulse train was properly re-shaped, using a combination of dispersive optical fibers, intensity EOM and/or bulk-optics Michelson interferometers, to obtain the optical SUT \( E(t) \) with prescribed amplitude and phase profiles (depending on the specific measurement experiment). The shaped SUT and the optical reference were combined using a 2x2 single-mode fiber-optic 50:50 coupler (centered at 1,550 nm with 3-dB power coupling ratio). The time delay between the signal and the reference was adjusted using an optical delay line (SMF-28). Two different spectral interference patterns were generated at the two outputs of the 2x2 fiber coupler, \( SI_+ \) and \( SI_- \). In particular, as expected for such a coupler, the phase of these two spectral interferograms were shifted by \( \pi \), namely:
\[ SI_+ (\omega) = 0.5 |R(\omega) + E(\omega)\cdot e^{-j\omega T}|^2 = 0.5 |R(\omega)|^2 + 0.5 |E(\omega)|^2 + \text{Re}\{R^*(\omega)\cdot E(\omega)\cdot e^{-j\omega T}\} \] (3a)

\[ SI_- (\omega) = 0.5 |R(\omega) - E(\omega)\cdot e^{-j\omega T}|^2 = 0.5 |R(\omega)|^2 + 0.5 |E(\omega)|^2 - \text{Re}\{R^*(\omega)\cdot E(\omega)\cdot e^{-j\omega T}\} \] (3b)

In order to launch the two interference signals through the same dispersive medium (LCFG), the two finite-time interference waveforms were time-delayed and combined into a common fiber path using a fiber-optic time interleaver. The time separation between the two interference waveforms was fixed to be sufficiently large so that to avoid temporal overlapping between the successive stretched signals after dispersion; in particular, the delay between successive interferences was fixed to (772) ~ 100 ns (first set of experiments) or ~29.5-ns (second set of experiments). Dispersion Shifted Fiber (DSF) spools (Corning Inc.) were used for implementing these delays so that the two spectral interferences were not distorted by dispersion when propagating through the fiber-optic time interleaver. To be more concrete, the output waveform from the balanced optical interleaver can be mathematically described as

\[ SI(\omega) = SI_+(\omega) + SI_-(\omega)e^{-j\omega T/2} \] (4)

The two spectral interferences were subsequently mapped into the time domain (RT-OFT) by reflection in a 10-m long LCFG (Teraxion Inc.) providing a GVD of ~2ns/nm over a total (full-width) bandwidth of ~42 nm (~5.2 THz), also centered at ~1,548 nm (for the interested reader, the LCFG measured characteristics are presented in [22]). The fiber grating was incorporated in an optical circulator to retrieve the reflected signal. In particular, assuming that the LCFG introduces a sufficiently large GVD, the reflected waveform from the dispersive LCFG can be approximated by the following expression:

\[ SI_{\text{stretched}}(t) = SI(\omega)|_{\omega = \Phi_0} = SI_+\left(\frac{t}{\Phi_0}\right) + SI_+\left((t-T/2)/\Phi_0\right) \] (5)

where \( \Phi_0 \) is the first-order dispersion coefficient of the LCFG device. In deriving Eq. (5) it is assumed that there is no overlapping between the two stretched consecutive interferograms. An erbium doped fiber amplifier (EDFA) (Pritel Inc.) was used to increase the signal to noise ratio of the waveform measurement. The amplified time intensity waveforms corresponding to the temporally stretched interference patterns were acquired using a 26-GHz high-speed photo-detector (New Focus Inc., model 1024) followed by a 20-GHz real-time digital phosphor oscilloscope (Tektronix Inc., DPO72004B). The two digitized consecutive time-domain π-phase-shifted interferograms, corresponding to a single interference between the SUT and optical reference, were numerically subtracted as follows

\[ SI_+(t) = SI_+\left(\frac{t}{\Phi_0}\right) - SI_+\left(\frac{t}{\Phi_0}\right) = 2\text{Re}\{R^*(\omega)\cdot E(\omega)\cdot e^{-j\omega T}\} \] (6)

where \( SI_+(t) \) is the interference part of the spectral interferogram corresponding to the interference of the SUT with the reference signal (see Eq. (1)). \( SI_+(\omega) \) is then calculated from \( SI_+(t) \) using the \( \omega = t/\Phi_0 \) relationship. This process of subtraction between two π-phase shifted spectral interferences [29], usually referred to as ‘dual balanced spectral interference detection’, enables an efficient suppression of the uncorrelated terms in the interferogram profiles, including the non-interference (background) component of these profiles and the...
common relative intensity noises from the light source (for simplicity, the common noise terms were not considered in the previous equations). The suppression of the DC term facilitates the characterization of signals closer to the reference, i.e. it enables extending further the record time. In our technique the required time delay between the reference pulse and the beginning tail of the SUT in the time domain can be very small, however since the ideal suppression of background signals at \( t=0 \) is challenging, a very small time delay \( (\tau>0) \) is still required to cancel the background signals around the origin. On the other hand, as we mentioned before, a time delay between the reference pulse and SUT is always needed to ensure there is no phase ambiguity in reconstruction of the SUT, so make it necessary to have a small time delay between the reference pulse and the SUT. On the other hand, the suppression of the common noise terms provides a direct improvement of the measurement signal-to-noise ratio (SNR).

Hence, after subtraction, the background-free spectral interferogram is numerically recovered by use of the frequency-to-time mapping law defined by the group-delay characteristic of the LCFG. In practice, this is first measured by using a transform-limited optical pulse (e.g. same pulse as the reference) as the SUT in our experimental setup [3]. The reconstructed spectral phase profile of the signal at the LCFG output provides precise information on the group-delay response of the dispersive fiber grating [3]. Finally, the amplitude and phase profiles of the optical SUT can be recovered from the spectral interferogram by means of the well-known FTIS algorithm based on the use of discrete Fourier transforms, as described in Section 2 above (see Eq. (2)). The reference spectrum is grabbed using the same configuration, i.e. using an LCFG followed by the photo-detector and the real-time oscilloscope. Signals that are further from the reference cause higher frequency modulation in the resulting interferogram. A higher frequency modulation translates into a decreased amplitude in the captured interference signal due to the expected frequency-dependant roll-off of the photo-detector. This artificial decay in the captured interferograms for signals delayed further from the reference could be calibrated in the numerical signal recovery stage using the information first obtained from multiple measurements with a single pulse that is subsequently delayed with a constant time delay step for each measurement. A similar procedure, including a demonstration example, is described in greater detail in [22].

Since this calibration was not considered necessary to demonstrate the main goal of our paper, we have manually increased the power of the input individual pulses as they were located further from the reference in order to display a normalized individual peak power for the pulses with different delays from the reference without the need to do any further numerical calibration.

![Figure 3](image-url)  

Fig. 3. Result of a real-time and single-shot measurement of an optical waveform (SUT) composed by two sub-picosecond (FWHM time-width ~600-fs) Gaussian-like pulses delayed from each other by ~336-ps. The plot in the inset shows the result of real-time and single-shot measurements of various individual sub-picosecond Gaussian-like pulses with different delays, ranging from 4ps to 350ps, with respect to the corresponding reference pulse. The presented plots show the recovered time intensity profiles (in normalized unit (n.u.)) of the SUTs (the recovered phase profile for each pulse was nearly linear and is not shown here).
The reference signal in our first set of experiments, which was directly generated from a wavelength-tunable passively MLFL, was a periodic train of transform-limited Gaussian-like pulses, each with a full-width spectral bandwidth of ~2 THz (~16 nm) centered at a wavelength of ~1550 nm, with a repetition rate of ~5 MHz. We first experimentally evaluated the resolution/record-length specifications of our optical oscilloscope through characterization of individual ultrashort pulses, each identical to those of the reference signal, delayed from the corresponding reference by different times. Since the time resolution of the used real-time digitizer was ~20 ps, we estimated that our configuration provided an equivalent spectral resolution of ~20 ps×(2 ns/nm)^-1 ~10 pm, corresponding to an approximate record length of ~350 ps. The inset of Fig. 3 shows the results (recovered time intensity profiles) from real-time and single-shot measurements of randomly selected individual pulses with delays ranging from 4 ps to 350 ps from the reference. Considering that the measured rising time (10% to 90% of the amplitude peak) of each of these pulses is ~400 fs, ultimately limited by the input optical source bandwidth, a remarkable time-bandwidth product of ~900 was experimentally estimated for our measurement setup. The minimum average optical power of the optical SUT that was required for accurate characterization varied from ~26 nW, for the pulse delayed by ~4 ps, to ~1 μW, for the pulse delayed by ~350 ps. In a complementary experiment, we characterized the time intensity profile of an optical signal composed by two replicas of the ultrashort laser pulse, relatively delayed by ~336 ps. Characterization of such a signal is particularly challenging because the fringes in the spectral interference pattern change very rapidly due to environmental fluctuations, making necessary the use of a single-shot and real-time measurement technique. The obtained results are shown in Fig. 3.

![Fig. 4. Real-time and single-shot complex-field characterization of an interference optical signal (SUT) having a time-bandwidth product of ~900: Recovered amplitude (a) and phase (b) time-domain profiles of the experimentally measured SUT (blue, solid) compared to the theoretically simulated phase profile (red, dashed). Insets are zoomed plots over the time interval between 210 ps to 220 ps. The measured spectral amplitude of the optical SUT is plotted in the inset of (a).](#)
We evaluated the anticipated capabilities of our setup by measuring the amplitude and phase temporal profiles of an optical signal with sub-picosecond time features and a total duration in the sub-nanosecond range, i.e. with an ultra-large time-bandwidth product approaching ~900. This complex SUT was prepared using a similar strategy to that followed in [2], i.e. by first interfering two replicas of the ultrashort laser pulse, relatively delayed by ~145.4 ps, which were subsequently linearly dispersed through a ~1,220 m long section of standard single-mode fiber, SMF-28e (Corning inc.). The optical signal average power was ~500 nW. The measured spectral amplitude of the SUT is shown in the inset of Fig. 4. An example of real-time, single-shot amplitude and phase characterization of this target signal is plotted in Fig. 4 (solid curves) compared to the theoretically simulated phase temporal profile of the SUT (dashed curve). Figure 4 shows that the recovered temporal phase profile for each dispersed pulse matches very accurately that expected from numerical simulations, according to the nominal group delay characteristics of the used dispersive fiber section. As shown in the plotted zooms (insets of Fig. 4), the predicted discrete phase shifts between the interference-induced sub-picosecond time lobes were also recovered with a fairly high precision. In the experiments carried out here, a long section of optical fiber (~1,220 m) was used for inducing a partial temporal interference between the two time-delayed pulses. Since the optical path length of the fiber section was disturbed by environmental perturbations such as temperature variations and/or vibrations, the interference amplitude envelope changed very rapidly in time, thus necessarily requiring the use of a single-shot acquisition technique. Only the period of the interference fringes and phase profile of the resulting interference waveform could be precisely predicted through numerical simulations, both being in excellent agreement with the experimentally recovered profiles (comparison between period of interference fringes and numerical calculations are not shown in the paper). It is worth noting that the amplitude roll-off due to the frequency response characteristics of the photodiode and amplifier may affect the measured waveform amplitude profile, i.e. the experimentally recovered amplitude envelope profile of the interference signal might be attenuated with respect to time, as compared with the actual signal’s envelope. As mentioned above, this could be precisely estimated and calibrated through a pre-acquisition of the roll-off amplitudes (an example of this procedure and acquisition is discussed in [22]). It is worth noting that according to the MLFL repetition rate of ~5 MHz, a sequence of interference SUTs was generated with a corresponding period of ~200 ns. Our technique allowed us to capture and characterize each of these SUTs separately, which clearly proves the capability of our method to provide the anticipated fast update rates.

In another set of experiments, we demonstrated the unique capability of our optical oscilloscope to characterize rapidly-changing, non-periodic THz-bandwidth optical waveforms at very fast (17-MHz) update rates. The complex waveforms to be tested were generated using the setup shown in Fig. 5(a). The references were nearly transform-limited Gaussian-like optical pulses, each with a full-width bandwidth of ~2 THz, directly generated from our MLFL at an increased repetition rate of ~17 MHz. The sequence of varying optical waveforms to be characterized was generated by linearly dispersing the ultrashort laser pulses through a ~500-m long SMF section followed by intensity electro-optic modulation (EOM) (EOspace Inc., 40 Gb/s modulator) with $V_g \approx 6.5$ V in which the bias level was rapidly swept. In particular, the EOM’s driving signal was a 17-MHz train of electronic pulses, each with a time-width of ~50 ps and a peak voltage of ~1 V, which was prepared by photo-detecting the reference pulses with a 40-GHz photo-detector (New focus Inc.) followed by electronic amplification with a 20-GHz RF-amplifier (New focus Inc.). The EOM’s DC bias was controlled by an RF signal generator producing a sinusoid waveform at a frequency of ~1.6 MHz, with an average voltage of ~0.3 V and a peak-to-peak voltage of ~1.3 V.

The fast sine variation of the EOM’s DC bias combined with the EOM’s driver voltages caused temporal modulation of the dispersed Gaussian-like optical signal, resulting in fast (MHz rate) variations of the amplitude and phase profiles of the optical waveform obtained at
the modulator output (SUT). Notice that each of these ultra-broadband waveforms (full-width spectral bandwidth ~ 2 THz) extended over a full-width temporal duration of ~110 ps, and the temporal separation between any two consecutive SUTs was ~59.1 ns, as determined by the laser pulse repetition rate. In each experiment, we grabbed 8,300 spectral interference profiles, corresponding to 8,300 consecutive single-shot optical waveforms, captured over a total time window of ~490.53 μs with our real-time oscilloscope. In this way, we successfully tracked the changes in the amplitude and phase profiles of the modulated ultrafast optical waveforms at every time period of ~59.1-ns. The recovered amplitude and phase temporal profiles of 30 consecutive modulated waveforms are plotted in Figs. 5(b) and 5(c), respectively. A 3D representation is used to better illustrate the measured rapid changes in the recovered profiles. Fig. 5(d) also shows the individual characterization of some of these complex optical waveforms at the measurement times of 236.4 ns, 354.6 ns and 827.4 ns, respectively. For comparison, the numerically predicted quadratic phase curve corresponding to propagation through a 500-m SMF section is also represented in the same plot, showing an excellent agreement with the experimentally recovered quadratic phase variations. Moreover, a discrete phase-jump on each quadratic phase profile was accurately observed at the zero-crossing point of the corresponding amplitude profile as this point was swept in time along the modulated signal duration.

In our experimental setup, the power of the input waveform to be characterized should be kept low enough to avoid non-linearities in the fiber devices, including fiber interleaver (with a DSF spool), LCFG and fiber spools; considering that the signal will propagate through a total equivalent length of conventional single-mode fiber of approximately 50 m, we estimate that the maximum allowed input average power to operate in the linear regime is about 67 μW, assuming an input pulse temporal duration of ~1 ps with a repetition rate of 5 MHz. Considering that the minimum measurable input average power for the same input pulse was ~26 nW (see above experimental results), a dynamic range of ~34 dB is estimated for our specific experimental measurement system.
Fig. 5. (a) Experimental setup for generating rapidly-changing ultrafast optical signals by intensity modulation of dispersed broadband pulses using an EOM driven by a synchronized train of electronic pulses in which the DC bias level is rapidly swept (the bias is driven by a 1.6-MHz electrical sinusoids). Amplitude (b) and phase (c) time profiles of 30 rapidly-changing ultrafast waveforms as measured at the EOM output with an update rate of ~17 MHz, expanding over a total duration of ~1.773 μs. Results corresponding to the individual characterization of 3 of these ultrafast waveforms at the measurement times of 236.4 ns, 354.6 ns and 827.4 ns are plotted in (d).

4. Conclusions

We have proposed and experimentally demonstrated a simple and practical (fiber-optics) method for complex-field ultrafast optical signal characterization using a balanced FTSI scheme combined with dispersion-induced real-time optical Fourier transformation. Using this new linear approach, we demonstrated single-shot characterization of complex-field optical events (including accurate measurement of continuous and discrete-time phase variations), with a resolution of ~400 fs over a record length as long as ~350 ps and average powers as
low as ~26 nW, at update rates in the MHz range, i.e. at least thousand times faster than with spectrometer-based solutions. In a remarkable application example, we fully characterized the dynamic ultrashort pulse response of an intensity EOM as its bias condition was rapidly swept at a measurement update rate of ~17 MHz.

Our experimental demonstrations clearly prove the outstanding performance provided by the developed real-time THz-bandwidth optical signal measurement method, including its capability for accurate characterization of the amplitude and phase profiles of sub-microwatt ultrafast waveforms over sub-nanosecond record lengths in a single shot and at update rates well in the MHz range. The latter is the most distinctive feature of the demonstrated concept. Using LCFGs with higher GVD factors and/or faster detection stages, the measurement record length could be readily extended to the nanosecond range without essentially affecting the rest of the system specifications. The simple strategy demonstrated here, namely incorporating dispersion-induced RT-OFT in a spectrometer-based measurement system, could be potentially used in many other well-established ultrafast signal characterization schemes to achieve a significant improvement in the system performance, particularly in terms of measurement update rates, as required for full and accurate characterization of rapidly-changing ultrafast waveforms in a variety of engineering and scientific fields.

Acknowledgements

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by le Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT).