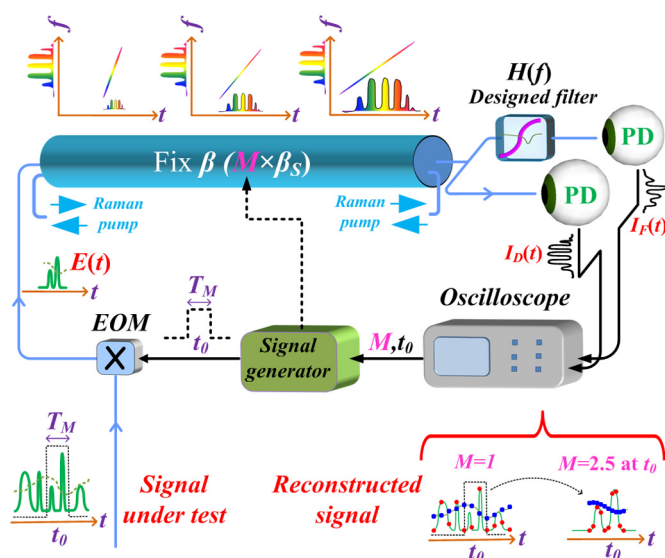


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Mohammad H. Asghari
Bahram Jalali, Fellow, IEEE



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Stereopsis-Inspired Time-Stretched Amplified Real-Time Spectrometer (STARS)

Mohammad H. Asghari¹ and Bahram Jalali,^{1,2,3} *Fellow, IEEE*

(Invited Paper)

¹Photonics Laboratory, Department of Electrical Engineering, University of California, Los Angeles, CA 90095 USA

²California NanoSystems Institute, University of California, Los Angeles, CA 90095 USA

³Biomedical Engineering Department, University of California, Los Angeles, CA 90095 USA

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Abstract: We introduce and demonstrate a single-shot real-time optical vector spectrum analyzer (VSA). This simple and powerful instrument combines amplified dispersive Fourier transform with stereopsis reconstruction algorithm and is inspired by binocular vision in biological eyes. Moreover, a dynamic time-stretch concept is employed to dramatically enhance the phase reconstruction accuracy and dynamic range for ultrashort optical signals (> 30 times). We show that, using a noniterative analytical expression, the phase profile of the input signal can be reconstructed using intensity-only measurements. The proposed method is experimentally proved by fully characterizing the time-varying amplitude and phase of single-shot THz-bandwidth optical signals, with durations ranging from sub-ps to 35 000 ps, with ultrasmall to ultralarge temporal phase variations and at 25-MHz update rate. We have also used this instrument to characterize the amplitude and phase of a prechirped 40-Gbps DQPSK optical signal using a 1.5-GHz digitizer and without using a reference signal.

Index Terms: Optical vector spectrum analyzer (VSA), complex-field optical signal characterization, ultrafast optics, continuous optical signal processing.

1. Introduction

Complex-field characterization of optical signals with durations ranging from sub-picoseconds to tens of nanosecond durations is highly desired for a variety of applications from telecommunications to information processing and applied sciences [1]–[6]. Solutions based on nonlinear optical gating or spectral shearing interferometry require high intensity signals; hence, they do not offer high sensitivity [2], [3]. In addition, they are well suited for characterization of ultrashort optical signals (e.g., femtosecond and picosecond pulses), while it is challenging to employ these techniques for characterization of optical signals with longer durations [2], [3]. Referencing methods for characterization of optical waveforms have been used to measure optical signals with durations in ns regime [4]–[6]; however, in these applications, a highly stable reference well synchronized with the signal under test (SUT) is required, which significantly increases their complexity [6].

One group of methods for self-referenced temporal phase reconstruction of optical signals is based on instantaneous-frequency (i.e., derivative of the phase profile) reconstruction from time-domain intensity measurements at the input and/or outputs of an optical frequency discriminator

(optical temporal differentiator) [7]–[9]. The range of applications of these techniques has been limited by the following issues: a) these techniques measure the instantaneous frequency of the SUT (i.e., derivative of SUT's phase profile) not the SUT's phase profile, b) the operation bandwidth is limited by that of photodetectors and backend electronic digitizers (< 50 GHz) because the measurement relies on time-domain intensity detection, c) the filter's specifications affect the performance of the measurement and these specifications cannot be flexibly modified or optimized; hence, measurements based on frequency discriminators offered a poor noise and sensitivity performance [7]–[10]. Prestretching the pulse under test before application of these methods improves the speed; however, the loss of dispersive elements used increases the noise figure. As such, ultrashort pulse characterization using these techniques was only possible with averaging, hence not in real time. Further, for better phase accuracy, a dispersive element with smaller group velocity dispersion (GVD) was required, but then, characterization of ultrashort pulses with high phase accuracy becomes challenging [10]. To give an example, to accurately reconstruct the optical signals passed through 20 m of dispersive fibers, stretching devices having a small GVD of 17.2 ps/nm was required with 150 times averaging a 40-GHz photodetector and a high-speed sampling oscilloscope [10]. It was also observed that characterization of optical signals passed through dispersive fibers with lengths < 20 m (e.g., transform-limited) was challenging for these methods (e.g., see Fig. 10(b) in [10]).

To tackle issues a) and c), a novel method for optical phase reconstruction, which is based on intensity measurements at the input and output of arbitrary optical filter, has been recently proposed [11]. Successful simulations showed that the phase profile can be unambiguously recovered [solving issue a)] using a noniterative algorithm based on causality arguments in linear optical filters. The filter can be designed to optimize the measurement performance, e.g., to increase the sensitivity and/or to minimize the influence of noise on the phase reconstruction [solving issue c)].

In this communication, we introduce and experimentally demonstrate a general concept for self-reference real-time vector spectrum analysis of low-power optical signals. This technique has temporal resolution in fs regime over millisecond time window that is only limited by the backend electronic digitizer record length. The technique expands on the aforementioned proposal by combining it with amplified dispersive Fourier transform and a dynamic time stretch [tackling issues a), b), and c)] [12]–[15]. As will be shown here, these enhancements are necessary to achieve real-time single-shot characterization of ultrashort pulses and to characterize such pulses with high phase accuracy. The far-field dynamic time-stretch concept enhances the phase reconstruction accuracy of ultrafast optical signals by more than 30 times [tackling issue c)]. In this fashion, we were able to use stretching devices with GVD factors as high as ~ 1312 ps/nm (providing very high resolution in temporal measurement) and simultaneously have very high phase accuracy while reconstructing the phase of ultrashort transform-limited pulses in single-shot fashion at 25-MHz update rate. These results were achieved using a backend digitizer with only 1.5-GHz bandwidth. To benchmark this against previously proposed methods [10] if this stretcher was used in previous methods, time averaging would be needed and chirped pulses with GVDs more than ~ 13 ps/nm (from Fig. 10(b) in [10]) could be characterized. Here, using our dynamic time-stretch concept with the same stretcher, we characterize optical signals with no limit on their minimum GVD (e.g., transform-limited) in real time and single shot. We have also used the same stretcher to characterize group delay of a chirped signal with GVD of ≈ -4640 ps/nm (equivalent to ~ 270 Km of single-mode fiber) in real time and single shot, which is the largest GVD ever measured in real time. To show this method's impact, we have also experimentally demonstrated applications of this instrument in single-shot and real-time ultrafast optical and electrical signal measurement, and signal demodulation in optical telecommunications.

2. STARS: Theory and Operation Principle

The schematic of the proposed concept is shown in Fig. 1. The ultrashort optical signal, SUT, defined as $E(t) = |E(t)|\exp(j\varphi_E(t))$ is first stretched using a long section of dispersive optical fiber powered by Raman distributed amplification with dispersion coefficient β and length L having a

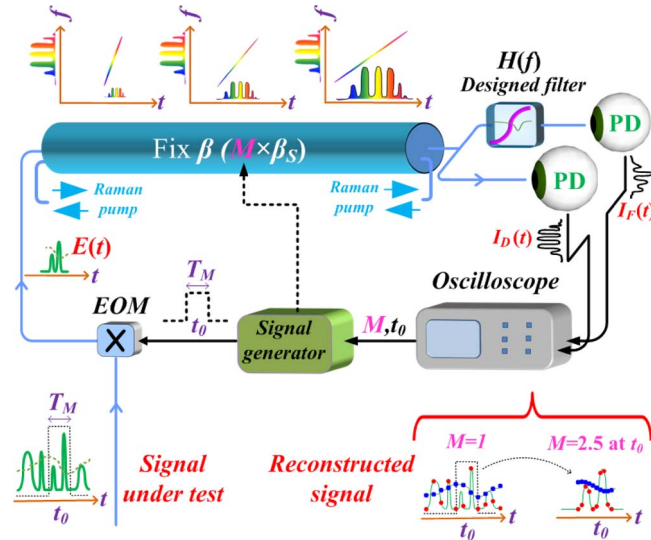


Fig. 1. Scheme of the proposed real-time and single-shot complex-field ultrafast optical signal measurement method. β : Group velocity dispersion, EOM: Electro-optic modulator, PD: Photo-detector.

well-characterized frequency transfer function $\Psi(f)$. The temporal field of the dispersed pulse is given by $D(t) = |D(t)|\exp(j\varphi_D(t))$. If $D(t)$ is sufficiently long so that its intensity can be precisely measured with the available temporal intensity detection schemes, the phase profile $\varphi_D(t)$ can be recovered by measuring the intensity at the input and output of a linear optical filter [7], [11]. The dispersed optical signal is launched into a linear optical filter with transfer function $H(f)$, corresponding to an envelope temporal impulse response $h(t) = |h(t)|\exp(j\varphi_h(t))$, where $h(t) = 0$ for $t < 0$ (causality). The discrete-time output (filtered-signal) temporal envelope is defined as $F(t_n)$, where $t_n = n/f_s$, f_s is the sampling frequency, and n is the discrete-time index. $F(t_n)$ is calculated as the convolution of the discrete-time (sampled) versions of the filter input, $D(t_n)$, and the filter's impulse response $h(t_n)$. The $\varphi_D(t_n)$ profile is calculated as follows [11]:

$$\varphi_D(t_n) = \cos^{-1} \left(\frac{I_F(t_n) - I_D(t_n)|h(t_0)|^2 - |A_n|^2}{2\sqrt{I_D(t_n)}|h(t_0)||A_n|} \right) + \phi_{A_n} \quad (1)$$

where $A_n = |A_n|\exp(j\phi_{A_n}) = \sum_{k=0}^{n-1} D(t_k)h(t_n - t_k)$, $I_D(t_n) = |D(t_n)|^2$, and $I_F(t_n) = |F(t_n)|^2$. For accurate phase reconstruction of input optical signals using this method, the following conditions must hold for the employed optical filter [11]: a) the filter's impulse response $h(t_n)$ must be fully characterized along its entire temporal support and it must have a minimum duration of two discrete samples, with $h(0) \neq 0$; b) the intensity profiles of the input and output waveforms should be available at the time t_n (as obtained through intensity-only measurements); and (c) full information of the amplitude and phase of the SUT should be known until the time t_{n-1} (so A_n is determined). The average reconstruction phase accuracy for $\varphi_D(t_n)$ is given by $\pi\Delta f/2f_s$, where Δf is the full bandwidth of the SUT [14], [15]. To give an idea about this phase accuracy, for a SUT with $\Delta f = 1$ THz and real-time digitizer sampling rate of 50 GHz, the reconstructed phase accuracy is ≈ 31.4 rad, which is clearly not enough to measure input SUTs with small phase variations. Since the phase accuracy is independent of the fiber length and fiber dispersion, for a given SUT, the reconstructed phase accuracy is strictly limited by the digitizer speed.

Here, we introduce a dynamic time-stretch concept to overcome this critical issue to enhance the phase reconstruction accuracy and sensitivity. Let's assume the length $S = L/M$ of the employed dispersive fiber [with corresponding dispersion coefficient β_S and transfer function $\Psi_S(f)$] is long enough so that the measured profile, $D_S(t_n)$ with time duration of T_M , is the real-time Fourier transformation of the SUT (far field regime) [14], [15]. In this case, the measured intensity profiles

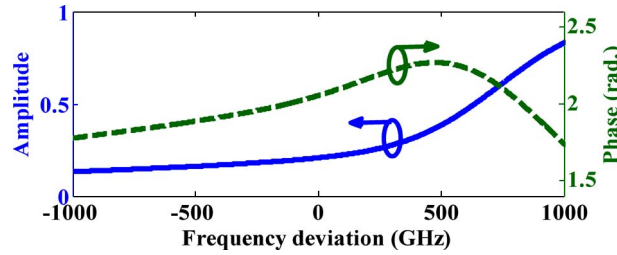


Fig. 2. Employed linear optical filter amplitude and phase profiles implemented using a C-band wave shaper.

$I_D(t_n)$ and $I_F(t_n)$, are the M times stretched versions of the intensity profiles at the length S of the dispersive fiber, i.e., $I_{D,S} = |D_S(t_n)|^2 = I_D(t_n/M)$ and $I_{F,S} = |F_S(t_n)|^2 = I_F(t_n/M)$. The reconstruction phase accuracy by putting these virtual intensity profiles in $\varphi_{DS}(t_n)$ phase reconstruction equation is given by $(\pi\Delta f/2f_s)/M$, which shows that M times higher phase accuracy can be achieved using this dynamic time-stretch scheme. Finally, the SUT profile is recovered from the measured stretched pulse profile by numerically compensating for the phase profile introduced by the stretcher

$$E(t_n) = \mathfrak{F}^{-1} \left\{ \frac{\mathfrak{F}\{D_S(t_n)\}}{\Psi_S(f)} \right\} \quad (2)$$

\mathfrak{F} being the Fourier transform.

3. Experimental Results

The proposed method was applied for characterization of various complex-field optical waveforms. In the experiments presented here, we designed the linear optical filter using a C-band wave shaper (Finisar Inc.). The filter was designed to fulfill the three conditions of the optical filter for accurate phase recovery mentioned in the previous section. The filter was designed to optimize the power efficiencies and noise performance of the phase reconstruction. The designed filter had a 2-THz frequency Bandwidth centered at 192.3 THz with amplitude and phase profiles shown in Fig. 2.

3.1. Characterization of Dispersed Optical Signals

In the first set of experiments, we applied the technique introduced above to accurately characterize linearly chirped ultrashort pulses by propagation through different dispersion compensating fiber (DCF) sections (dispersion factors ranging from -5 ps/nm to -4640 ps/nm). In these experiments, the phase sensitivity was high enough so the Raman distributed amplification was not used. The experimental setup for our proof-of-concept demonstrations is shown in Fig. 3.

The source of the seeding optical pulses was a passively mode-locked fiber laser (Calmar Inc.), which generated transform-limited Gaussian-like optical pulses with 1.25-THz full frequency bandwidth. The seeding pulses propagated through the different DCF sections to generate the input SUT. The SUTs were launched into the designed optical filter with 2-THz bandwidth around 192.3 THz (central frequency of the input SUT; see Fig. 2). The output pulses were then temporally stretched using a well-characterized linear stretching device (-1312 -ps/nm DCF section). The intensity profiles of the stretched signal $[I_D(t)]$ and its filtered version $[I_F(t)]$ were measured using a 16-GHz digitizer with 20-ps time resolution. The dynamic time-stretch magnification concept, together with explained phase reconstruction algorithm, was used to characterize the absolute phase of the SUTs. Using the dynamic time-stretch magnification concept was necessary to increase the resolution of the phase reconstruction to be able to characterize the phase profiles corresponding to small GVDs. Notice that, for SUTs with shorter time duration (i.e., pulses with smaller chirp/phase variations), which requires higher reconstruction phase accuracy, a higher stretch factor can be

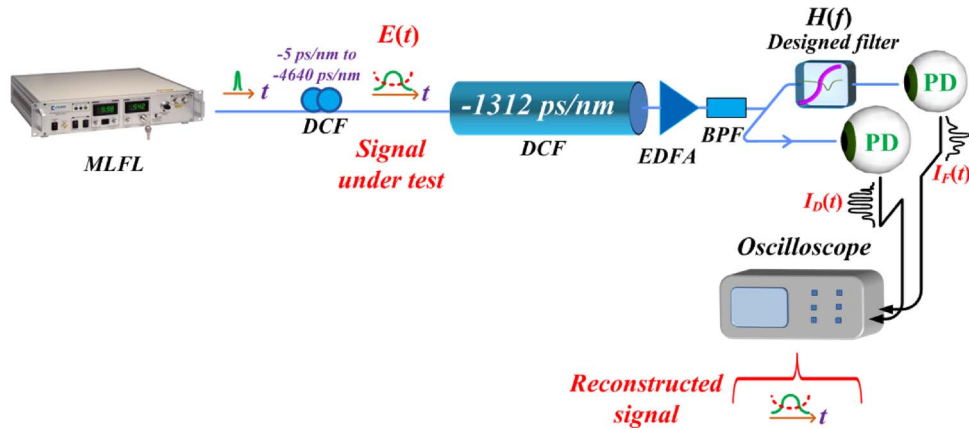


Fig. 3. Experimental setup for single-shot and real-time characterization of dispersed optical signals using the proposed method. MLFL: Mode-locked fiber Laser, DCF: Dispersion compensating fiber, EDFA: Erbium-doped fiber amplifier, BPF: Bandpass filter, PD: Photodetector.

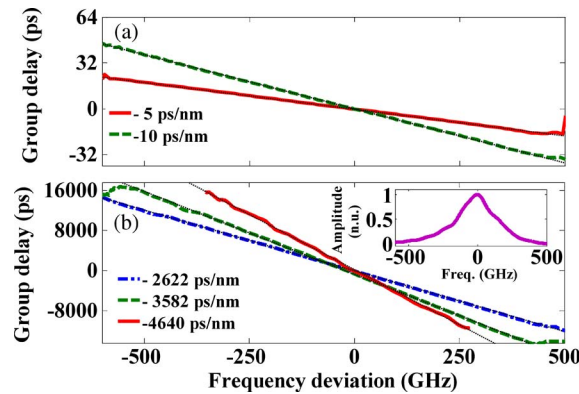


Fig. 4. (a) and (b): Reconstructed group delay profiles (solid lines) of SUT for the different evaluated DCF sections compared to the corresponding simulated ideal group delay profiles (dotted lines). Employed filter transfer function is shown in Fig. 2. Reconstructed energy spectrum of the SUT is also plotted in the inset of (b).

used (because real-time Fourier transformation can occur at shorter fiber lengths) giving a higher phase accuracy. The recovered spectral amplitude profile of the SUTs is plotted in the inset of Fig. 4(b). The single-shot and real-time recovered group delay profiles (numerically calculated derivative of the reconstructed spectral phase profiles) of the SUTs at 25-MHz update rate are plotted in Fig. 4 compared with the corresponding simulated group delay profiles (dotted lines). There is an excellent agreement between the reconstructed group delay profiles and the simulated ideal group-delay profiles, which proves the viability of our technique for optical phase profile reconstruction. Notice that, in the case of characterization of the SUT having a GVD of ~ -4640 ps/nm, the optical SUT has a bandwidth of 1.25 THz with duration of $\sim 35\,000$ ps (time-bandwidth product of $\sim 43\,750$), which we have successfully reconstructed using our method. This is the largest time-bandwidth product ever reported for characterization of THz bandwidth optical signals in real time and single shot [1], [4].

3.2. Characterization of Ultrashort Optical Signals

As mentioned before, one of the advantages of STARS is to characterize transform-limited ultrashort pulses in real time and single shot with high phase accuracy. To prove this, in a second

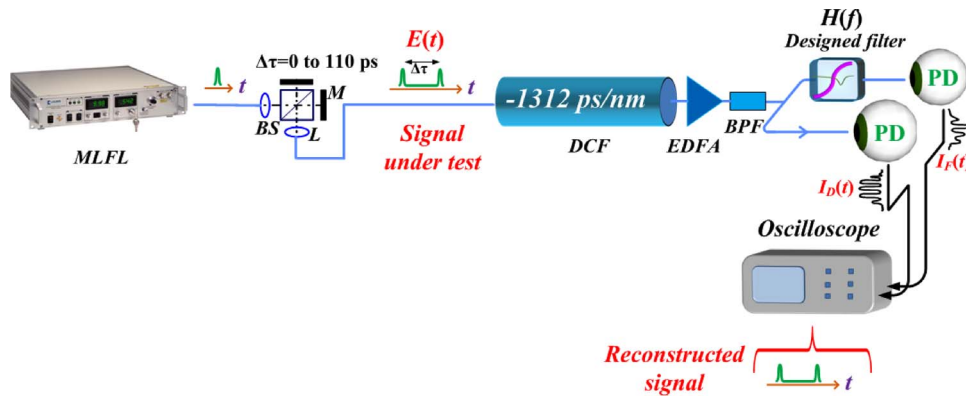


Fig. 5. Experimental setup for single-shot and real-time characterization of ultrashort optical signals using the proposed method. M: Mirror, L: Lens, BS, Beam-splitter.

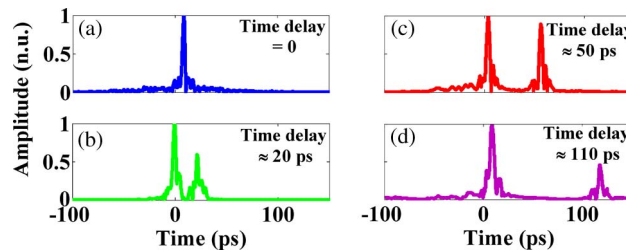


Fig. 6. (a)–(d) Real-time single-shot complex-field characterization of ~ 1 ps Gaussian pulses passed through a MZ interferometer with different delays (from 0 to ~ 110 ps). Plot shows the amplitudes of the optical SUTs (the recovered phase profile for each pulse was linear and is not shown here).

set of experiments, the input SUTs to be characterized were individual pulses generated from a mode-locked fiber laser with ~ 1 -ps time duration and then passed through a Michelson interferometer with different time delays. The experimental setup is shown in Fig. 5.

The SUTs were first temporally stretched using a DCF section with GVD factor of -1312 ps/nm and their intensity profiles $[I_D(t)$ and $I_F(t)]$ were measured using a 16-GHz digitizer (Tektronix Inc.). Real-time and single-shot complex-field characterization of the SUTs at update rate of 25 MHz with randomly selected pulses for three different delays are plotted in Fig. 6 (0, 20 ps, 50 ps, and 110 ps). Using the dynamic time-stretch magnification concept was necessary to increase the resolution of the phase reconstruction to be able to characterize these transform-limited pulses. These experiment results show the strong capability of our technique to characterize single-shot ultrashort optical pulses with high phase accuracy.

3.3. Optical Telecommunications Signal Demodulation/Ultrafast Electrical Signal Digitization

In the third set of experiments, we have shown that the instrument proposed and demonstrated in this paper can be used to demodulate and digitize free-running optical telecommunication signals. We also show that the same setup can be used to digitize ultrafast electrical signals using low-speed electronic digitizers. The experimental setup for these set of demonstrations is shown in Fig. 7.

To generate the optical SUT in these experiments, the output ultrashort pulses from a mode-locked fiber Laser was dispersed using a small DCF section (GVD of -100 ps/nm) and then encoded using a 40-GHz dual-input optical QPSK modulator (Covega Inc.). The SUT here emulates a prechirped 40-Gbps optical signal modulated with QPSK format. To prepare the 20-GHz

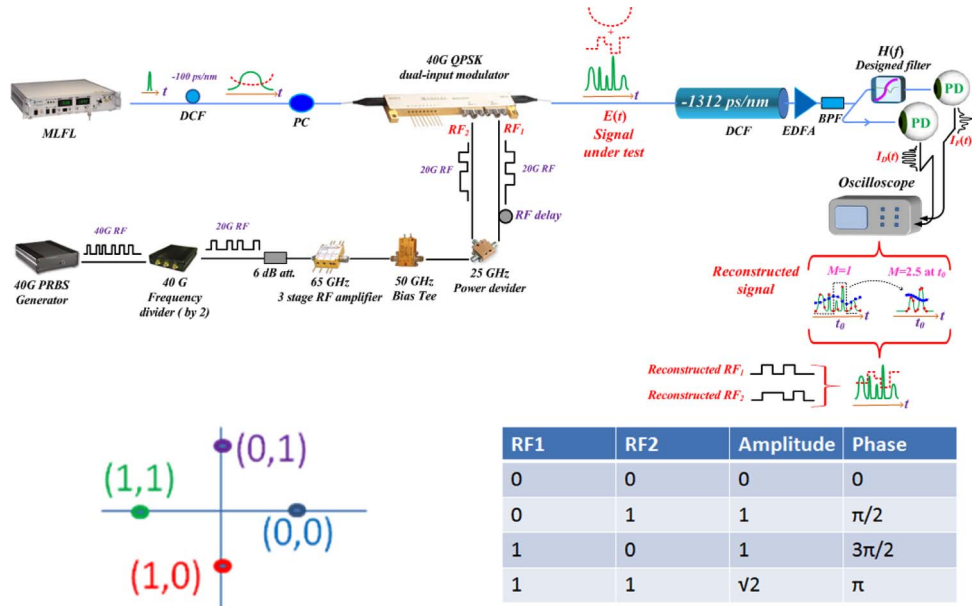


Fig. 7. Experimental setup for single-shot and real-time demodulation of optical telecommunication signals using the proposed method. Phase-constellation diagram and amplitude and phase table for the modulated optical signal are also shown. PC: Polarization controller, RF: Radio frequency.

dual electrical drive signals (RF1 and RF2; see Fig. 7) for the employed optical QPSK modulator, a 40-GHz pseudorandom binary sequence (PRBS) generator (Centellax Inc.) was concatenated with a frequency divider ($\div 2$) and a high-speed RF amplifier. The 20-GHz dual drive signals (RF1 and RF2) were then generated by using a 50/50 power divider and a RF delay line. A high-speed Bias Tee element was also used to control the required phase delay in the optical QPSK modulator. Notice that, for an actual implementation of 40-Gbps QPSK modulator, a precoder is required to generate the two 20-Gbps data streams from the 40-Gbps PRBS generator (RF1 and RF2). Since we did not have access to such a precoder, in order to drive the optical QPSK modulator for our proof of concept demonstrations, we first generated a 20-Gbps bit stream (RF1) and temporally delayed it to generate another 20-Gbps data stream (i.e., RF2) so it can be assumed that $RF2 \neq RF1$ at each sampling time. The phase-constellation diagram and the corresponding table for amplitude and phase values of the modulated optical signal at the output of the modulator based on different RF1 and RF2 binary values are shown in Fig. 7.

To recover the phase profile of the modulated optical signal after the optical QPSK modulator, i.e., the optical SUT, it was first temporally stretched using a DCF section with GVD of -1312 ps/nm, and the intensity profiles of the direct and filtered signals were measured using a low-speed photodetector and a 16-GHz digitizer. Notice that we used a 1.5-GHz RF bandpass filter before the digitizer to emulate a 1.5-GHz digitizer. Single-shot and real-time amplitude and phase characterization of randomly selected 18 demodulated bits (9 QPSK symbols) is shown in Fig. 8. The corresponding recovered bits are also shown at sampling times ($T_s \approx 50$ ps). Again, using the proposed dynamic time-stretch magnification concept was necessary to have enough phase accuracy to characterize these modulated optical signals. Comparison between the results in Fig. 8 and the phase-constellation diagram and corresponding table for amplitude and phase values of the modulated optical signal in Fig. 7 proves the accuracy of this new instrument for recovery of optical signals modulated with high modulation formats. Notice that we have not used any reference signal in these experiments.

It is worth mentioning that, if the 40 Gbps PRBS electrical signal was used as an electrical signal under analysis and a precoder was used to drive the 40-Gbps optical QPSK modulator, the bits recovered from these experiments (reconstructed RF1 and RF2) could be used to reconstruct the

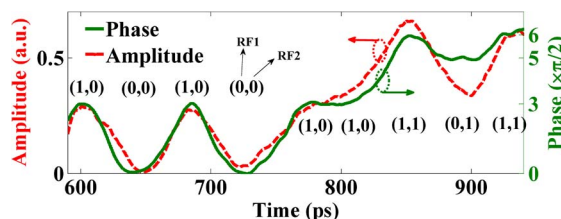


Fig. 8. Real-time single-shot complex-field characterization of 40 Gbps QPSK optical signal using a 1.5-GHz electronic digitizer using the proposed method.

40-Gbps PRBS ultrafast electrical signal under analysis. This shows the capability of our method to digitize a 40-Gbps ultrafast electrical signal using a low-speed 1.5-GHz digitizer. Notice that using the well-known time-stretch analog-to-digital conversion (TS-ADC) concept [16] with the same stretching devices and using a 40-GHz electro-optic intensity modulator, a 3-GHz digitizer was required to digitize a 40-Gbps electrical signal. This proves the capability of our technique to measure both ultrafast optical and electrical signals using the same instrument with a low-speed backend electronic digitizer.

4. Conclusion

We introduced and experimentally proved a real-time optical vector spectrum analyzer (VSA) for single-shot self-referenced phase reconstruction with time durations ranging from fs to ms regime. It is based on dispersive Fourier transform and a method for optical phase recovery from binocular (two point) intensity measurements. We have also introduced a novel dynamic time-stretch concept based on time-stretch magnification in far-field region to enhance the phase reconstruction accuracy of ultrafast optical signals for more than 30 times. We have experimentally demonstrated the accurate characterization of low-power optical pulses ranging from sub-ps to $\sim 35\,000$ ps. We have also shown that using this method, ultrafast optical and electrical signals can be digitized using the same instrument. In particular, we have shown that a 40-Gbps optical QPSK signal /electrical binary bit stream signal can be demodulated/digitized using the same instrument with a 1.5-GHz backend digitizer.

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