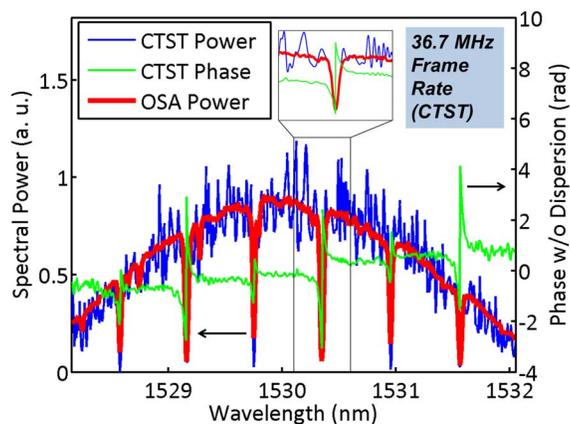


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# Coherent Time-Stretch Transform for Near-Field Spectroscopy

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**Abstract:** The coherent time-stretch transform enables high-throughput acquisition of complex optical fields in single-shot measurements. Full-field spectra are recovered via temporal interferometry on waveforms dispersed in the temporal near field. Real-time absorption spectra, including both amplitude and phase information, are acquired at 37 MHz.

**Index Terms:** Ultrafast measurements, ultrashort pulse characterization, temporal near-field, optical vector spectrum analyzer, optical signal processing, complex-field optical signal characterization, time-resolved spectroscopy, absorption spectroscopy instrumentation.

Many natural phenomena, such as impairments in data networks, phase transitions, protein dynamics in living cells and chemical reactions, occur on fast time scales and are non-repetitive, creating a need for high-throughput real-time measurements. The time-stretch dispersive Fourier transform (TS-DFT) [1]–[6] has proven invaluable for high-throughput, real-time detection of fluctuations in nonlinear processes, including optical rogue waves and pulse-to-pulse fluctuations in modulation instability and supercontinuum generation [7]–[11]. It has also enabled a new class of imaging systems able to identify cancer cells with a one-in-a-million sensitivity [12]–[14], as well as high-resolution, fast analog-to-digital-converters [15]–[18]. The time-dilation process along with the inherent fiber losses results in reduction in peak power and loss of sensitivity; a key innovation has been the introduction of distributed Raman amplification (with a concomitant lower noise figure and distortion than discrete amplification), resulting in single-shot and high-sensitivity performance [12], [19], [20]. Additionally, the TS-DFT has been applied to real-time spectroscopy in a variety of systems [5], [20]–[24]. In short, the TS-DFT chirps a pulsed source of radiation so that its temporal envelope matches its spectral profile (frequency-time mapping), and the waveform is slow enough to be captured by a real-time digitizer. The former result has been termed the far-field regime in analogy with the corresponding situation in spatial diffraction theory—the Fraunhofer limit.

We may also consider the temporal near-field regime in analogy with the corresponding case in spatial diffraction, i.e., the Fresnel limit. Specifically, a waveform may be stretched with a reduced



Fig. 1. The unknown optical field input is stretched with group-velocity dispersion (GVD), slowing down the signal in time and reducing its modulation bandwidth so that it may be captured by electronic instruments. The complex optical field is detected (using an independent reference signal or self-referenced), and the desired input is reconstructed digitally.

amount of dispersion, resulting in a temporal near-field signal [25]. In this limit, the time-stretch transform may permit capture of the waveform in the time domain, but the intensity envelope does not correspond to the spectral profile: in other words, a one-to-one correspondence between frequency and time is not achieved [25]. However, it has been demonstrated that an iterative procedure can be used to recover both the spectral amplitude and the phase from dual near-field measurements, eliminating the need to work exclusively in the far-field regime [25]. This recovery is possible because the constituent spectral components are not fully separated in the near-field waveform, resulting in an interferogram that contains amplitude and phase information. Thus, the dispersive element generates a near-field time-stretch transform of the waveform in this limit. Alternatively, the result can be considered a coherent dispersive Fourier transform as both spectral amplitude and phase information are available, comprising a vector measurement. In many systems, the spectral phase can be computed from the amplitude spectrum based on the causal requirements formulated in the Kramers–Kronig relations. Nevertheless, phase measurements provide a complementary source of information, which can supplement or enhance spectral amplitude data impaired by, e.g., noise, finite frequency resolution, and limited frequency span. For example, proper phase reconstruction via the Kramers–Kronig relations may require measurement of spectral features outside the measurement bandwidth. Indeed, simultaneous measurements of spectral amplitude and phase have proven useful in the investigation of a variety of physical processes [26]. Moreover, in the general case, phase and amplitude are not uniquely connected [27]; thus, amplitude and phase channels can contain distinct information, and dramatically different phase profiles may even be measured for identical amplitude spectra [28].

Here, we introduce a form of the time-stretch transform wherein near-field measurements are enabled by dispersive stretching with simultaneous optical amplification followed by complex-field detection and reconstruction. In this coherent time-stretch transform (CTST), interfering the signal with a reference waveform and stretching the interferogram in time allows recovery of the spectral amplitude and phase in the near-field limit [cf. Fig. 1]. Other detection schemes may also be possible (e.g., self-referenced using optical filters [29], [30]). Complex-field detection offers another route to near-field operation, which avoids the usual far-field requirement of the TS-DFT. Near-field acquisition reduces the dispersion requirement, decreasing loss and allowing measurements at an increased repetition rate (i.e., avoiding pulse overlap). The bandwidth limitations of the photodetector and digitizer are then the remaining constraints on smallest permissible dispersion [25]. The coherent DFT, which is similar to the CTST but assumes the far-field regime, has enabled real-time coherent digitizers [18], phase-sensitive imagers [31], and vector optical spectrum analyzers [32], [33].

Use of a well-characterized reference signal (local oscillator—LO) provides the benefits of coherent detection, including heterodyne gain and reduced noise. We demonstrate real-time near-field spectroscopy of time-stretched narrow absorption lines of acetylene gas. Fig. 2 shows an experimental implementation of the CTST technique. An optical source provides both the signal and reference radiation, both of which are chirped in a Raman-amplified dispersive element. The signal travels through an absorption cell and beats with a time-delayed reference that upshifts the beating term into an intermediate frequency. At the photodetector, the recorded signal is:

$$I_{\pm}(t) = \frac{1}{2} \left[ |E_r(t)|^2 + |E_s(t)|^2 \pm 2\text{Re}\{E_r(t)E_s^*(t)\} \right]$$

where  $I_{\pm}(t)$  is the recorded intensity/current,  $E_r(t)$  and  $E_s(t)$  are the reference and signal optical fields, and  $\text{Re}$  denotes the real part. By performing the Hilbert transform on the beating term, the

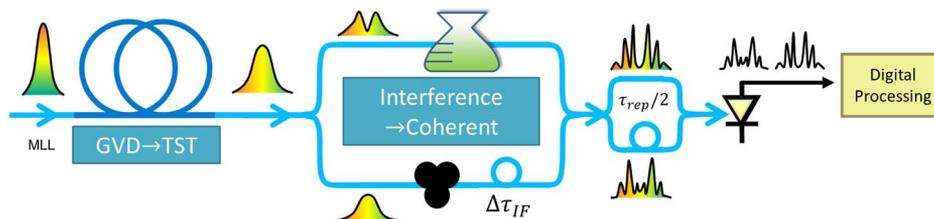


Fig. 2. Experimental block diagram of the coherent time-stretch transform (CTST) applied to spectroscopy. Pulses of 350 GHz full-width at half maximum bandwidth around 1530 nm are stretched using group-velocity dispersion (GVD). One copy traverses the sample (80 cm  $^{12}\text{C}_2\text{H}_2$  acetylene gas cell), and another passes through the reference path, delayed at  $\Delta\tau_{IF}$  to create the upshift frequency. The complimentary outputs of the interferometer are interleaved at half the pulse period  $\tau_{rep}/2$  and detected by a photodetector and 16 GHz oscilloscope. The time-stretch segment can be applied at any point in the sequence prior to the photodetection and does not necessarily have to be applied in the particular order shown here. MLL: mode-locked laser.

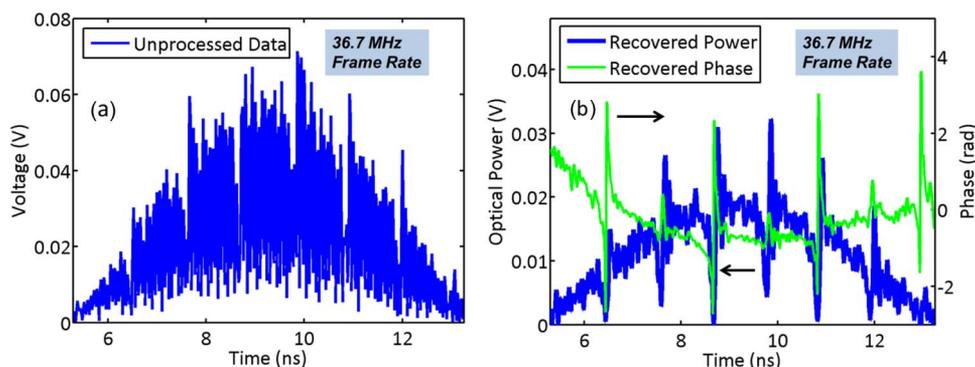


Fig. 3. (a) Unprocessed experimental trace, voltage versus time. The beat (or intermediate) frequency  $f_{IF}$  at 15 GHz between the reference and signal is observed, created by a time delay  $\Delta\tau_{IF}$  between the two waveforms. This interference allows the spectral amplitude and phase to be recovered via the Hilbert transform for complex field spectroscopy. Refresh rate is 36.7 MHz set by the mode-locked laser. (b) Reconstructed time-domain power (blue, left axis) and phase (green, right axis) versus time, as measured by the oscilloscope. The power trace alone is equivalent to the time-stretch dispersive Fourier transform, but the coherent time-stretch transform also captures the phase information, allowing reconstruction of the spectrum without a frequency-time mapping. The overshoots following the absorption features are a signature of the temporal near field [25].

phase difference is recovered, and knowledge of the reference allows reconstruction of the full optical field. This procedure works as long as the background envelope is in the far field, whereas the spectral features themselves may be in the near field. In contrast to algorithms that make the far-field assumption [34]–[36], here the interferometry and phase recovery is performed in the time domain. Once the time-domain waveform is reconstructed, a discrete Fourier transform with back-propagation results in the complex spectrum; thus, the instrument operates as a complex-field spectrum analyzer. The phase accuracy depends on a sufficiently large upshift frequency so that the interference term separates into two sidebands with no frequency overlap and the proper analytic representation is obtained. On the other hand, the upshift frequency must be within the bandwidth of the receiver for proper detection.

Figs. 3 and 4 show results from experimental measurements of an 80 cm Triad Technology  $^{12}\text{C}_2\text{H}_2$  acetylene gas cell at a pulse repetition rate of 36.7 MHz. The CTST measurements are able to recover the narrow gas lines with only  $-1910$  ps/nm of dispersion. Fig. 3(a) shows an unprocessed digitizer waveform which contains a 15 GHz beat frequency from the unbalanced interferometer. Although the dominant absorption features in this range have very narrow linewidths ( $\sim 450$  MHz FWHM native linewidth), the large absorption of this gas cell broadens the perceived widths of the features in a normal spectral measurement:  $\sim 3$  GHz and  $\sim 5$  GHz for the odd and even-numbered lines,

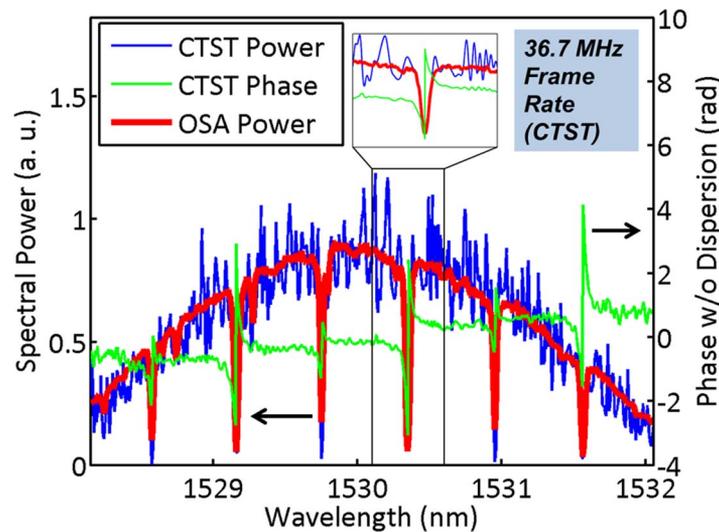


Fig. 4. Spectral power (blue, left axis) and phase (green, right axis) recovered from the coherent time-stretch transform (CTST) applied to an acetylene gas cell. Time-averaged spectrum obtained with an optical spectrum analyzer (OSA) shown for reference.

respectively, given the dynamic range of the experiment. These features are dispersed into near-field waveforms with the present dispersion, evidenced in the reconstructed time domain shown in Fig. 3(b). (A discussion of dispersion requirements separating the near and far field is presented in [25].) Thus, the unprocessed trace is not the actual spectrum, although acetylene features can be discerned as dips. Dispersing the lines into the far field would require significantly more dispersion; as noted, large amounts of dispersion introduce loss and limit the maximum repetition rate.

The reconstructed spectrum is shown in Fig. 4. Neither averaging nor smoothing have been used. The overshoots in the near-field features in Fig. 3(b) are absent upon spectral reconstruction, demonstrating that the coherent time-stretch transform can reconstruct the spectrum from near-field measurements. The present absorption feature widths provide a conservative measure of the spectral resolution ( $\sim 4$  GHz); given the bandwidth of  $\sim 500$  GHz, the time-bandwidth product (TBP) is at least 125. Much larger bandwidths (and hence time-bandwidth products) should be possible with system improvements. A measurement by a conventional optical spectrum analyzer (OSA) is also shown for reference. Small discrepancies between the traces may arise from uncompensated optical nonlinearities, incomplete knowledge of the reference phase, and limited oscilloscope bandwidth; refinement of the recovery algorithm is also likely to bring improvement. For perspective, it may be noted that the CTST spectra are collected  $\sim 10^8$  times faster than those from the OSA. Also, as the CTST data are obtained in a single shot, interferometric stability is not as critical as it would be in time-averaged interferometry, where interference fringes must remain stable over a very large number of pulse pairs. Simulations of the full CTST system are shown in Fig. 5 and include the full complex transfer function, where the phase has been determined from the HITRAN absorption data [37] by applying causal requirements to a Lorentzian approximation of the lineshape. They support the experimental measurements and demonstrate that residual artifacts in the reconstruction can be reduced by employing a digitizer with larger electronic bandwidth. A larger digitizer bandwidth will also better resolve narrower linewidths, further improving the time-bandwidth product. Fig. 5(a) shows a simulation of the spectral amplitude under the experimental conditions (16 GHz digitizer bandwidth and 15 GHz intermediate frequency). In the case of unlimited electronic bandwidth, the ripples in the spectral amplitude are eliminated [cf. Fig. 5(b)]. With a 32 GHz bandwidth, double that used in the experiment, some amplitude ripples remain, but fidelity is improved [cf. Fig. 5(c) and (d)]. A simulated phase trace is included in Fig. 5(d), showing the characteristic dispersive shape seen in the experimental measurement.

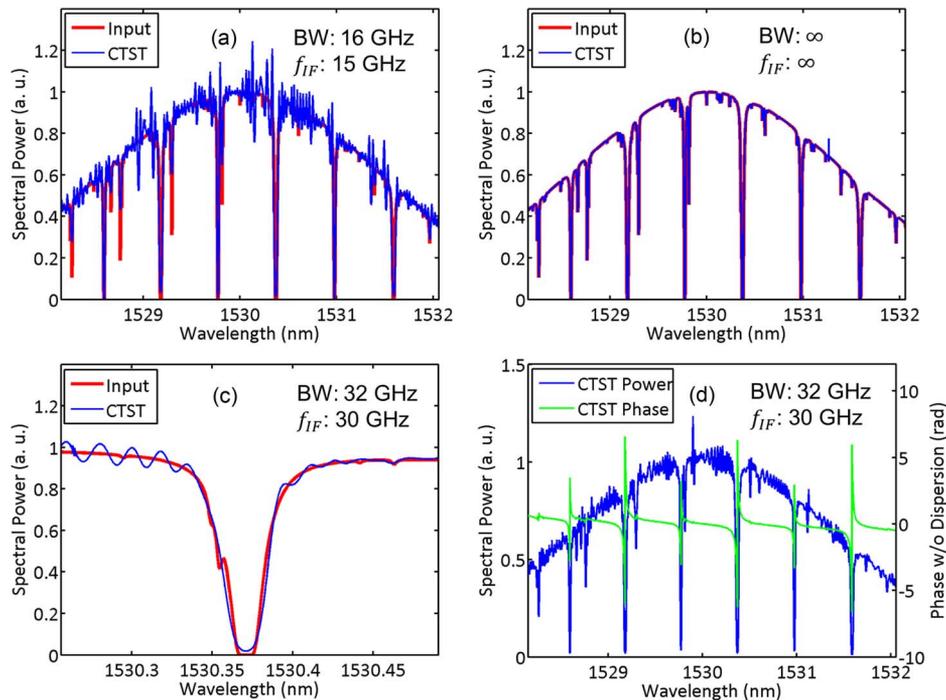


Fig. 5. Simulations of spectral power versus frequency of the input spectrum (red) and the recovered spectrum (blue) using the coherent time-stretch transform. (a) The reference is delayed to create a 15 GHz beat (intermediate) frequency ( $f_{IF}$ ), and is detected with a 16 GHz bandwidth (BW) receiver. (b) Infinite beat frequency and bandwidth. (c) 30 GHz beat frequency and 32 GHz bandwidth receiver. (d) Simulations of coherent time-stretch transform power (blue) and phase (green) with a 30 GHz beat frequency and 32 GHz bandwidth receiver.

As previously mentioned, it should also be noted that the absorption lines are actually much stronger than observed in the present amplitude spectra and that the even numbered lines are approximately  $3\times$  stronger than the odd lines on a logarithmic scale, as calculated from information in the HITRAN database [37]. The absorption strengths observed with the OSA and time stretch are limited by both spectral resolution and noise in the former case and primarily by the noise in the latter case. Although these limitations mask the difference in the absorption strengths of the even and odd lines, the phase measurements record a much larger phase shift for the even lines. Thus, even though amplitude measurements frequently have difficulty distinguishing differences in very strong resonances, the phase shifts can be indicative of activity beyond the dynamic range of the amplitude measurements. The absolute phase shifts observed in the present measurements have been reduced by the finite electronic bandwidth of the digitizer; a simulation assuming detection with double the electronic bandwidth shows larger phase shifts [cf. Fig. 5(d)]. Nevertheless, a comparison of the phase shifts of the even and odd lines from the experimental data still indicates that the lines have substantially different absorption strengths, even though the digitizer bandwidth is limited to 16 GHz.

In conclusion, the coherent time-stretch transform retrieves spectral amplitude and phase information from near-field interference measurements at extremely high throughput. It builds upon the time-stretch dispersive Fourier transform by adding complex field detection and operating in the near field, and the ability to capture phase data offers an additional source of information, which may enhance both dynamic range and sensitivity. We have demonstrated for the first time that this method can be used to perform phase-sensitive absorption spectroscopy of a gaseous sample at millions of frames per second. This technique can also be applied to spectral measurements of other samples and scattering processes. It may also find application in the study of the statistical and dynamical properties of laser sources and supercontinuum generation. Both the TS-DFT and CTST utilize linear or near-linear dispersive profiles, conserving the time-bandwidth product of the intensity envelope.

Yet, in some cases, measurement efficiency can be enhanced by altering the waveform's native time-bandwidth product. The anamorphic stretch transform (AST), which also measures the complex-field in real-time, aims to engineer the time-bandwidth product of the waveform by harnessing specific dispersion functions [38]. This type of manipulation has great potential to facilitate real-time measurements over long record intervals by compressing the data volume.

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