Measuring Simultaneously Spatially and Temporally Focused Ultrafast Laser Pulses Using the Dispersion Scan Technique

Alex M. Wilhelm, David D. Schmidt, Daniel E. Adams, Charles G. Durfee
Department of Physics, Colorado School of Mines, 1500 Illinois St, Golden, Colorado, 80401
amwilhelm@mines.edu

Abstract: We demonstrate a novel dispersion scan algorithm using grating dispersion. We also propose using the intrinsic dispersion of temporally focused laser pulses to characterize the pulse structure by scanning a nonlinear crystal through focus.

1. Dispersion Scan Retrieval Algorithm

The difficulty of measuring the spectral phase, and therefore the temporal structure, of ultrafast laser pulses has spawned a large array of pulse characterization techniques such as FROG and SPIDER [1]. More recently, the dispersion scan (or d-scan) technique has been introduced as an experimentally simple method for measuring few-cycle pulses [2]. In the conventional d-scan technique, the pulse compressor is adjusted to vary the dispersion (predominately second-order) while the spectrum of the second harmonic (SH) is recorded. The 2D trace is then inverted using an iterative algorithm.

We have developed our own retrieval algorithm, inspired by the ptychographic FROG algorithm [3]. In the d-scan trace, each column represents a SH spectrum taken with different amounts of applied dispersion, $\phi_j^{App}(\omega)$. Our algorithm makes an initial guess for the fundamental field, $X_j^G(\omega)$ and applies the known dispersion for a given column j to the guess field: $X_j^{G\prime}(\omega) = X_j^G(\omega)\exp(i\phi_j^{App}(\omega))$. The SH field is then calculated by $\psi_j^G(t) = \left(\mathscr{F}^{-1}\{X_j^{G\prime}(\omega)\}\right)^2$. The modulus of the guess SH spectral field is then replaced by the square root of the measured spectrum $\psi_j^{G\prime}(\omega) = \sqrt{M(\omega)}\exp(i\arg(\psi_j^G(\omega)))$. This updated SH field $\psi_j^{G\prime}(\omega)$ is then transformed back to the time domain and used to update the guess field with a weighting function $X_{j+1}^G(t) = X_j^G(t) + \alpha\frac{X_j^{G\prime}(t)^*}{|X_j^{G\prime}(t)|^2}(\psi_j^{G\prime}(t) - \psi_j^G(t))$. Lastly, the added dispersion for the current column is removed from the guess field and the algorithm repeats by moving to a new column on each iteration until it converges on a stable solution.

In addition to this serial version of the algorithm, we have developed a parallel version where a guess field is applied to each column of the trace simultaneously. The updated guesses from each column are then averaged together to generate a guess for the next iteration of the parallel algorithm. The parallel version applies an additional constraint to the retrieval in that it enforces the notion that the trace is generated from a single unique pulse structure. It also has the added benefit of improved stability and speed of convergence over the serial version.

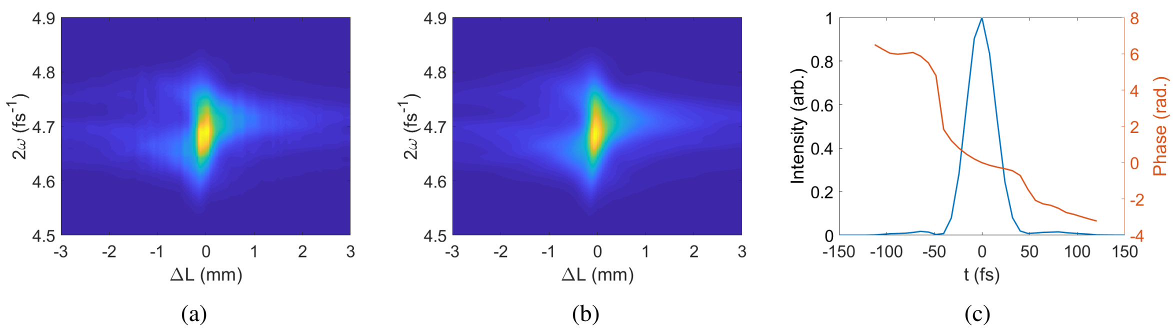


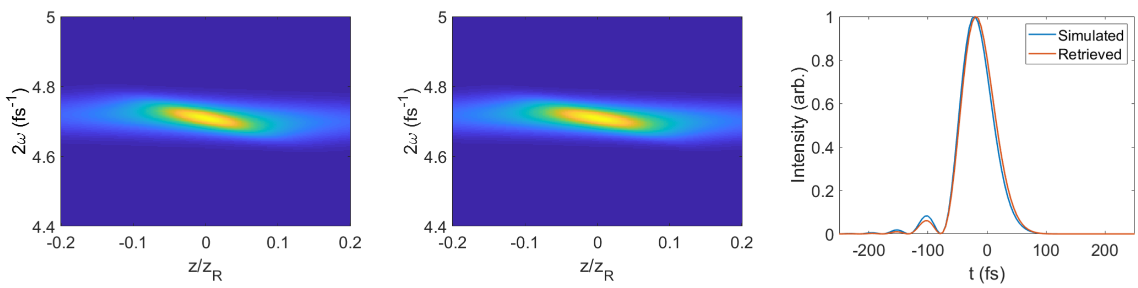
Fig. 1: a) Experimentally measured d-scan trace showing parabolic features indicative of a fourth-order dispersion limited pulse. b) Retrieved trace using the parallel algorithm. c) Retrieved pulse intensity (blue) and temporal phase (orange).

Figure 1 shows an experimentally measured trace, the retrieved trace, as well as the retrieved temporal pulse intensity for a dispersion scan taken by varying the grating separation in a standard double-pass grating compressor. Strong agreement is seen between the measured and retrieved traces, and the retrieved intensity profile exhibits features we expect based on the shape of the trace. Additionally, we obtain good agreement when comparing our retrieval against the pulse retrieved from a commercial single-shot FROG measurement (Grenouille).

2. Dispersion Scans of SSTF Pulses

Simultaneous spatial and temporally focused (SSTF) pulses have many applications in materials processing and nonlinear optics. A grating compressor is modified to create a beam with pure transverse chirp at the output. When focused, the resulting angular dispersion leads to temporal focusing at the same time the beam is spatially focused. Here we propose using the axial dependence of the second order spectral phase, which is given by $\phi_2^{SSTF}(z) = -\frac{\gamma^2 \omega_0 z}{2c}\left(1+\frac{z^2}{z_R^2}\right)^{-1}$, to perform an in-situ dispersion scan on the focused pulse. Here, γ is a parameter that defines the angular chirp of the pulse, ω_0 is the central frequency, and z_R is the Rayleigh range of the central frequency. D-scan is a single-pulse technique that only requires the dispersion to be varied in a known manner. This makes it advantageous for characterizing SSTF pulses, since a trace can be generated by placing a nonlinear crystal at the geometric focus and varying the compressor grating separation. Since the dispersion depends on the axial position within the focus, it is important to vary the compressor separation for different axial positions to find the one that gives the maximum SH signal. A simpler way to obtain a d-scan trace is by scanning a thin nonlinear crystal axially through the focal plane, using the intrinsic geometric dispersion of the temporal focusing (i.e. $\phi_2^{SSTF}(z)$) to perform the d-scan measurement. We call this technique the through-focus d-scan.

The spatial evolution of the individual beamlets, in addition to the axial dispersion, will effect the measured trace and its ability to be retrieved. The size and reduced overlap of the beamlets tends to suppress the intensity as well as the local bandwidth of the pulse. However, in the near-focus limit ($z \ll z_R$), these effects are mitigated and the SSTF dispersion becomes linear in z. Now, to generate a retrievable trace, sufficient dispersion must be applied to the pulse at the edges of the trace. In the small z limit, this means that a relatively large γ (i.e. a large amount of spatial chirp) must be used to generate large ϕ_2^{SSTF} in a short distance.



(a) (b) (c)

Fig. 2: a) Simulated through-focus d-scan trace for a third-order pulse. b) Retrieved trace using the near focus approximation of ϕ_2^{SSTF} c) Simulated and retrieved pulse intensities with a retrieval error of $\sim 1\%$.

Figure 2 shows a simulated through-focus d-scan for a pulse with a duration of $\tau_0 = 40fs$, a spot size of $w_0 = 100\mu m$, $\gamma = .25fs$, and third order dispersion of $\phi_3 = 10^4 fs^3$. The pulse was retrieved using the linear approximation for the dispersion function in the parallel retrieval algorithm. The trace is tilted, as would be expected for a third-order trace in a conventional d-scan. Strong agreement can be seen between the simulated and retrieved traces, as well as the intensities. It should be noted that due to beamlet walk-off effects that aren't included in the dispersion function in the retrieval algorithm, the retrieval error cannot approach machine precision even in simulation. However, the RMS error between the simulated and retrieved pulses is still less than 1%. Due to the simplicity of the experimental setup (a single movable nonlinear crystal), the ease with which one can interpret the traces, and the surprising robustness of the retrieval algorithm to errors in the assumed dispersion, the through-focus d-scan technique shows promise as a simple and effective way to measure SSTF pulses in-situ. We plan to implement this technique experimentally in the near future.

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References

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