Transient Grating Single-shot Supercontinuum Spectral Interferometry (TG-SSSI)

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Characterization of structured ultrashort laser pulses such as spatiotemporal optical vortices [1,2] demands a technique capable of capturing the spatiotemporal phase and amplitude of such pulses. Transient grating single-shot supercontinuum spectral interferometry (TG-SSSI) was developed to meet these demands and was successfully demonstrated in [2]. Here we present the details of TG-SSSI [3] and its possible extensions.

Our prior technique, single-shot supercontinuum spectral interferometry (SSI) can only extract spatiotemporal amplitude: it spectroscopically interferes a chirped supercontinuum (SC) reference \( E_{\text{ref}} \) temporally preceding a chirped SC probe \( E_{\text{probe}} \) to extract the phase shift \( \Delta \phi(x, \omega) \) imposed on \( E_{\text{probe}} \) by pulse \( E_s \) in a thin instantaneous Kerr medium [4] (witness plate in Fig. 1) where \( E_{\text{probe}} \propto \chi^{(3)} E_s^2 E_{\text{ref}} \), \( x \) is position in a 1D spatial slice and \( \chi^{(3)} \) is the nonlinear susceptibility. Fourier analysis of \( \Delta \phi(x, \omega) \) [3] recovers the 1D spatiotemporal phase shift, \( \Delta \phi(x, \tau) \propto |E_s(x, \tau)|^2 \propto I_s(x, \tau) \), where \( I_s(x, \tau) \) is the spatiotemporal intensity envelope and \( \tau \) is the time coordinate local to \( E_s \).

TG-SSSI is an extension of SSSI which enables extraction of spatiotemporal phase as well as amplitude. An interferometric reference, \( E_i \), crosses \( E_s \) at a small angle \( \theta_w \), resulting in a transient grating which is then measured by SSSI. The output SC probe pulse becomes \( E_{\text{probe}} \propto \chi^{(3)} (|E_s|^2 + |E_i|^2 + E_s E_i^* + E_s^* E_i) E_{\text{ref}} \). A chopper in the path of \( E_s \) enables \( \chi^{(3)} |E_s|^2 \) to be subtracted as background. Fourier analysis then yields \( \Delta \phi(x, \tau) \propto |E_s(x, \tau)|^2 + 2|E_s||E_i| \cos(2k_w x \sin(\theta/2 + \Delta \phi(x, \tau))) \), where \( k_w = n_d k \) and \( \Delta \phi(x, \tau) \) is the spatiotemporal phase of \( E_s \) relative to \( E_i \).

Figure 1(a) illustrates the TG-SSSI setup, where \( E_{\text{ref}} \) precedes \( E_{\text{probe}} \) by \( \Delta t \) and \( E_i \) crosses \( E_s \) at a small angle \( \theta_w \), forming a transient nonlinear phase grating. Frequencies in \( E_{\text{probe}} \) overlapping with the transient grating are diffracted at an angle \( \theta_m \). The output face of the witness plate is relay imaged, via a high numerical aperture, achromatic relay, onto the slit of an imaging spectrometer yielding a spectrogram shown in Fig. 1(b). The extracted \( \Delta \phi(x, \tau) \) from the interferogram is shown in Fig 1(c). Low pass image filter of \( \Delta \phi(x, \tau) \) recovers the intensity envelope, \( I_s(x, \tau) \) which is shown in Fig. 1(d). Extraction of the spatiotemporal phase of \( E_s \) is performed via Fourier analysis along \( x \), \( \Delta \phi(x, \tau) = \arg(\mathcal{F}_x^{-1}(\mathcal{F}_x(\Delta \phi(x, \tau)|\Theta(k)))) \), where \( \mathcal{F}_x(\Delta \phi(x, \tau)) = \Delta \phi(k, \tau) \) is the Fourier transform along \( x \) and is shown in Fig. 1(e) as \( \log(|\mathcal{F}_x(\Delta \phi(x, \tau))|) + 1 \) and \( \mathcal{F}_x(k) \) is the inverse Fourier transform along \( k \), \( \Theta(k) \) is a sideband windowing and shifting \( (k \rightarrow k - 2\pi/\Lambda) \) function, and \( \Lambda \) is the x-component of the spatial frequency. The extracted phase of the pulse, \( \Delta \phi(x, \tau) \), is plotted in Fig. 1(f).

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