Optimized ancillae generation for ultra-broadband two-dimensional spectral shearing interferometry

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Recent years have witnessed a tremendous progress in the generation of ultra-broadband few-optical-cycle pulses. Accurate characterization of the temporal profile of pulses with such extreme bandwidth and broad frequency tunability poses a severe experimental challenge. Birge *et al.* [1] introduced two-dimensional spectral shearing interferometry (2DSI); this can be seen as a zero-delay SPIDER and requires the generation of two spectrally sheared replicas of the pulse under test by interaction with ancillary fields. The information on the spectral phase is obtained by acquiring many interference patterns as a function of the delay between the two replicas; exact retrieval of the phase requires very careful calibration of their spectral shear Ω. Traditional techniques to generate the sheared replicas are based on ancillary fields produced by a stretcher and an unbalanced Michelson interferometer: the strong limitation of this arrangement is that it allows only approximate characterization of Ω by indirect measurements [2].

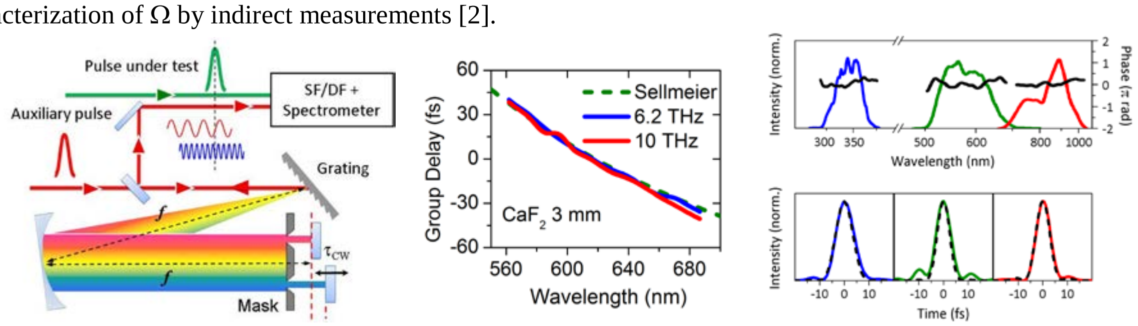

Fig. 1. (a) Experimental setup. (b) Dispersion introduced by a CaF_2 plate, obtained with two values of the shear. (c) Spectral phase retrieval of pulses from 320 to 1000 nm and intensity profiles compared to the transform-limit pulses (dashed line).

Here we propose a new method for the generation of the sheared ancillae in 2DSI, which allows exact and direct determination of Ω, thus leaving no unknown parameters in the retrieval of the spectral phase. In our proposal (Fig. 1(a)), the auxiliary pulse travels in a 4-*f* pulse shaper, with a diffraction grating as dispersive element. A double-slit mask placed in the Fourier plane allows us to spectrally filter the auxiliary pulse, selecting two monochromatic components, whose shear can be easily varied by changing the slits distance and, most important, directly measured with a spectrometer. The folding mirror in the Fourier plane is replaced by two independent mirrors, one of which is translated with mounted on a high precision for the scanning of the ancillae delay τ_{CW}. After the pulse shaper, the two collinear ancillae are synchronized with the pulse under test and both beams are non-collinearly focused onto a nonlinear crystal for sum-frequency (SF) or difference-frequency (DF) generation. To validate the accuracy of our method, we measure the frequency-dependent group delay (GD) introduced by a glass plate. Figure 1(b) shows the GD of a 3-mm-thick CaF_2 plate measured by our 2DSI apparatus with two different choices of the shear. The very good agreement of both raw measurements with the expected GD (dashed line) shows the reliability and robustness of the technique, enabled by our direct measurement of the shear. We also demonstrate the flexibility of our approach by characterizing the spectral phase of few-optical-cycle pulses, with carrier ranging from 320 nm to 1000 nm (Fig. 1(c)). Addressing various spectral regions only requires to adjust the phase-matching conditions for the nonlinear DF/SF interaction. This result demonstrates that 2DSI, also thanks to our improved approach for the generation of the ancillae, is able to characterize broadly tunable few-optical-cycle pulses, since it can independently measure the phase of adjacent spectral portions of an ultra-broadband pulse, thus removing the need to phase-match simultaneously its whole band. For this reason, this improved scheme of 2DSI is particularly suitable to characterize synthesized sub-cycle pulses. Our approach is not sensitive to the bandwidth or wavelength of the auxiliary pulse, and can be adapted to most ultrafast lasers.

[1] J. R. Birge, R. Ell and F. X. Kaertner, “Two-dimensional spectral shearing interferometry for few-cycle pulse characterization”, Opt. Lett. **31**, 2063-2066 (2006).
[2] R. Borrego-Varillas, A. Candeo, D. Viola, M. Garavelli, S. De Silvestri, G. Cerullo, and C. Manzoni, "Microjoule-level, tunable sub-10-fs UV pulses by broadband sum-frequency generation," Opt. Lett. **39**, 3849-3852 (2014).