Implementation of electro-optic spectral shearing interferometry for ultrashort pulse characterization

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Electro-optic spectral shearing interferometry is implemented for the highly sensitive characterization of ultrashort pulses from a free-running source. A simple phase-locked-loop clock recovery circuit is used to extract the high-frequency microwave clock signal to drive the phase modulator for spectral shearing. We demonstrate accurate full temporal characterization of 200-fs pulses from an optical parametric oscillator at 5-μW average power.

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Self-referencing measurement techniques for characterizing the temporal electric field of a short optical pulse such as frequency-resolved optical gating[1] and spectral phase interferometry for direct electric-field reconstruction[2] (SPIDER) are successfully used in many areas of ultrafast sciences. With these techniques, temporal gating or spectral shearing is achieved by use of nonlinear optics, and the sensitivity for a self-referencing multishot implementation is of the order of 1 mW in average power for a train of pulses at 100 MHz.[1,2] Although test plus reference characterization techniques can display much better sensitivity, self-referencing temporal diagnostics with a better sensitivity would be extremely valuable in applications such as optical telecommunication or phase-sensitive detection of nonlinear polarization-induced emission,[3] where nonlinear optics is impractical owing to the low power level of the optical pulses used. Dorrer and Kang recently demonstrated highly sensitive self-referencing pulse characterization techniques based on spectrography,[4] interferometry,[5] and tomography.[6] These techniques use a temporal modulator to implement a gate[4] or a temporal phase modulator for linear[5] or quadratic phase modulation[6] and can achieve sensitivity better than 1 μW owing to the linearity of the diagnostic without resorting to well-characterized reference pulses. The optical pulses characterized in these implementations were derived from sources whose repetition rate was actively controlled. However, the free-running sources, which are more representative of the sources used in the ultrafast community, such as Kerr-lens mode-locked lasers, would also benefit from such an approach.

We present an implementation of electro-optic spectral shearing interferometry for an ultrafast optical pulse source operating without external control of the repetition rate: ultrashort (~200-fs) pulses from a commercial optical parametric oscillator (OPO) (Spectra Physics Opal) are accurately characterized with high sensitivity of 5 μW, as measured at the input of the phase modulator. We used an easy-to-implement optical clock recovery circuit to generate the small-jitter 10-GHz microwave drive signal for the phase modulator that provides the spectral shearing. A novel method of fast interferogram acquisition minimizes the effect of the drift of the interferometer or the repetition rate of the laser source and would allow for real-time characterization.

A schematic of the experimental implementation is depicted in Fig. 1(a). The optical pulses are derived from an OPO synchronously pumped by a mode-locked Ti:sapphire laser free running at an approximate repetition rate of 82 MHz. The OPO produces ~200-fs pulses with a 16-nm bandwidth at a central wavelength of 1571 nm. A free-space Michelson interferometer generates two replicas of the OPO pulse separated by 50 ps. The replicas are coupled into a commercial fiber-optic $LiNbO_3$ phase modulator (JDS Uniphase, PM 150), which is driven by an amplified 10-GHz sinusoid generated as explained below. The chromatic dispersion that is due to the input fiber lead of the phase modulator and free space-to-fiber coupler is compensated by insertion of a combination of standard single-mode fiber (SSMF) ($D \sim 18$ ps/nm/km) and inverse dispersion fiber ($D \sim -19$ ps/nm/km) between the coupler and the phase modulator. As in SPIDER, chromatic dispersion after the spectral shearing operation does not affect the measurement.

The 10-GHz electronic clock needed for the electro-optic spectral shearing[5] is extracted by use of a clock recovery circuit based on a phase-locked-loop (PLL) microwave oscillator: the output of the OPO is tapped off and detected by a 1-GHz bandwidth detector. The electrical waveform is filtered by a bandpass filter centered at 82 MHz, and the resulting

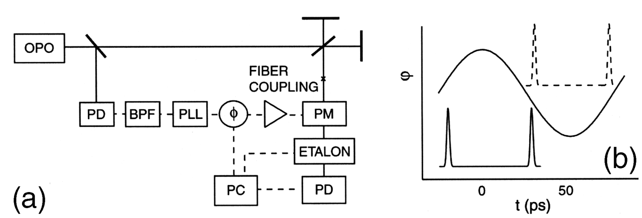

Fig. 1. (a) Schematic of the experimental setup: PDs, photodiodes; BPF, bandpass filter; ϕ, phase shifter; PM, phase modulator. Optical paths are plotted as a continuous line, electrical connections are plotted as a dashed line. (b) Two different timing alignments between the optical pulses and the 10-GHz drive of the phase modulator.

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82-MHz sinusoid is used as a reference in a PLL dielectric resonator (CTI PDRO-14538). The PLL oscillator consists of a 10-GHz voltage-controlled oscillator (VCO) and a double-balanced mixer that monitors and minimizes the phase error between the VCO output and the 123rd harmonic of the 82-MHz reference. The PLL is fast enough to track the changes of the repetition rate of the OPO owing to mechanical vibration (~kHz) and thermal drift (~Hz) of the cavity. The phase noise of the OPO is magnified in the frequency multiplication and results in the temporal jitter of the 10-GHz output of the PLL, which is 3 ps as measured by a high-speed sampling scope. A voltage-controlled rf phase shifter allows rapid (up to 10-kHz) adjustments of the relative temporal delay between the pulse replicas and the 10-GHz drive of the phase modulator. Finally, the phase shifter output is amplified to 28 dBm to drive the phase modulator.

Interferograms of the spectrally sheared replicas are measured by a fast-scanning microelectromechanical system (MEMS) Fabry–Perot etalon filter (Nortel MT15CL-025) and a 50-kHz bandwidth photodiode. The etalon has a scanning range and a free spectral range larger than 100 nm and can cover the spectrum of a pulse with a transform-limited pulse width of ~150 fs. The 15-pm resolution is sufficient to resolve the interference fringes with a mean spacing of 160 pm. The wavelength scanning can be performed at rates up to 1 nm/μs, but the limited bandwidth of the detector restricted the scanning frequency to 50 Hz over a 70-nm scanning range so that the fringes could be resolved.

The timing alignment T between the phase-modulator drive $\varphi_0 \sin[\nu(t - T)]$ and the optical pulse replicas needs to be properly adjusted so that the replicas are modulated by linear modulation of opposite signs.[5] At 10 GHz, the time window over which the sinusoidal modulation is sufficiently linear is approximately 20 ps, and thus the 3-ps timing jitter is insignificant. Both the timing T and the magnitude of spectral shear $\Omega = \varphi_0 \nu$ are initially calibrated by measuring the shift of the centroid of the spectrum with one arm of the interferometer blocked and fitting it with $\varphi_0 \nu \cos[\nu(t - T)]$. The relative error with regard to the value of the shear, typically of the order of 1%, leads to an identical multiplicative error in the reconstructed phase. We confirmed the accuracy of such calibration by measuring the dispersion of known dispersive elements. There are two possible temporal positions for the pulse replicas relative to the drive voltage [Fig. 1(b)] that correspond to extracted phase differences $\varphi(\omega + \Omega) - \varphi(\omega - \Omega) + \omega\tau$ and $\varphi(\omega - \Omega) - \varphi(\omega + \Omega) + \omega\tau$, where τ is the delay between the replicas. The effects of possible defects in frequency calibration or drift of the relative delay can be eliminated by taking the difference between the two recovered phases, yielding $2[\varphi(\omega + \Omega) - \varphi(\omega - \Omega)]$. The interferograms are measured in rapid succession by alternating the control voltage to the phase shifter between the two settings that correspond to the temporal arrangements depicted by the solid and dashed curves in Fig. 1(b). The fast modulation speed of the phase shifter is especially helpful to reduce the effects from the mechanical vibration and other perturbations that affect the interferometer. We average 100 interferograms for each case and extract the spectral phase differences from the two averaged interferograms. The etalon is scanned at 50 Hz, so it takes 4 s to acquire a total of 200 interferograms. Full temporal information of the electric field is directly reconstructed from the acquired interferograms and the spectral intensity as in SPIDER.

The recovered spectral and temporal intensity and phase of the output pulses of the OPO are shown in Fig. 2. The full width at half-maximum (FWHM) of the autocorrelation is inferred to be 300 fs, in excellent agreement with the FWHM of the measured autocorrelation by use of two-photon absorption in silicon. Note that ~200-fs pulses ($\Delta\omega = 12\ \mathrm{ps}^{-1}$) are accurately characterized with a relative spectral shear of $2\Omega = 0.4\ \mathrm{ps}^{-1}$ obtained with a rf modulation power of 28 dBm.

We validated the accuracy of the diagnostic by characterizing the spectral phase acquired by the pulses after a known amount of dispersion, which is controlled by the insertion of a known length of SSMF. In Fig. 3(a) we show the spectral phase differences between the initial pulses and the pulses that travel 1.2 m less (circles) and 1.2 m (squares) and 6.2 m (triangles) more along the SSMF. The measured phase differences are in good agreement with the expected parabolas calculated by use of the known dispersion value of SSMF ($D = 18$ ps/nm/km). The measurement technique also works for highly chirped pulses (longer than 6 ps). We measured the quadratic dispersion after −1.2, 1.2, 6.2, 11.2, and 16.2 m of SSMF and plotted it against the fiber lengths in Fig. 3(b). The dispersion value from the fitting, $D = 17.9$ ps/nm/km, is in excellent agreement with the known value of SSMF.

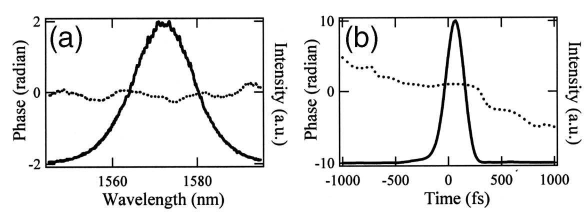

Fig. 2. (a) Spectral phase (dashed curve) and intensity (solid curve) and (b) temporal phase (dashed curve) and intensity (solid curve) of the OPO pulses.

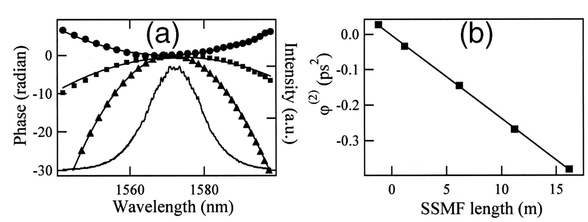

Fig. 3. (a) Measured spectral intensity (solid curve) and phase induced by removing 1.2 m (circles) and adding 1.2 m (squares) and 6.2 m (triangles) of SSMF. The expected parabolic spectral phases calculated with $D = 18$ ps/nm/km are also plotted. (b) Second-order dispersion $\varphi^{(2)}$ versus the SSMF length.

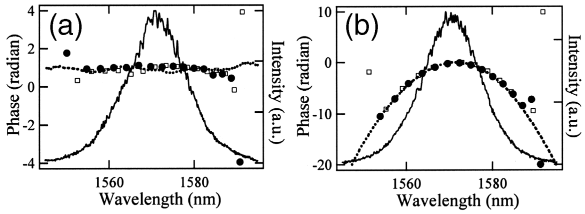

Fig. 4. (a) Spectral intensity (solid curve) and phase of the initial pulse for 100 (dashed curve), 20 (squares), and 5 μW (circles) of power. (b) Spectral intensity (solid curve) and phase of the pulse after propagation in 5 m of SSMF for 160 (dashed curve), 20 (squares), and 5 μW (circles) of power. Spectral intensities are plotted for only the highest powers for clarity.

The test of the measurement sensitivity is shown in Fig. 4. We measured the optical power launched into the input fiber of the phase modulator; in the case of ideal free-space-to-fiber coupling, the optical power at the interferometer input would be twice the power that we measured. If the pulses were drawn from a fiber-based source, a waveguide interferometer would be preferable to the free-space one because of better stability and less insertion loss. Shown in Fig. 4(a) are the spectral phases of the initial chirp-free pulses measured at 100, 20, and 5 μW. In Fig. 4(b) the data of the pulses after 5 m of SSMF were measured for 160, 20, and 5 μW. We averaged ten times more ($\sim$40 s) only for the data measured at 5 μW. Essentially the same spectral phases are recovered independently of the power. An important limitation of the sensitivity is the resolution of the etalon filter (15 pm), which is too narrow for our purpose to resolve $\sim$160-pm fringes and unnecessarily restricts the light throughput; an optimal resolution would be $\sim$60 pm. The fringe spacing of the interferograms, and thus the required filter bandwidth is inversely proportional to the delay between the interfering pulses. The sensitivity and speed of the measurements can be improved by use of a faster detector with comparable or better sensitivity. As discussed earlier, the measurement speed is limited by the bandwidth of the detector (50 kHz); however, the MEMS etalon can be scanned much faster (up to 10 kHz) if the detector is fast enough to resolve the interference and then it should be feasible to achieve a submicrowatt sensitivity with less than a 1-s acquisition time. Also, the use of a grating-based spectrometer with an array detector would provide much better sensitivity since no rejection of spectral intensity is performed in this case. This could provide faster update rates, such as the 1-kHz repetition rate recently demonstrated for SPIDER.[7]

Finally, we point out that the presented measurement technique can be extended to sources that operate at different wavelength ranges and produce shorter pulses. The commercial phase modulator can be used down to $\lambda \sim 1.2$ μm, below which the waveguide and the fiber leads are no longer single mode. Nevertheless, it is possible to use the same device if we carefully launch a single mode into the device, for example, by using short lead fibers, minimizing perturbations on the fibers, and using a good polarizer at the phase modulator input. The electro-optic efficiency of $LiNbO_3$ in fact increases as the wavelength gets shorter, and a $LiNbO_3$ waveguide phase modulator optimized for shorter wavelengths could be fabricated. We note that photorefractive effects would not be a concern if we consider the small powers involved in electro-optic spectral shearing interferometry. It can be shown that the only extraneous effect of the combined phase modulation (time–nonstationary operation) and chromatic dispersion (time–stationary operation) in the phase modulator is an extra phase equal to half of the linear propagation phase in the modulator. The chromatic dispersion from the various fibers located before the phase modulator as well as that of the phase modulator can be compensated exactly experimentally or numerically, and an accurate characterization of shorter pulses should be feasible. In our case, the relative shear was 3% and the signal-to-noise ratio was $\sim$200, calculated as the ratio of the amplitude of the fringes to the rms noise in the spectral measurements. A comparable accuracy for shorter pulses could be obtained by increasing the spectral shear (for example, by using a higher rf power or a larger rf frequency) or increasing the signal-to-noise ratio.

In conclusion, we have implemented highly sensitive electro-optic shearing spectral interferometry for a free-running mode-locked ultrafast laser. The components of the setup are compact and could be easily integrated, for example, with a waveguide interferometer. Fast measurements are made possible thanks to a high-speed phase shifter and a fast scanning MEMS etalon filter. Various technical modifications and considerations should lead to the real time accurate measurement of optical pulses in the sub-100-fs range with microwatt average power. Also, the clock recovery circuit should be useful in other applications for the characterization and shaping of femtosecond pulses.

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