# Self-referenced spectral phase retrieval of 28-attojoule ultrashort pulses by modified interferometric field autocorrelation measurement

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***Abstract*—We report on spectral phase and intensity retrieval with 28-aJ coupled pulse energy by measuring two modified interferometric field autocorrelation (MIFA) traces using long periodically poled lithium niobate (PPLN) waveguide. The corresponding sensitivity is $1.1 \times 10^{-7}$mW$^2$.**

Diagnosis and control of the spectral phase of ultrafast optical signals plays a pivotal role in coherently controlled nonlinear spectroscopy, pulse formation from externally modulated CW laser comb, and signal monitoring in coherent telecommunications. In terms of self-referenced schemes with femtosecond resolution, nonlinear optical effects are widely used to provide ultrafast spectral shearing (SPIDER) or temporal gating (FROG) to measure spectral phase or complex field. These existing techniques typically utilize thin nonlinear crystals to phase match the broad nonlinear polarization spectrum in the upconversion processes, which compromise the measurement sensitivity. Thick nonlinear crystals have also been used for ultrashort pulse measurements [1]–[3], yet these schemes still rely on a broad phase-matching (PM) spectrum. We have proposed and demonstrated a modified interferometric field autocorrelation (MIFA) method for spectral phase recovery by utilizing a thick nonlinear crystal with extremely narrow ($\delta$-like) PM spectrum in a typical intensity autocorrelator [4]. Here, we utilize a PPLN waveguide with 49-mm-long quasi-phase matching (QPM) grating in a MIFA measurement and achieve a sensitivity of $1.1 \times 10^{-7}$mW$^2$, about 20 times better than the previous record [3]. The further enhancement of the measurement sensitivity over that in Reference [3] is attributed to: (1) elimination of loss due to frequency-resolving optics; (2) employment of a sensitive point detector (photomultiplier tube, compared to an intensified CCD camera) and lock-in detection; (3) maximized SHG yield of short pulses when using a $\delta$-like PM spectrum aligned with the nonlinear polarization spectral peak [5].

Assume the pulse has a complex spectral envelope $A(f) = |A(f)| \times \exp[j\psi(f)]$ and a carrier frequency $f_0$. As explained in Reference [4], processing a single MIFA trace measured by using a thick crystal with central PM frequency of $2f_0$ gives a complex even spectral function:

$$A_{e1}(f) = A(f) \cdot A(-f) = P_{e1}(f) \cdot \exp[j2\psi_{e1}(f)], \quad (1)$$

where $P_{e1}(f) = |A(f) \cdot A(-f)|$, $\psi_{e1}(f) = [\psi(f) + \psi(-f)]/2$ are the even spectral intensity and phase, respectively. A second MIFA trace due to a shifted central PM frequency of $2(f_0 - \Delta)$ leads to another spectral function:

$$\begin{aligned} A_{e2}(f) &= A(f) \cdot A(-f - 2\Delta) \\ &= P_{e2}(f) \cdot \exp[j2\psi_{e2}(f)], \end{aligned} \quad (2)$$

where $P_{e2}(f) = |A_{e2}(f)|$ and $\psi_{e2}(f) = [\psi(f) + \psi(-f - 2\Delta)]/2$, containing all spectral components symmetric with respect to the frequency of $f_0 - \Delta$. A recursive relation has been derived to combine Eqs. (1) and (2) to reconstruct the complete (second order and higher) spectral phase $\psi(f)$:

$$\psi(f - 2\Delta) - \psi(f) = 2[\psi_{e2}(f - 2\Delta) - \psi_{e1}(f)]. \quad (3)$$

Here, another recursive relation is used to retrieve the power spectrum using the two even spectral intensity functions $P_{e1}$, $P_{e2}$ (normalized to $P_{e1}(0) = P_{e2}(-\Delta) = 1$), and a constant $\alpha = |A(0)/A(-\Delta)|^2$:

$$|A(f - 2\Delta)/A(f)|^2 = [\alpha P_{e2}(f - 2\Delta)/P_{e1}(f)]^2. \quad (4)$$

Since $\alpha$ is typically measured by an optical spectrum analyzer (OSA), the usefulness of Eq. (4) mainly lies in the inherent consistency check of the experimental data traces. Note that the experimentally measured MIFA trace cannot determine the absolute amplitude and phase of $A_{ei}(f)$ ($i$=1, 2), thus resulting in ambiguities in the relative amplitude between $P_{e1}$, $P_{e2}$, and relative phase between $\psi_{e1}$, $\psi_{e2}$. As a result, the insertion of constant $\alpha$ in Eq. (4) becomes essential to uniquely determine the power spectral shape. In contrast, the ambiguity of $\psi_{ei}$ is irrelevant to the temporal pulse shape.

Fig. 1 shows the fiber-based ultra-sensitive MIFA setup. The signal pulse with 50-MHz repetition rate at 1560 nm comes from a passively mode-locked Er-doped fiber laser, and is being combined with the CW reference at 1480 nm using a wavelength division multiplexer (W1). They are sent

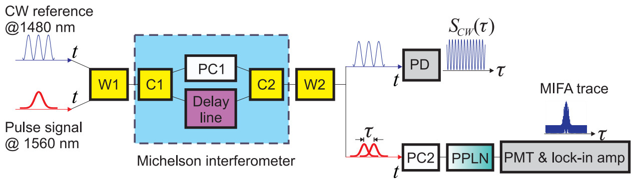


Fig. 1. Experimental setup of MIFA measurement. W#: WDM, C#: 3-dB coupler, PC#: polarization controller, PD: InGaAs photodetectors, PMT: Photomultiplier Tube.

into a collinear Michelson interferometer, where an electrically controlled delay line (VariDelay II, General photonics) is used to scan the optical delay at a speed of 1 ps/s. The interfered CW reference trace $S_{CW}(\tau)$ is used for fringe correction. The signal pulse pair are coupled into a fiber-pigtailed PPLN waveguide with 49-mm-long QPM grating for SHG. The PM tuning curve of the PPLN waveguide has a sinc$^2$-shape with an FWHM of $\approx 0.24$ nm, and the peak wavelengths are set to 1559.86 nm and 1560.34 nm (PPLN temperature at 46°C and 50°C) when acquiring the two MIFA traces, respectively. The average second-harmonic power at each delay is detected by a PMT (Hamamatsu, R636-10) and lock-in amplifier. The lock-in time constant is set at 640$\mu$s, corresponding to a delay resolution of 0.64 fs. It only takes 10 seconds to acquire one MIFA trace with a 10-ps delay window.

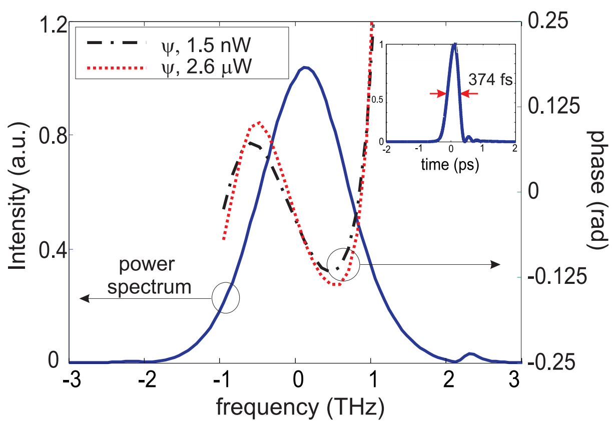


Fig. 2. Power spectrum measured by OSA (solid), and retrieved spectral phase profiles for input average powers of 1.5 nW (dash-dot) and of 2.6 $\mu$ W (dash). The inset shows the retrieved temporal intensity profile.

Fig. 2 illustrates the retrieved spectral phase profiles of a nearly bandwidth-limited pulse at average powers (coupled into the waveguide) of 1.5 nW (dash-dot) and 2.6 $\mu$W (dot), respectively. Fitting the phase profile over a frequency range of $\approx$ 1 THz gives rise to quadratic and cubic coefficients of $c_2$=0.065 ps$^2$ ($c_2$=0.061 ps$^2$), $c_3$=0.29 ps$^3$ ($c_3$=0.36 ps$^3$) for a coupled power of 1.5 nW (2.6 $\mu$W), where the spectral phase is defined as $\psi(f) = c_2 f^2 + c_3 f^3$. Even with a 32-dB input power difference (64-dB difference in SHG power), the retrieved spectral phase profiles agree well with each other. The 1.5-nW average power is equivalent to a 75-$\mu$W peak power, 28-aJ pulse energy, corresponding to an unprecedented sensitivity (the product of peak power and average power of minimum detectable signal) of $1.1 \times 10^{-7}$mW$^2$.

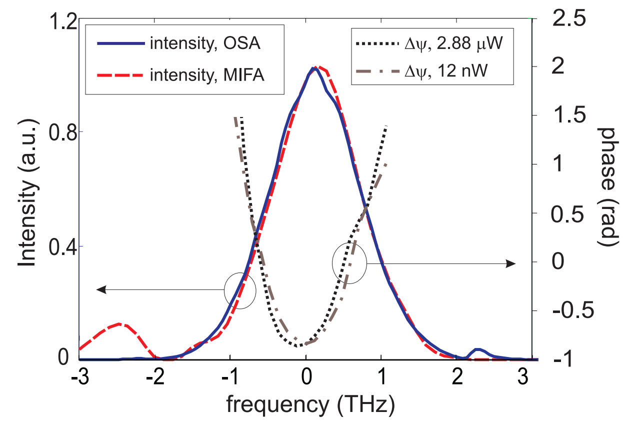


Fig. 3. Spectral phase difference due to 5.15-m-long SMF retrieved at average input powers of 2.88 $\mu$W (dot) and 12 nW (dash-dot). Spectral intensity measured by OSA (solid) and MIFA method at 12 nW (dash).

To further verify the measurement capability, we inserted a 5.15-m-long single-mode fiber (SMF) into the link to increase the quadratic spectral phase and performed the MIFA measurement at two different average input powers to retrieve the spectral phase and the power spectrum. For simplicity, Fig. 3 only shows the phase difference ($\Delta\psi$) due to the dispersion of the additional SMF. At input powers of 2.88 $\mu$W (dot) and 12 nW (dash-dot), the change in the retrieved quadratic phase coefficients are 2.32 ps$^2$ and 2.41 ps$^2$, respectively, close to the prediction of the SMF specifications ($c_2$ = 2.36 ps$^2$ at 1560 nm). The cubic phase coefficients are almost identical, since SMF is known to predominantly add quadratic phase. Using the same MIFA traces and relative spectral intensity of the pulse at wavelengths of 1559.86 nm and 1560.34 nm ($\alpha$ = 1.023), we can retrieve the power spectrum using Eq. (4). As shown in Fig. 3, the retrieved power spectrum at input power of 12 nW (dash) is in good agreement with that measured by OSA (solid). The bump around $f = -2.5$ THz and the missing fine structure around $f = +2.2$ THz are primarily due to the recursive reconstruction error when the value of $P_{ei}(f)$ is low and dominated by the measurement noise .

We have demonstrated that the MIFA method using long PPLN waveguides can analytically retrieve the spectral phase of ultraweak ultrashort pulse. The achieved sensitivity is $1.1 \times 10^{-7}$mW$^2$, improving on the previous record by about 20 times. This material is based upon work supported by the National Science Council of Taiwan under grant NSC 97-2221-E-007-028-MY3, and U.S. Air Force Office of Scientific Research under grant FA9550-09-1-0233.

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