400-photon-per-pulse Ultrashort Pulse Autocorrelation Measurement with Aperiodically Poled Lithium Niobate Waveguides at 1.55 μm

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Abstract: We demonstrate accurate ultrashort pulse autocorrelation measurements for coupled energy of 52aJ per pulse using aperiodically poled lithium niobate waveguides. The corresponding sensitivity is 3.2×10^{-7} mW^2, about 500 times better than the previous record.

OCIS codes: (320.7100) Ultrafast measurements; (320.7110) Ultrafast nonlinear optics; (130.3730) Lithium niobate; (120.3180) Interferometry

Lowering the minimum power requirements for ultrashort pulse measurements is highly desirable for characterizing ultrafast lightwave communications signals or for nonlinear optical material characterization. Although linear measurement of 42 zeptojoule (42×10^{-21} J) pulses has been reported using spectral interferometry [1], this experiment relied on fully-characterized strong reference pulses, which are not always available. Other experimental efforts exploit the two-photon absorption (TPA) mechanism in silicon avalanche photodiodes [2], GaAs photomultiplier tubes [3], or InGaAsP laser diodes [4] to improve the sensitivity. The best sensitivity (defined as the peak power – average power product for the minimum detectable input) reported to date is 1.5×10^{-4} mW^2 [4], approximately three orders of magnitude better than with conventional bulk second harmonic generation (SHG) crystals. In this paper we report autocorrelation measurements using long quasi-phase-matched (QPM) lithium niobate waveguides, which permit extremely high SHG efficiency by confining the optical beam within a small area for a long propagation distance [5]. By longitudinally chirping the poling period of the waveguides (aperiodically poled lithium niobate, or A-PPLN) [6] in order to controllably broaden the SHG phase matching (PM) bandwidth (BW), we circumvent the measurement distortion normally associated with the narrow phase matching bandwidth imposed by large group velocity mismatch (GVM) [7]. Furthermore, this broadening can be achieved without substantially sacrificing SHG efficiency. As a result we achieve a sensitivity of 3.2×10^{-7} mW^2, about 500 times better than the previous record!

The experiment uses a mode-locked fiber laser to generate ~220 fs pulses, with 50 MHz repetition rate, 1545 nm central wavelength, and ~13 nm spectral width. The pulses are relayed through a dispersion-compensated fiber link into a collinear-type autocorrelator. The autocorrelator uses a 6.6cm-long lithium niobate chip with both unchirped PPLN waveguides (0.17 nm SHG BW) and various chirped A-PPLN waveguides (BWs of 5, 10, 15, 20, and 25 nm). The output second harmonic signal is detected by a photomultiplier tube along with a lock-in amplifier, and further processed by computer routines to get background-free autocorrelation functions. The typical data acquisition time is three minutes. Fig. 1 illustrates two autocorrelation traces derived by a chirped A-PPLN waveguide with 25 nm SHG BW. The coupled energies per pulse are 12 fJ (dashed) and 52 aJ (dotted), respectively; the latter corresponds to only ~400 photons per pulse and 1.3 nW average power. This corresponds to a record measurement sensitivity of 3.2×10^{-7} mW^2. Even with a 23 dB input power difference, these two curves agree extremely well. The deconvolved pulse durations are essentially identical: 215 fs and 214 fs, respectively.

To further confirm the accuracy of our traces, we also performed a standard autocorrelation measurement using a 1mm-thick lithium iodate ($LiIO_3$) bulk crystal, which has a GVM of 88 fs. Since this is less than the input pulse duration, the resulting trace should have negligible distortion. Fig. 2 compares the autocorrelation traces derived by the $LiIO_3$ bulk (dashed) and our 25-nm bandwidth A-PPLN waveguide (dotted). There is no noticeable difference between them even though the A-PPLN waveguide has an enormous GVM (~20 ps). This is attributed to the fact that accurate autocorrelation measurements require only sufficient SHG BW regardless of the GVM, a concept similar to that which has been applied in the GRENOUILLE scheme of frequency-resolved optical gating [8].

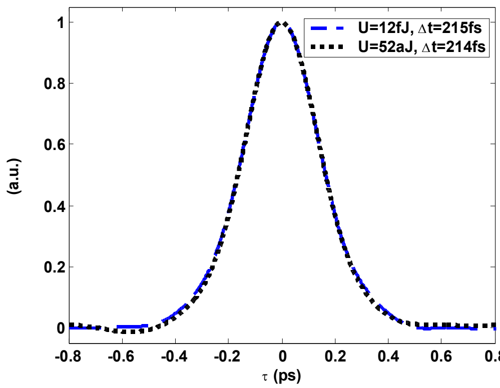

Fig. 1. Autocorrelation traces using a chirped A-PPLN waveguide (SHG BW=25 nm) with different input power levels

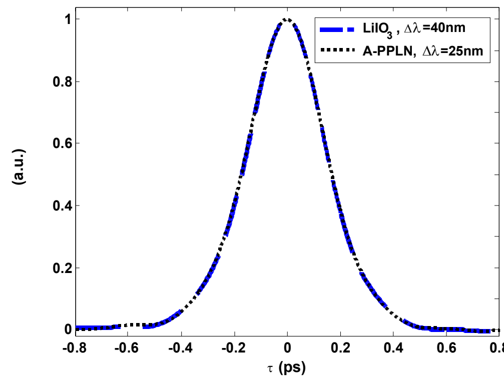

Fig. 2. Autocorrelation traces using bulk $LiIO_3$ and A-PPLN waveguide

An important observation is that the chirped A-PPLN waveguides retain almost the same efficiency as the unchirped PPLN guides. Fig. 3 shows the dependence of SHG efficiency on SHG BW, measured using A-PPLN waveguides with different chirps. For example, with a 10 nm SHG BW, which is sufficient to accurately measure our 220 fs pulses, the SHG efficiency is still ~80% compared to an unchirped PPLN waveguide, even though the bandwidth is broadened by 60 times. The explanation is that chirping the poling period doesn't change the area under the SHG PM spectrum; the SHG efficiency remains approximately proportional to this area until the PM curve becomes broader than the input spectrum (13 nm in our case). This trend is in agreement with simulations (also in Fig. 3) for bandwidth-limited pulses with the same power spectrum as our input pulses.

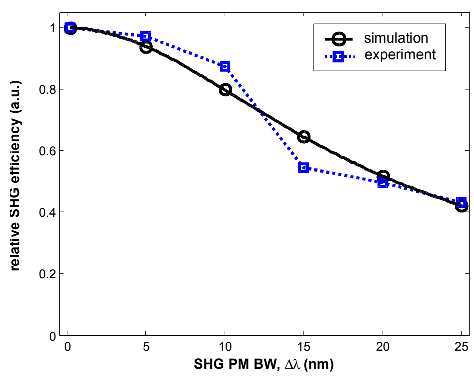

Fig. 3. Relative SHG efficiency versus SHG BW. The simulation (circle) assumes bandwidth-limited input pulses with a power spectrum same as that used in the experiment (square), and squared-shape SHG PM spectra with full widths Δλ.

In conclusion, we have shown properly designed chirped A-PPLN waveguides can accurately measure ultraweak input pulses with an unprecedented sensitivity of 3.2×10^{-7} mW^2. This promising technique can also be extended to more sophisticated measurements such as spectral interferometry for direct electric-field reconstruction (SPIDER).

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