400-photon-per-pulse ultrashort pulse autocorrelation measurement with aperiodically poled lithium niobate waveguides at 1.55 μm

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We demonstrate ultrasensitive intensity autocorrelation measurements of subpicosecond optical pulses in the telecommunication band by using aperiodically poled lithium niobate (A-PPLN) waveguides. The tightly confined optical beam in the waveguides and the chirped poling period facilitate simultaneous high second-harmonic generation (SHG) efficiency and broad phase-matching (PM) bandwidth. The resulting measurement sensitivity is 3.2×10^{-7} mW^2, ~500 times better than the previous record for intensity autocorrelations. We also show that chirped A-PPLN waveguides retain nearly the same SHG efficiency as the unchirped guide as long as the PM bandwidth is not significantly broader than the input spectrum. © 2004 Optical Society of America

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Characterization of subpicosecond optical pulses relies on all-optical techniques because the temporal durations of interest are much shorter than any available electronic response. In practical applications, lowering the power requirements of measurement techniques is desirable because the signal pulse energy in ultrafast light-wave communications or nonlinear optical material characterizations could be of the order of femtojoules (10^{-15} J) or less. The TADPOLE technique has been used to characterize 42-zeptojoules (42×10^{-21} J) pulses at 860-nm wavelength[1]; however, it requires strong, synchronized, and precisely characterized reference pulses, which are unavailable at the intermediate or receiving ends of an optical communication link. Intensity autocorrelation measurements, however, are widely used in characterizing ultrashort pulse durations without the requirement of a reference. A quantitative measure of the sensitivity of quadratic nonlinear measurement techniques is the minimum peak-power–average-power product needed to generate a detectable nonlinear signal. In conventional autocorrelation measurements that use second-harmonic generation (SHG) in bulk crystals, the nonlinear efficiency is restricted in part by Gaussian beam diffraction, which prevents the coexistence of a small beam cross-sectional area and a long interaction length. When ultrashort pulses are involved, the broad input spectrum should be phase matched (PM) to prevent measurement distortion.[2] As the PM bandwidth (BW) is inversely proportional to the group-velocity mismatch (GVM) walk-off (which is the product of interaction length and GVM between fundamental and second-harmonic fields), short nonlinear crystals are typically employed, further limiting the nonlinear efficiency. As a result, bulk SHG crystals offer a sensitivity of only ~1 mW^2. Several recent experiments at 1.55-μm wavelength exploited broadband two-photon absorption in silicon avalanche photodiodes,[3] GaAs photomultiplier tubes,[4] and InGaAsP laser diodes.[5] Measurement sensitivity as low as 1.5×10^{-4} mW^2 was reported,[5] improving the sensitivity by 4 orders of magnitude. In this Letter we report autocorrelation measurements by use of long, quasi-phase-matched (QPM) lithium niobate ($LiNbO_3$) waveguides, which permit extremely high SHG efficiency by tightly confining the optical beam over a long interaction distance.[6] By longitudinally chirping the poling period of the waveguides [aperiodically poled lithium niobate (A-PPLN)],[7] we can controllably broaden the PM BW to circumvent measurement distortion. Furthermore, this spectral broadening can be achieved without substantially sacrificing SHG efficiency. As a consequence we push the measurement sensitivity to 3.2×10^{-7} mW^2, which is ~500 times better than that of the previous record.[5]

The waveguide sample used in our experiments was made by electric field poling and annealed proton exchange[6] in a z-cut $LiNbO_3$ substrate. The largest nonlinear tensor component of $LiNbO_3$ ($d_{33} = 27$ pm/V) can be exploited for SHG by coupling a z-polarized beam into the waveguide, which supports a single TM (z-polarized) mode. The poling region of the waveguides is 5.95 cm long, corresponding to a 22-ps GVM walk-off (the GVM in the waveguides is 0.37 ps/mm). Characterization of SHG PM spectra

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shows that an unchirped PPLN waveguide has a 0.17-nm PM BW [Fig. 1(a)], consistent with the value evaluated from GVM walk-off. Measurements of subpicosecond pulses with such a narrowband crystal could be seriously distorted.[2] A series of chirped A-PPLN waveguides were fabricated on the same $LiNbO_3$ sample with PM BWs of 5, 10, 15, 20, and 25 nm. The waveguides with the broadest BW [25 nm, as shown in Fig. 1(b)] should be sufficient to accurately characterize ~100-fs bandwidth-limited pulses. Comparing the two PM spectra in Fig. 1 indicates that chirping the poling period reduces the PM spectral peak height but leaves the spectral area approximately unchanged.[8] As is shown in a discussion below, this property circumvents the trade-off between SHG efficiency and PM BW, enabling measurements to be made with good sensitivity and good accuracy. It should be possible to reduce the ripple in the broadband PM curve [Fig. 1(b)] by longitudinally apodizing the strength of the QPM grating.[7] Nevertheless, autocorrelation measurements are expected to be weakly sensitive to such ripple.

Our experiments used a mode-locked fiber laser to generate ~220-fs pulses, with a 50-MHz repetition rate, a 1545-nm central wavelength, and an ~13-nm spectral width. The pulses are relayed through a dispersion-compensated fiber link into a collinear-type autocorrelator and then coupled into the selected waveguide. The sample is heated to 84 °C to shift the central PM wavelength from 1538 nm at room temperature to 1545 nm. The output second-harmonic signal is detected by a photomultiplier tube and a lock-in amplifier and manipulated in software to yield autocorrelation traces free from interferometric fringes and background. The sampling time is less than 60 ms/delay step. Figure 2 illustrates two autocorrelation traces obtained by a chirped A-PPLN waveguide with 25-nm PM BW. The energies per pulse coupled into the waveguide (referring to the total of those from both autocorrelator arms) are 12 fJ and 52 aJ. The latter value is equivalent to 400 photons per pulse, 0.24-mW peak power, and 1.3-nW average power, corresponding 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 (assuming a $sech^2$ profile) are essentially identical: 215 and 214 fs.

To further confirm the accuracy of our traces we also performed autocorrelation measurements by using a 1-mm-thick lithium iodate ($LiIO_3$) bulk crystal with 88-fs GVM walk-off and 40-nm PM BW. Because the temporal walk-off is less than the input pulse duration, the distortion of the resultant trace should be negligible. Figure 3 compares autocorrelation traces obtained by the bulk $LiIO_3$ and our 25-nm BW A-PPLN waveguide. There is no noticeable difference between them even though the A-PPLN waveguide has a huge GVM walkoff (22 ps). This is so because accurate autocorrelation measurements require only sufficient PM BW regardless of the GVM, a concept that was also applied in the GRENOUILLE (grating-eliminated no-nonsense observation of ultrafast incident laser light fields) scheme[9] of frequency-resolved optical gating (FROG).

Another important observation is that the chirped A-PPLN waveguides retain almost the same efficiency as the unchirped PPLN guide. For an

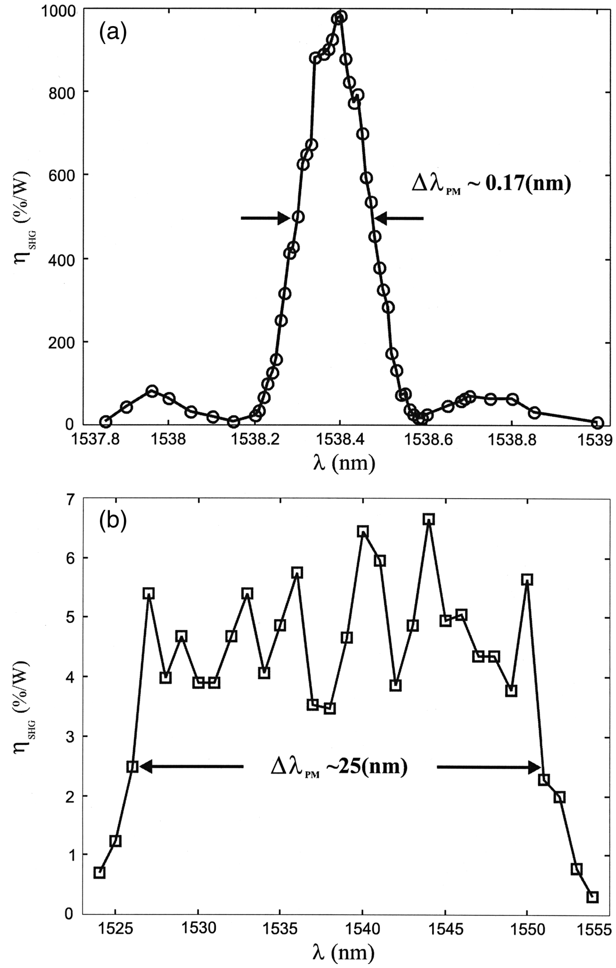

Fig. 1. SHG PM spectra of (a) an unchirped PPLN waveguide and (b) a 25-nm BW chirped A-PPLN waveguide. The vertical axis gives the efficiency in percent per watt.

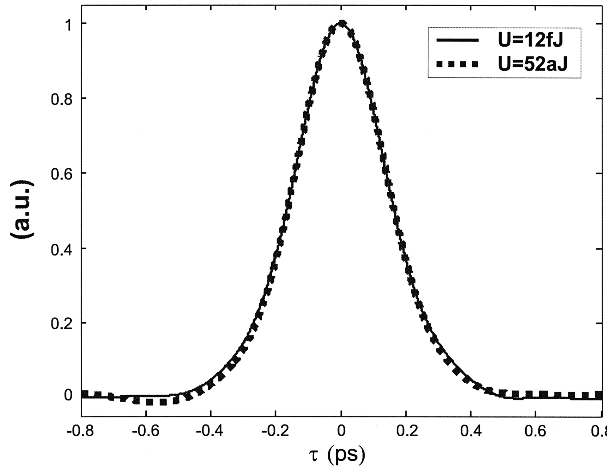

Fig. 2. Autocorrelation traces obtained by a 25-nm BW A-PPLN waveguide for coupled pulse energies of 12 fJ and 52 aJ.

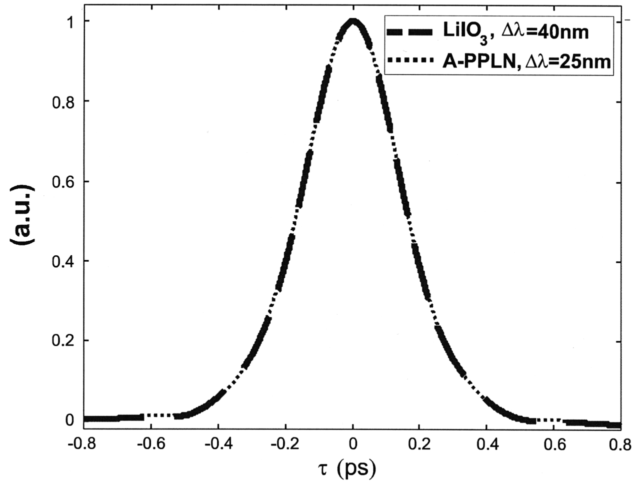

Fig. 3. Autocorrelation traces for bulk $LiIO_3$ and a 25-nm BW A-PPLN waveguide.

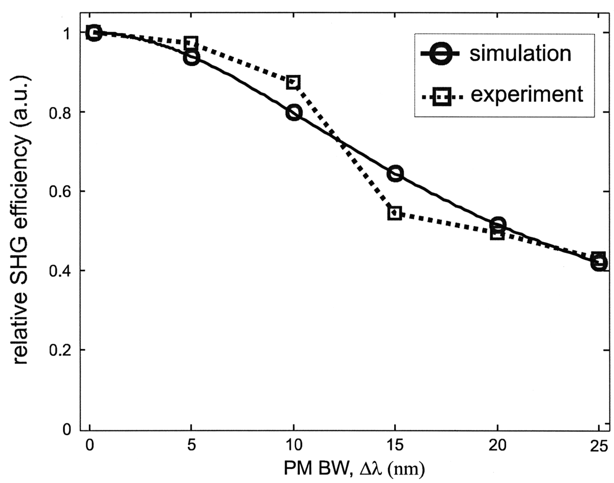

Fig. 4. Relative SHG efficiency versus PM BW for unchirped (PM BW = 0.17 nm) and chirped (PM BW = 5, 10, 15, 20, 25 nm) waveguides. The simulation assumes square $|H(\omega)|^2$ with different widths but constant areas.

input pulse with complex spectral amplitude $A_\omega(\omega)$, the output second-harmonic pulse has complex spectral amplitude $A_{2\omega}(\omega) = P_{\mathrm{NL}}(\omega)H(\omega)$,[2] where $P_{\mathrm{NL}}(\omega) \propto A_\omega(\omega) \otimes A_\omega(\omega)$ represents the nonlinear polarization spectrum derived by the autoconvolution of the input field spectrum and $H(\omega)$ is the complex PM spectrum of the nonlinear crystal. In autocorrelation measurements, the slow detector measures only the second-harmonic pulse energy, formulated by a spectral integration:

$$U_{2\omega} \propto \int_{-\infty}^{\infty} |A_{2\omega}(\omega)|^2 \mathrm{d}\omega = \int_{-\infty}^{\infty} |P_{\mathrm{NL}}(\omega)|^2 |H(\omega)|^2 \mathrm{d}\omega \,. \tag{1}$$

If $|P_{\mathrm{NL}}(\omega)|^2$ is constant, output signal $U_{2\omega}$ is proportional to the area of $|H(\omega)|^2$. As chirping the poling period ideally does not change this area, $U_{2\omega}$ is independent of the PM BW broadening of the A-PPLN waveguides. In practice $U_{2\omega}$ may decrease slowly with PM BW broadening owing to the gradual roll-off of $|P_{\mathrm{NL}}(\omega)|^2$. However, this degradation in efficiency remains weak if the PM BW is not made much broader than the input spectral width. Figure 4 demonstrates the dependence of SHG efficiency on PM BW, obtained experimentally by use of A-PPLN waveguides with different chirps. For example, with a 10-nm PM BW (which is sufficient to measure 220-fs pulses), the SHG efficiency is still ~80% of that of an unchirped PPLN waveguide, although the bandwidth is broadened by 60 times. Even with a 25-nm PM BW (approximately twice that of input spectral FWHM and 150 times wider than the PPLN counterpart), a relative SHG efficiency of ~40% is retained. This trend agrees with simulations (also shown in Fig. 4) for the SHG of bandwidth-limited pulses with the same power spectrum as our input pulses.

In conclusion, we have shown that chirped A-PPLN waveguides can accurately measure ultraweak input pulses with an unprecedented sensitivity of $3.2 \times 10^{-7}\ \mathrm{mW}^2$. To maximize the output second-harmonic signal while simultaneously minimizing measurement distortion, one should choose the chirp of the QPM structure to synthesize a PM BW comparable to that of the input spectrum. This approach can also be extended to more-sophisticated measurement schemes such as FROG and spectral interferometry for direct electric-field reconstruction.[10] SHG spectral broadening through chirping may also be advantageous for optical performance monitoring in a wavelength-division light-wave system environment.

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