# Extremely Low-power Intensity Autocorrelation and Chromatic Dispersion Monitoring for 10-GHz, 3-ps Optical pulses by Aperiodically Poled Lithium Niobate (A-PPLN) Waveguide

**S.-D. Yang, Z. Jiang, and A.M. Weiner**
*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907*
*shangda@purdue.edu*

**K.R. Parameswaran**
*JDS Uniphase, Santa Rosa, CA 95407*

**M.M. Fejer**
*Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305*

**Abstract:** We demonstrate intensity autocorrelation of 10-GHz, 3-ps pulses at –43 dBm average input power with an A-PPLN waveguide. Chromatic dispersion monitoring at -45 dBm and 100-ms sampling time is also demonstrated.

**OCIS codes:** (060.2330) Fiber optics communications; (320.7100) Ultrafast measurement; (130.3730) Lithium niobate

**Introduction:** Chromatic dispersion monitoring and compensation of transmitted optical pulses becomes essential as the bit rate per channel of TDM and WDM fiber communication systems exceeds 40 Gbit/s [1]. Even at lower bit rate situations, dynamic changes of optical paths due to network reconfiguration also introduce dispersion variation, where monitoring and dynamic compensation is required [2]. Since chromatic dispersion (spectral phase modulation) changes the pulse width and shape without changing the average power, nonlinear techniques are usually employed for high bit rate monitoring. In real applications, monitoring should tap off less than 1-3% transmitted power, and the detecting speed has to be faster than the time scale of dispersion variation to validate real-time performance recovery [3]. Recent publications reported 10-GHz pulse measurements using two-photon absorption (TPA) in silicon avalanche photodiodes and GaAs photomultiplier tubes (PMT) at input powers of -21 dBm (7.2 μW) and -26 dBm (2.3 μW), respectively [4-5]. Nevertheless, the corresponding sensitivities ($>1.7\times10^{-4}$ mW$^2$) are still insufficient for signal monitoring at some intermediate points of a communication link, such as the input to an amplifier where signal power can be as low as -40 dBm [6]. Alternatively, we have demonstrated that second-harmonic generation (SHG) with chirped aperiodically poled lithium niobate (A-PPLN) [7] waveguides are several hundred times more sensitive (sensitivity $\sim3.2\times10^{-7}$ mW$^2$) than the TPA devices in measurements of 50-MHz, 220-fs pulses down to the nW level [8]. In this work, we use an A-PPLN waveguide for autocorrelation measurements of 10-GHz, 3-ps pulses at a power level 17-dB less than the previous record. We also use the A-PPLN waveguide to measure the nonlinear signal degradation induced by chromatic dispersion with -45 dBm input power and 100-ms sampling speed. This ultra-sensitive detection scheme enables bit-rate transparent dispersion monitoring at almost any point in an optical communication link without amplification.

**Experiment:** Fig. 1 shows a schematic diagram of our experiments. An actively mode-locked fiber laser produces ~3-ps nearly bandwidth-limited pulses with 10-GHz repetition rate and 1542-nm central wavelength. The power spectrum (inset of Fig. 2) has an FHWM of ~1.2 nm, corresponding to ~130 GHz frequency bandwidth (BW). We use a reflective-type pulse shaper [9] to apply quadratic spectral phases upon the optical pulses to simulate the chromatic dispersion of fiber links. The pulses are relayed through a ~50m-long dispersion-compensated fiber link into a free-space Michelson interferometer (MI), where one of its arms is dithered by a few optical wavelengths to average out the interferometric fringes. The recombined pulse pair is then coupled into an A-PPLN waveguide with 5.95-cm-long poling region, and 5-nm phase-matching BW, which is sufficient to cover the entire input spectrum, and yield correct autocorrelation traces [10]. Since the waveguide made by annealed proton exchange process can only guide the TM mode, a polarization controller is used before the MI input to maximize the nonlinear yield. In principle, a fast polarization scrambler can be incorporated prior to the A-PPLN to remove polarization sensitivity at the cost of small decrease in sensitivity. The output SHG signal is detected by a PMT (Hamamatzu R636-10) along with a lock-in amplifier and manipulated in software to remove signal background and residual fluctuation due to incomplete fringe removal. We use the same apparatus in monitoring chromatic dispersion, except that one MI arm is blocked and no delay dithering is required.

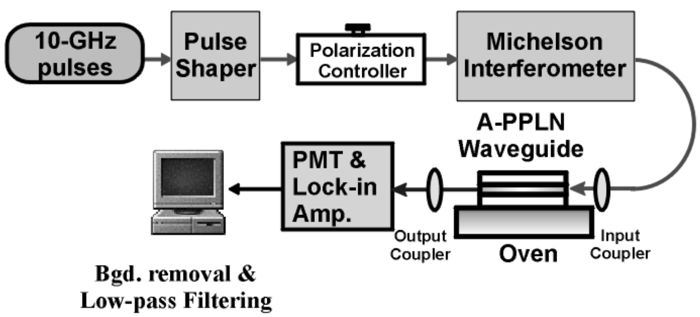


Fig 1. Schematic diagram of the experimental apparatus.

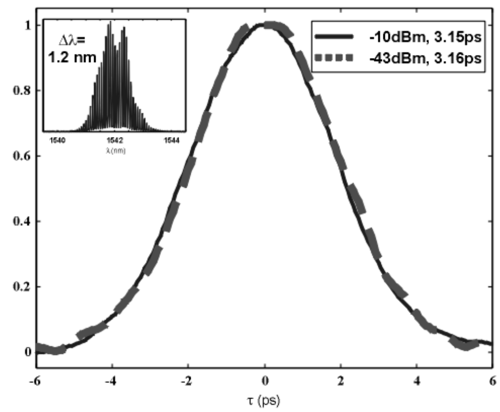


Fig. 2. Intensity autocorrelation traces obtained by an A-PPLN waveguide with 5-nm phase-matching BW. Coupled average powers are –10 dBm (solid) and –43 dBm (dashed), respectively. Inset shows input power spectrum

Fig. 2 illustrates two autocorrelation traces obtained by the A-PPLN waveguide with coupled input powers of –10 dBm (solid) and -43 dBm (dashed), respectively. Even with a 33-dB power difference, these two curves agree well with each other. The deconvolved pulse durations (assuming a Gaussian profile) are 3.15 ps and 3.16 ps, respectively, only differing by ~0.3%. The latter corresponds to -25 dBm peak power, 9.6-aJ pulse energy, and a measurement sensitivity of $1.5\times10^{-7}$ mW$^2$, even better than the value we achieved in [8]. Note this ultra-weak pulse measurement is carried out with 300-ms integration time per delay step. A trace from –6 ps to 6 ps delay with 100-fs temporal resolution takes 36 sec.

To demonstrate the ultimate sensitivity of this scheme, we measured the SNR (defined as the ratio of SHG signal and PMT dark noise with 10-Hz BW) using only one arm of the interferometer in a dispersion-free case for a series of input powers. The log-log plot (Fig. 3) shows a well-fitted line with a slop of 1.95 within the 14.7-dB measurement range, confirming the nonlinear signal integrity of our measurement. Extrapolation of the line indicates that we can get a dark noise-limited SNR of 10 dB with less than –47 dBm input average power and a 10-Hz sampling speed. In our experiments, the residual optical noise (~2.5-dB larger than dark noise), input power fluctuation, and dispersion measurement margin slightly increase the required power. Fig. 4 demonstrates the dispersion monitoring functionality of the A-PPLN waveguide. We use the pulse shaper to apply different quadratic spectral phases: $\exp[j\alpha\delta\omega^2]$ on the pulses, where $\alpha$ would correspond to the dispersion strength counting material dispersion and length in a real fiber link, and $\delta\omega$ is the angular frequency deviation from the spectral center (1542 nm). One can translate the spectral phase modulation into the accumulated dispersion (D) via $D \approx 4\pi c\alpha/\lambda_o^2$, where $c$ represents the light speed. The normalized SHG power $P_{SHG}$ (circle) generated by the differently chirped pulses with fixed –45 dBm average input power is recorded as a function of accumulated dispersion. For the unchirped pulses the measurement

SNR is about 13 dB (see error bar) for a 10-Hz measurement bandwidth. We also obtained the pulse widths $\Delta t$ (asterisk) by autocorrelation traces, and the product of $P_{SHG}$ and $\Delta t$ nearly remains constant for all dispersion values, further justifying the integrity of our experimental data. The asymmetric feature of Fig. 4 is attributed to residual cubic phase of input pulse and input spectral asymmetry.

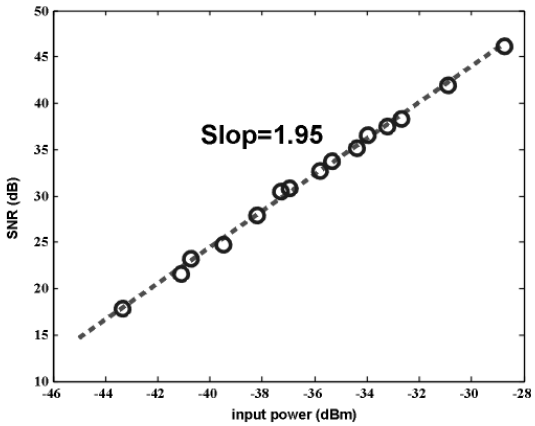


Fig. 3. SNR (actual SHG signal power normalized to PMT dark noise at 10-Hz measurement BW) versus input power.

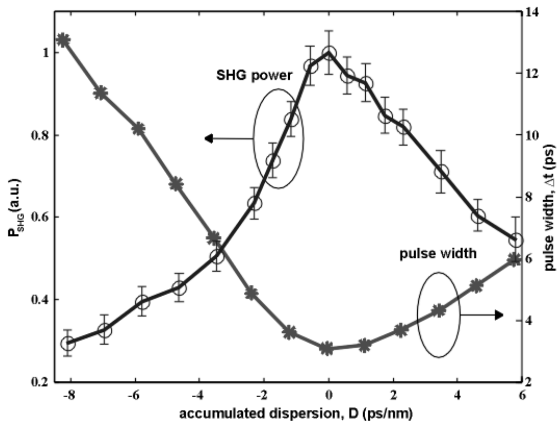


Fig. 4. Normalized SHG power with error bars (left scale) and measured pulse width (right scale) versus accumulated dispersion. The former is performed with a 10-Hz sampling speed.

**Conclusion:** We have used A-PPLN waveguide to demonstrate ultra-sensitive autocorrelation traces and dispersion monitoring at unprecedented input power levels of –43 dBm and –45 dBm, respectively. The A-PPLN waveguides scheme is bit-rate transparent [6], and can monitor multiple WDM channels simultaneously by choosing adequate phase-matching BW [8]. The nonlinear signal is also sensitive to PMD impairment, making it suitable for monitoring PMD with kHz bandwidth [6]. It can also be applied in well-developed techniques to identify sign of dispersion [2], temporal pulse asymmetry [11], and more generalized optical performance monitoring [6].

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