Ultrasensitive chromatic dispersion monitoring for 10 GHz pulse train by quasi-phase-matched $LiNbO_3$ waveguides

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Chromatic dispersion monitoring is demonstrated for a 10 GHz train of 3 ps pulses at -45 dBm coupled average power and 100 ms sampling period by using a chirped quasi-phase-matched $LiNbO_3$ waveguide with 625 GHz active bandwidth. The feasibility of monitoring 10 GHz, 24 ps pulses at -40 dBm power is verified by intensity autocorrelation measurements.

Introduction: Chromatic dispersion monitoring and compensation become essential as the bit rate of TDM and WDM fibre transmission systems exceeds 40 Gbit/s (per channel). Since chromatic dispersion (spectral phase modulation) distorts signal pulses in the time domain without changing their average power, nonlinear optical effects, as used in ultra-short pulse measurements, can be employed for high bit-rate monitoring without high-speed electronics [1]. In real applications, monitoring should tap off less than 1–3% of the transmitted power, and the detection response should be faster than the time scale of dispersion variation (~100 ms) to support real-time performance recovery [2]. A recent publication demonstrated dispersion monitoring of 40 Gbit/s return-to-zero (RZ) signals with 11 dBm (14 mW) average power using four-wave mixing in a 1 km-long dispersion-shifted fibre [3]. Highly sensitive intensity autocorrelation of a 10 GHz train of 1.56 ps pulses at -26 dBm (2.3 μW) average power was reported using two-photon absorption (TPA) in a GaAs photomultiplier tube (PMT) [4]. Similar measurement sensitivity was also achieved by TPA in an InGaAs laser diode at slower (4 MHz) repetition rate [5]. Nevertheless, the corresponding sensitivity ($>1.5\times10^{-4}\,\text{mW}^2$) is still insufficient for dispersion monitoring (see (4)) at some intermediate points of a communication link, where signal powers can be as low as -40 dBm [1]. Alternatively, in measurements of 50 MHz, 220 fs pulses at nanowatt average power levels, we have demonstrated that second-harmonic generation (SHG) with chirped quasi-phase-matched (QPM) $LiNbO_3$ waveguides can be several hundred times more sensitive (sensitivity $\sim3.2\times10^{-7}\,\text{mW}^2$) than the TPA devices [6]. In this Letter, we extend our technique to dispersion monitoring of 10 GHz trains of 3 ps pulses at -45 dBm coupled average power and 100 ms sampling period by using a chirped QPM waveguide with 625 GHz SHG phase-matching (PM) bandwidth (BW). The feasibility of monitoring 10 GHz, 24 ps pulses at -40 dBm power is also verified through intensity autocorrelation measurements using an unchirped QPM waveguide with 63 GHz PM BW. This ultrasensitive detection scheme enables bit-rate-transparent dispersion monitoring without amplification at almost any point in an optical communication link.

Theory: The feasibility of monitoring chromatic dispersion using SHG can be illustrated by the Gaussian pulse model. Assume the complex spectrum of a chirped Gaussian pulse envelope is:

$$A_\omega(\omega) = \exp\left[\frac{-\omega^2}{(\Delta\omega)^2}\right]\exp[j\alpha\omega^2] \tag{1}$$

where the quadratic spectral phase parameter α corresponds to the dispersion strength (dispersion–length product) in a real fibre link. The accumulated dispersion (D) is related to α via: $D \simeq -4\pi c\alpha/\lambda_o^2$, where c represents the speed of light, and λ_0 is the central wavelength. The temporal intensity profile $I_\omega(t)$ and the average SHG power $P_{2\omega}$ corresponding to (1) can be characterised as:

$$I_\omega(t) \propto [1+\alpha^2(\Delta\omega)^4]^{-1/2} \times \exp\left[\frac{-(\Delta\omega)^2t^2}{2(1+\alpha^2(\Delta\omega)^4)}\right] \tag{2}$$

$$P_{2\omega}(\alpha) \propto \int I_\omega^2(t)dt \propto P_{2\omega}(0) \times [1+\alpha^2(\Delta\omega)^4]^{-1/2} \tag{3}$$

Equations (2) and (3) indicate that a common dispersion-dependent factor $\sqrt{(1+\alpha^2(\Delta\omega)^4)}$ governs pulse broadening, peak intensity reduction and SHG power degradation. Consequently, the product of pulse width and $P_{2\omega}$ should be a constant for different dispersion strength α, which is useful in checking the experimental results. The required average power to generate a detectable SHG signal can be estimated by:

$$P_{\text{avg}} \sim \sqrt{Sd} \tag{4}$$

where S represents the quadratic measurement sensitivity (in mW^2) defined in [6], and d is the signal duty cycle. In our chirped QPM waveguide scheme, a PM BW (controlled by the QPM chirp rate) just covering the input spectrum would give rise to the best sensitivity S [6] and require the least power P_{avg}. Overextending the PM BW by a factor of N allows diagnosis of $\sim N$ distinct WDM channels (one at a time) at the cost of $\sqrt{N}$ times more power.

Experiments and discussion: Fig. 1 shows the experimental apparatus. An actively modelocked fibre laser produces 10 GHz, 3 ps ($d \sim 3\%$), nearly BW-limited pulses centred at 1542 nm. We use a Fourier pulse shaper (resolution ~17 GHz/pixel) [7] to apply variable quadratic spectral phases ($\exp[j\alpha\omega^2]$) to the optical pulses in order to simulate the chromatic dispersion of real fibre links. The pulses are coupled into a 6.6 cm-long chirped QPM waveguide with ~625 GHz PM BW, which is sufficient to cover the entire input spectrum (FWHM ~ 150 GHz). The waveguide total insertion loss (coupling plus propagation) is about 8.2 dB, but can be reduced to 2–3 dB by using fibre-pigtailed devices like that used in [7]. We use a polarisation controller to maximise the nonlinear yield; however, polarisation-insensitive schemes can be achieved by a fast polarisation scrambler incorporated prior to the QPM waveguide at the cost of a small decrease in sensitivity. The output SHG signal is detected by a PMT along with a lock-in amplifier at a sampling period of 100 ms.

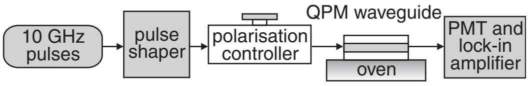

Fig. 1 *Experimental apparatus*

To illustrate the ultimate sensitivity of this scheme, we measured the SHG power using dispersion-free pulses (shaper inactive) at different coupled input powers. The log–log plot (Fig. 2) is well fitted by a line with a slope of 1.95 over the 14.7 dB range of input powers, in good agreement with the expected slope of 2 for SHG. The fit line indicates that we can obtain a PMT dark-noise-limited signal-to-noise ratio (SNR) of 10 dB with less than -47 dBm input power. In our experiments, the residual background light, input power fluctuations and a margin for dispersion measurement slightly increase the required power. Fig. 3 shows normalised SHG power $P_{2\omega}$ (circles) generated by the differently chirped pulses against accumulated dispersion D, at fixed -45 dBm input power. The measurement SNR (at 10 Hz sampling BW) is about 13 dB (see error bar) for the dispersion-free pulses. We also measured the pulse widths Δt (asterisks) using autocorrelation, and the product of $P_{2\omega}$ and Δt remains nearly constant for all dispersion values, confirming the integrity of our experimental data. The asymmetric feature of Fig. 3 is mainly attributed to the residual cubic phase and spectral asymmetry of the input pulses.

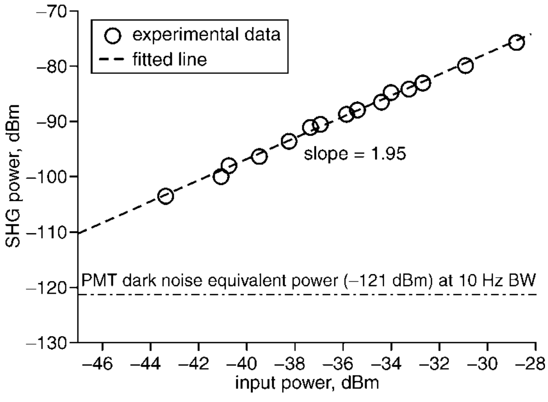

Fig. 2 *Log–log plot of SHG power against coupled input power when dispersion-free pulses are sent into the chirped QPM waveguide*

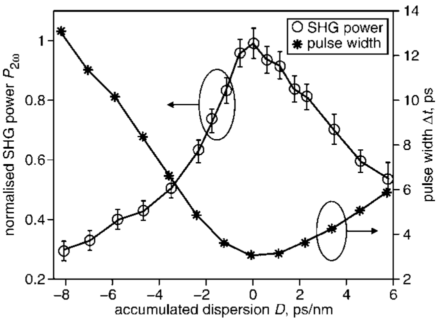

Fig. 3 *Normalised SHG power with error bars (left scale) and measured pulse width (right scale) against accumulated dispersion*

Since real communication systems normally use signal pulses with duty cycle d larger than 3%, we tested the monitoring sensitivity for 10 GHz, 24 ps ($d \sim 24\%$) pulses by performing intensity autocorrelation measurements. The pulse train is produced by spectrally filtering the laser source using the amplitude modulation functionality of the pulse shaper. Note that, at this pulse duration, stronger dispersion beyond the tuning range of our pulse shaper is required to affect the SHG signal noticeably. Fig. 4 illustrates two autocorrelation traces obtained by an unchirped QPM waveguide (~63 GHz PM BW) with coupled powers of −31 dBm (solid line) and −40 dBm (dashed line), respectively. The deconvolved pulse durations (assuming a Gaussian profile) are in good agreement: 23.5 and 24.4 ps, respectively. We measured a PMT dark-noise-limited SNR of 13 dB at 10 Hz sampling BW for −40.5 dBm unchirped pulses. The −40 dBm measurement corresponds to a record sensitivity S of 8.7×10^{-8} mW^2 (3.8×10^{-6} mW^2 if the 8.2 dB insertion loss is included; improving to $\sim 2.2 \times 10^{-7}$ mW^2 if using fibre-pigtailed devices with 2 dB insertion loss). Compared with [6], the sensitivity improvement results from closer BWs of input and SHG PM spectra, and better isolation from optical background light.

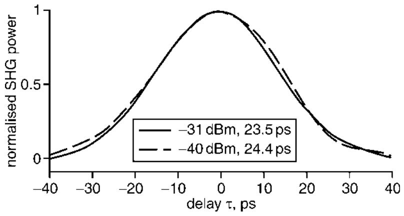

Fig. 4 *Intensity autocorrelation traces at −31 dBm (solid) and −40 dBm (dashed) coupled power levels obtained by unchirped QPM waveguide*

Conclusions: We have used QPM LiNbO$_3$ waveguides to demonstrate ultra-sensitive dispersion monitoring for a 10 GHz, 3 ps pulse train at an unprecedented low input power level of −45 dBm. The feasibility of monitoring 10 GHz, 24 ps pulses is also experimentally verified by intensity autocorrelation at −40 dBm. The QPM waveguide scheme is bit-rate transparent, applicable to RZ and carrier-suppressed-RZ modulation formats [1], and can monitor distinct WDM channels with a single device by choosing adequate PM BW. It can also be applied together with previously reported techniques to identify the sign of dispersion [8], and for more generalised optical performance monitoring [1].

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