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A Novel High-Resolution and High-Sensitivity FROG Configuration Based on Cascaded $^{(2)}$ Interactions in a PPLN waveguide

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Abstract

We experimentally demonstrate a novel frequency-resolved optical gating (FROG) configuration based on cascaded $^{(2)}$ interactions in a PPLN channel waveguide. This provides improvements in terms of the sensitivity/temporal-resolution trade-offs relative to single-step $^{(2)}$ interactions.

Introduction

The tremendous progress in ultrafast optics over the past three decades has had a significant impact in both fundamental and applied research, allowing for example the stimulation and measurement of ultrafast processes in biology and chemistry, and increased data rates in ultrahigh-capacity optical telecommunications systems. Central to this progress has been the development of both practical ultrafast laser sources, and reliable and accurate pulse measurement techniques that allow complete characterisation of ultrashort pulses.

Frequency-resolved optical gating (FROG) has now become a well-established and widely-employed technique for the complete (intensity and phase) characterisation of ultrafast optical pulses [1]. However, despite its versatility, the sensitivity of FROG technique is ultimately limited by the efficiency of the nonlinear interactions it relies on. One promising way of increasing the sensitivity is to use guided-wave geometries in periodically poled $^{(2)}$ materials [2,3], since this provides for tight optical confinement, long interaction lengths, and thus higher efficiencies. Unfortunately, as the interaction length is increased, the acceptance bandwidth for the nonlinear process decreases, limiting the temporal resolution that can be achieved. A trade-off therefore needs to be established between temporal resolution and sensitivity. Quasi-phase-matching (QPM) engineering [3,4] can be used to broaden the acceptance bandwidth of the nonlinear process, providing a mean to improve this trade-off. However, the complexities in its design and fabrication are significant, and thus there is great interest in developing simpler approaches to mitigate the problem. In a previous paper, we proposed a new FROG technique based on cascaded second-harmonic generation and difference-frequency generation (SHG:DFG) in a QPM waveguide device [5]. Its robustness against temporal walk-off effect would offer superior sensitivity and temporal resolution compared to single-step $^{(2)}$ FROG configurations in a waveguide of equivalent length.

In this paper, we experimentally demonstrate this novel FROG configuration and confirm the theoretical predictions. In our cascaded SHG:DFG FROG configuration, a test pulse ($_T$) is characterised by a pump pulse ($_P$) in a $LiNbO_3$ QPM waveguide device. The pump pulse is upconverted to its second-harmonic ($_{SH}$ $_P$), which then mixes via DFG with the test pulse to generate an output pulse at $_O$ $_P$- $_T$. By introducing a variable time-delay between the input pulses and recording the spectrum of the output pulse (as a function of delay) a spectrogram can be obtained. The spectrogram can then be fed into a blind-deconvolution algorithm to retrieve the intensity and phase of the test pulse.

Experiment

We fabricated the waveguide device used in our experiment by annealed and reverse proton exchange in periodically-poled $LiNbO_3$. The device was 26 mm long, with a waveguide width of 6 m and a QPM period of 15 m. The SHG phase-matching wavelength between TM_{00} modes at 121 ^{0}C was 1541.9 nm. The device SHG acceptance bandwidth was 0.75 nm and its normalised efficiency (with respect to the full device length) was ~50 %$[W cm^2]^{-1}$.

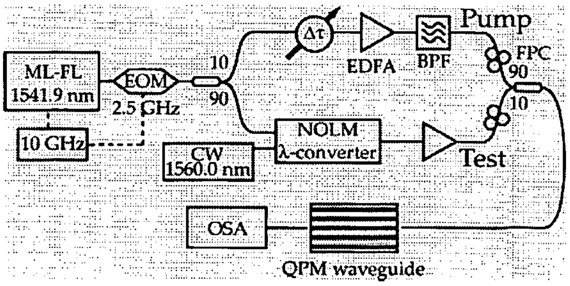

Fig. 1 Schematic illustration of our experimental

setup.

Figure 1 shows a schematic illustration of our experimental setup. The output from a 10GHz mode-locked fibre laser (ML-FL) operating at wavelength of 1541.9 nm was first gated down to a repetition rate of 2.5 GHz and then split into two using a 90:10 coupler. The 10% path was used to generate our pump pulse. This path contained a motorised variable optical delay line, an erbium-doped fibre amplifier (EDFA), and an optical band-pass filter (BPF). The pulses in the 90% path were wavelength converted (to 1560 nm) in a nonlinear optical loop mirror (NOLM) and then amplified with a variable-gain EDFA to provide a stream of test pulses. The test and pump pulses were then recombined into a single fiber using a further 90:10 coupler and the resulting optical signal coupled into (and out of) the waveguide using fibre butt-coupling. The average powers (energies) of the pump and test pulses launched into the waveguide were 36 mW (14 pJ) and 72 W (29 fJ), respectively.

Results and Discussions

The cascaded SHG:DFG pulses at the output of the waveguide were analysed by an optical spectrum analyser (OSA). Figure 2(a) shows the measured spectrogram around the generated output pulse frequency after an interpolation onto a 64x64 Fourier grid. Noise suppression was performed by background subtraction only. The intensity and phase retrieval was achieved by means of a blind-deconvolution algorithm based on the principal component generalised projection method [7]. Figure 2(b) shows the retrieved spectrogram. Although we did not impose additional constraints, nontrivial ambiguities were not found. The algorithm converged after ~100 iterations to a root-mean-square error of 0.009.

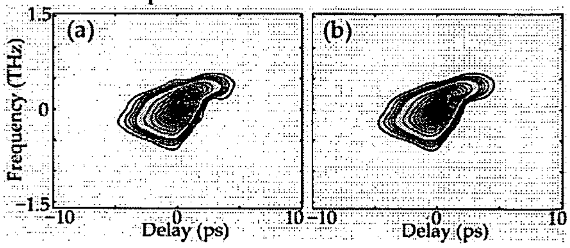

Fig. 2 a) Measured and b) retrieved spectrograms.

Figure 3(a) shows the intensity and chirp of the test pulses as retrieved from the spectrogram in Fig. 2. We compared the autocorrelation and the spectrum of the retrieved pulses to the measured data to provide a further measure of the retrieval quality. Figure 3(b) shows the excellent agreement between the directly measured and retrieved autocorrelation trace. Similarly, measured and the retrieved spectra, shown in Fig. 3(c), compare extremely well. Note that the coherent peak in the measured spectrum corresponds to a residual CW component from the NOLM, which has little contribution towards the nonlinear interaction and thus is not present in the retrieved spectrum. The temporal full width at half-maximum of the retrieved pulse is 2.1 ps, whilst its spectral FWHM is 0.18 THz (1.5 nm), yielding a temporal-bandwidth product of 0.39. The acceptance bandwidth of SFG/SHG FROG in the same waveguide (0.75 nm) would have made it impossible to accurately characterise pulses with durations of less than ~4.5ps in the same device.

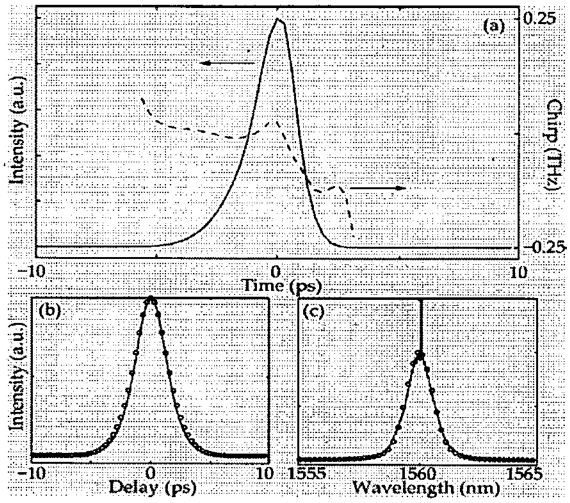

Fig. 3 a) The intensity (solid line, left ordinate) and the chirp (dashed line, right ordinate) of the retrieved test pulse. b) Measured (solid line) and calculated (circles) autocorrelation traces of the test pulse. c) Measured (solid line) and retrieved (circles) spectra of the test pulse.

Conclusion

We have demonstrated a novel FROG configuration based on cascaded SHG:DFG interactions in a LiNbO$_3$ QPM waveguide device. We successfully characterised a train of 2.1 ps pulses in the 1.5- m-band with pulse energies as low as 29 fJ. The same device could in principle allow characterisation of subpicosecond pulses, whilst the efficiency could be improved with the use of longer devices.

References

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