Femtosecond Pulse Characterization using Nanophotonic Parametric Amplification

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Abstract: We introduce and experimentally demonstrate a FROG-based ultrashort pulse characterization technique using nanophotonic parametric amplification as a crucial tool for ultrafast nanophotonic circuits, and measure sub-50-femtosecond pulses.

On-chip pulse characterization capabilities are essential for advancing the understanding and technological development of ultrafast nanophotonic circuits for a myriad of applications including computing, communication, sensing, as well as quantum information processing. When considering ultra-short pulses in nanophotonic circuits, off-chip temporal characterization poses challenges such as high pulse-energy requirements and temporal distortion arising from additional optical components for efficient extraction of pulses from the chip. Hence, developing on-chip characterization capabilities are of immense interest for ultrafast nanophotonic circuits [1].

Here, we introduce and experimentally demonstrate a new pulse characterization technique based on dispersion-engineered optical parametric amplifiers (OPAs) in lithium niobate nanophotonic waveguides combined with a frequency-resolved optical gating (FROG) - based retrieval algorithm [2]. We call this technique degenerate, collinear optical parametric amplification cross FROG (DCOPA-XFROG). While XFROG based on non-collinear OPAs has been previously demonstrated in bulk as one of the most sensitive ultrashort pulse characterization techniques [3], its non-collinear nature makes it incompatible with nanophotonics. In contrast, our technique operates in the degenerate and collinear regime, which makes it compatible with nanophotonic realization. Moreover, on-chip degenerate OPAs provide unparalleled gain, especially in nanophotonic lithium niobate with low-energy pump pulses [4]. Such gain values, unavailable in bulk crystals, enable ultrashort pulse characterization towards sub-attojoule pulses. Such a high sensitivity is particularly promising for quantum information processing [5]. Dispersion engineering in nanophotonics not only enables minimizing the chirp, but it can also relax the sensitivity-bandwidth tradeoff which is an inherent limitation of bulk pulse characterization systems. Our scheme paves the way toward the measurement of ultrashort-ultraweak optical pulses that were not possible with bulk crystals.

Figure 1 shows the experimental setup for the DCOPA-XFROG. The unknown pulses at 2090-nm are sent to the nanophotonic OPA which is pumped with 1045-nm delayed gate pulses. The pulse energies for the gate pump pulses and the unknown pulses were estimated to be $\sim$ 100-fJ on the device. The spectrogram is created by keeping the stage in scan mode while detecting the output signal one frequency component at a time on the optical spectrum analyzer. The output signal is simultaneously collected in a 2-μm detector and used to calibrate for experimental variations. The measured spectrogram is passed through a custom FROG algorithm modified for the nanophotonic OPA. For the DCOPA-XFROG, the output electric field, $E^{DCOPA}(t,\tau)$ of the pulse emerging from the waveguide defines the mathematical constraint of the algorithm [2] given by

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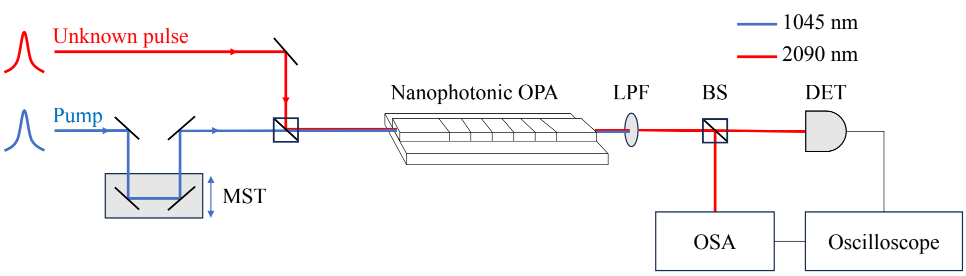

Fig. 1. **Experimental setup for DCOPA-XFROG.** OPA: Optical Parametric Amplification; BS: Beam Splitter; MST: Moving Stage; LPF: Low Pass Filter; OSA: Optical Spectrum Analyzer; DET: Detector.

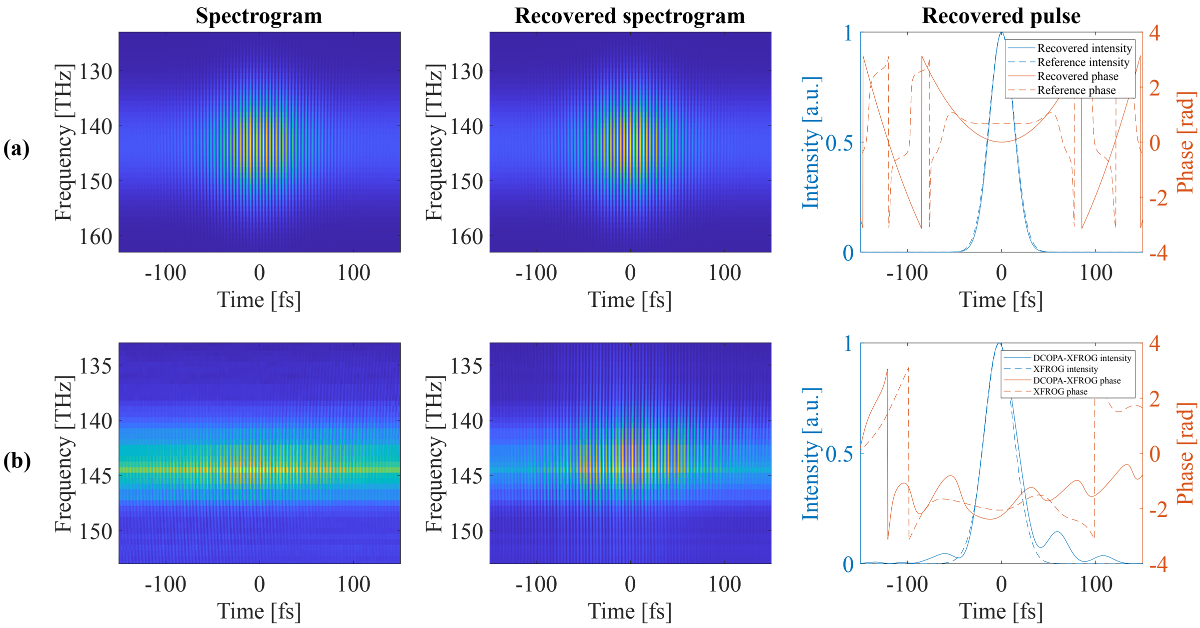

Fig. 2. **Experimental and Simulation Results. (a) Simulations.** (Left) Simulated spectrogram for a reference pulse. (Center) Recovered spectrogram using DCOPA-XFROG algorithm. (Right) Comparison of recovered pulse profile with reference pulse. **(b) Experiments.** (Left) Experimentally measured spectrogram. (Center) Recovered spectrogram using DCOPA-XFROG algorithm. (Right) Comparison of recovered pulse profile with expected profile (measured with a tabletop FROG).

the signal and the pump. $\kappa = \frac{2zd_{eff}\omega^2}{kc^2}$ is the gain parameter for the OPA where d_{eff} is the nonlinear coefficient, z is the length of the OPA, and ω, k are the angular frequency and wavenumber of the signal respectively. The optimization for the mathematical constraint is done with gradient descent that was analytically derived from Eq. 1. The algorithm was tested with a simulated spectrogram (Fig. 2 (a, Left)) generated from a chirped 2090-nm pulse (Fig. 2 (a, Right, reference pulse)). Fig. 2 (a, Center), shows the recovered spectrogram, and a comparison of the recovered pulse profile with the original pulse is shown in Fig. 2 (a, Right). Fig. 2 (b, Left), shows the experimentally measured spectrogram. The DCOPA-XFROG algorithm was run and the unknown pulse was recovered. Fig. 2 (b, Center), shows the recovered spectrogram, and Fig. 2 (b, Right), shows a comparison of the recovered pulse intensity and phase with the actual pulse profile measured using a standard table-top FROG. The intensity FWHM of the reference and unknown pulses were measured to be 103-fs and 40-fs, respectively using this reference FROG. Fig. 2 demonstrates that the DCOPA-XFROG is successfully able to retrieve the amplitude and phase of the pulse.

In conclusion, we developed a novel temporal characterization technique, named DCOPA-XFROG, and demonstrated how it can be used for in-situ pulse measurements in a lithium niobate optical chip. This is promising for the measurement of ultra-weak pulses creating a path toward the temporal characterization of sub-atto-Joule level optical pulses.

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