Cascaded Optical Parametric Amplification: A Novel Approach to Efficient THz Wave Generation

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Abstract — We report on the theoretical and experimental spectro-temporal characterization of cascaded optical parametric amplification as a promising novel method for efficient THz wave generation.

Keywords—terahertz generation; parametric amplification; nonlinear optics

The generation of high-energy THz signals is of highest significance for strong-field THz physics, nonlinear THz spectroscopy and THz-driven particle acceleration. Especially THz acceleration is in search of a compact, if possible laser-driven efficient THz source, eventually producing tens of mJ multi-cycle THz pulses. Here, we report on our numerical and experimental investigations to circumvent the Manley-Rowe limitation and provide a pathway toward multi-mJ THz frequency optical pulses. Our approach relies on cascaded optical parametric amplification (COPA), a particular regime of optical parametric amplification that allows multiple OPAs to operate coherently in a single nonlinear crystal [1]. Experimentally, we temporally overlapped two narrow linewidth ($\Delta\lambda < 0.4$ nm), heavily chirped ($\tau = 300$ ps) near-IR pump ($\lambda = 1029.45$ nm) and seed ($\lambda = 1031.2$ nm) optical pulses in a nonlinear medium in a collinear geometry. The nonlinear medium consists of a 2-cm-long MgO-doped periodically poled lithium niobate crystal optimized for 0.5-THz idler wave generation at room temperature.

The spectral characterization of the COPA in the optical domain revealed the generation of evenly spaced spectral lines separated by the THz photon energy and an enhancement of this cascading process with increasing crystal length and increasing pump fluence. Our experimental results show that increasing the seed-pulse energy leads to preferential red-shifted cascading, resulting in an increase in measured THz generation efficiency. Our numerical simulations support these findings and provide insight into the underlying mechanisms.

In order to obtain a full picture of this new regime of parametric amplification and confirm its suitability for efficient THz wave generation, we performed a detailed study of the temporal behavior of this amplifier. We characterized the temporal behavior of the COPA optical output with second-harmonic generation frequency resolved optical gating (SHG-FROG). The FROG-retrieved spectrum shown in Fig. 1 is in good agreement with the input spectrum (the pump was filtered before entering the FROG setup). Fig. 2 shows the reconstructed temporal profile of the pulses, with a clear signature of the 0.5-THz pulses (2-ps period) imprinted on the optical pulses interacting with the THz pulses, with a nearly 100-% contrast.

In conclusion, we have explored a new regime of optical parametric amplification that shows great promises toward efficient generation of multi-cycle THz frequency pulses. This new regime of OPA also holds promises for the generation of high-energy, sparse THz frequency combs.

Fig. 1: spectral intensity (black line) and phase (blue line) retrieved from SHG-FROG compared with the measured spectrum (red line).

Fig. 2: temporal intensity (black line) and phase (blue line) profiles retrieved from SHG-FROG. Inset: zoom exhibiting 2-ps oscillations.

[1] G. Cirmi *et al.*, talk SM2L.4, CLEO 2016; K. Ravi *et al.*, talk SM2L.6, CLEO 2016; M. Hemmer *et al.*, talk UTu2A.6, Ultrafast Phenomena 2016.