Narrowband THz generation via chirp-and-delay in PPLN

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High-peak-field, narrowband terahertz (THz) sources are well suited for compact electron acceleration [1], however, these sources are still under development and yet to reach optimal energies. A high conversion efficiency via difference frequency generation is established by quasi-phase matching in periodically poled lithium niobate (PPLN). Moreover, to achieve the required mJ-level THz pulses high energy input pulses are inevitable [2]. Chirp-and-delay pumping offers a method to increase the NIR pulse duration and to scale up the energy without damaging the crystal. Here, we present chirp-and-delay in PPLN of varying poling periods and study the effect of crystal length and temperature.

A 5 Hz Ti:Sa-based laser system (ANGUS) delivers uncompressed pulses up to 5 J with a 35 nm FWHM bandwidth at 800 nm with a pulse duration of 260 ps. A train of this chirped pulses with a delay (Δt) co-propagates through the PPLN mounted in a cryostat for cooling (Fig. 1a). In order to verify the mechanism we measured the dependence of the THz output on the delay and frequency of the generated THz ($\Omega = 2\pi\nu_{\text{THz}}$), which is related to the poling period as: $\Omega = 2\pi c/(\Lambda|n(\Omega) - n_g|)$ [3]. The THz pulse energy was measured with a pyro detector (Fig. 1b) and the THz frequency with an interferometer (Fig. 1c). The THz frequency was varied by using crystals with the poling period of $\Lambda = 125, 212$, and $400 \mu\text{m}$. Fig. 1d shows that the optimum delay (Δt_{opt}) depends inversely on the poling period. The substructure for higher delays originates from the third-order dispersion in the chirped pulses and the pulse train. The relation between the measured delays and the measured frequencies agrees well with our prediction using the GDD (ϕ_2) of the pulses: $\Delta t_{\text{opt}} = \Omega \phi_2$.

Fig. 1. **a)** Setup to generate a train of chirped pulses. Detection setup for **b)** THz pulse energy and **c)** THz frequency. **KEY:** PR/HR: partial/high reflector; WP: half wave-plate; $L_{s/t/TPX}$: sagittal/tangential/TPX lens; M: Silver mirror; Si BS: silicon beam splitter. **d)** Normalized THz signal vs. delay for poling periods of 400, 212, and 125 μm . **e)** Conversion efficiency of 212 μm poling period PPLNs at room- (dotted) and cryogenic (solid) temperature as a function of pump fluence.

Figure 1e shows the internal efficiency vs. pump fluence at room and cryogenic temperatures for two crystal lengths of 212 μm -poled PPLN. A record extracted multi-cycle THz energy of 40 μJ was achieved at a frequency of 0.544 THz using the 10 mm- long crystal (3 mm $\times$ 10 mm aperture) at 82 K. Although the 20 mm piece exhibited a higher peak efficiency of 0.13 % already at lower pump fluence, the energy output was less due to a smaller aperture. Optimizing the pump laser bandwidth and increasing the aperture size, chirp-and-delay pumping of PPLN is a promising candidate to reach the mJ-level of multi-cycle THz pulses with conversion efficiencies on the 1%-level.

References

1. F. Kärtner *et al.*, “Axisis: Exploring the frontiers in attosecond x-ray science, imaging and spectroscopy,” Nuclear Instruments and methods in Physics Research A **829**, 24 (2016).
2. K. Ravi, D. N. Schimpf, and F. X. Kärtner, “Pulse sequences for efficient multi-cycle terahertz generation in periodically poled lithium niobate,” Opt. Express **24**, 25,582 (2016).
3. K. L. Vodopyanov, “Optical generation of narrow-band terahertz packets in periodically-inverted electro-optic crystals: conversion efficiency and optimal laser pulse format,” Optics Express **14**, 2263 (2006).