Circumventing Limitations of Tilted-pulse-front Terahertz Generation Using a Stair-step Echelon

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Abstract— Ultrafast terahertz (THz) transients are of great interest for linear and nonlinear THz spectroscopy and compact particle acceleration. Tilted-pulse-front (TPF) [1] THz generation in lithium niobate (LN) has become ubiquitous due to its compatibility with easily accessible high-power 800 nm/1 μ m laser technology. However, the use of diffraction grating (DG) based TPFs (DG-TPFs) present formidable imaging challenges, particularly for large pump bandwidths and beam sizes. Furthermore, as the optical pump spectrum red-shifts and broadens due to repeated down-conversion to THz frequencies (referred to as cascading), a spatio-temporal break-up of the pump pulse results [2]. This limits the energy conversion efficiency (η) and produces THz pulses with spatio-temporal distortions.

We describe new mechanisms to eliminate these limitations by engineering the transverse-momentum distribution of the pump pulse via a stair-step echelon [3]. The structure (Fig. 1(a)) produces a discrete optical pulse front composed of many beamlets. Each beamlet propagating in LN at the optical group velocity c/n_g produces a THz wavelet that propagates at phase velocity c/n_{THz} in

Figure 1: (a) Schematic illustration of echelon depicting THz generation by relatively delayed optical beamlets. (b)–(d) Numerical simulations of echelon: Individual THz wavelets superpose coherently when the temporal delay Δt and spatial offset Δx between beamlets are related by $\Delta t = \Delta x \tan \gamma n_g / c$, where $\gamma = 63^\circ$ is the Cherenkov angle for LN (e) Inherent bandwidth limitation due to group velocity dispersion (GVD) produced by DG-TPFs. Phase-matching conditions are satisfied only for small bandwidths. (f) Echelons contain overlapping transverse momentum (k_x) distributions, which solves the bandwidth limitation. (g) Higher conversion efficiencies, broader THz spectra predicted for echelons. (h) Spectral broadening due to cascading in echelons is larger than with DG-TPFs.

a direction given by the Cherenkov angle $\gamma = \cos^{-1}(n_{\text{THz}}/n_g)$ where $\gamma = 63^\circ$ for LN. The THz wavelets superpose constructively if the time delay Δt and spatial offset Δx between successive optical beamlets are related by $\Delta t = \Delta \tan \gamma n_g / c$ (Fig. 1(c)), yielding a single-cycle THz plane wave with uniform spatial properties (Fig. 1(d)).

In DG-TPFs, each frequency component of the pump is mapped to a different angle (or transverse momentum k_x) due to angular dispersion (Fig. 1(e)). However the variation of angle with frequency is non-uniform due to group velocity dispersion caused by angular dispersion. Consequently, phase-mismatch occurs for large pump bandwidths or due to cascading (Fig. 1(e)). For the echelon, when beamlets are sufficiently sparse, all frequencies have an overlapping distribution in $k_x(1f)$, which circumvents bandwidth limitations. In Fig. 1(g), THz spectra resulting from DG-TPFs and echelons are compared theoretically. The simulations incorporate spatio-temporal distortions, cascading, absorption and dispersion [2]. For the conditions in Fig. 1(g), significantly larger conversion efficiencies with broader spectra and larger THz frequencies are observed for the echelon. This is consistent with trends from experiments [3]. The pump spectral broadening due to cascading is also larger (Fig. 1(h)).

The use of echelons for THz generation may result in significantly higher conversion efficiencies of several percent ($\eta = 3.5\%$ for 0.5 ps pump pulses is predicted for echelons), superior beam properties, and broader THz spectra by eliminating limitations posed by DG-TPFs. The method also alleviates some experimental challenges, particularly for large beam sizes.

REFERENCES

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