

Nonlinear phonon-polaritonic flat-optics for temporal edge detection in the THz

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Abstract: Edge detection is a crucial application of nanophotonic platforms for signal processing. Temporal edge detection with a nonlinear phonon-polaritonic sheet is theoretically demonstrated, detecting optical events through rectification to the THz. The performance is optimized by resorting to a metasurface— $\chi^{(2)}$.

Recently, emerging nanophotonic metadevices of sub-wavelength thickness have been proposed as an alternative to bulky diffraction-limited optical systems for image processing, providing high sensitivity, broadband response and compactness for functionalities such as spatial boundary detection, which is a key issue for applications in microscopy, computer vision or automation [1]. In time domain, edge detection allows for the recognition of events occurring in an optical signal over time, a task for which metamaterial-based technology could entail an ulterior innovative approach by engineering the spectral response of the system at will. In this work, a theoretical concept for temporal edge detection in a flat nonlinear slab with second-order nonlinearity $\chi^{(2)}$ is presented; the events to be detected are contained in one or two time-dependent near-infrared (NIR) images impinging on the nonlinear layer where, via the $\chi^{(2)}$ —mediated difference-frequency generation (DFG) process in the vicinity of phonon resonances, the time domain derivative of the optical envelope is imprinted on the temporal profile of the nonlinearly generated terahertz (THz) signal. The results are supported by full-wave numerical simulations and an AlGaAs metasurface is proposed to enhance the nonlinear THz event detection signal with respect to that of the unpatterned thin film.

As a reference scenario, a spatially uniform non-centrosymmetric dielectric sheet concentrated at $z = 0$ is considered in the limit of vanishing thickness (Fig. 1a). Assuming that the latter contains a single non-vanishing $\chi^{(2)}$ tensor component, $\chi_{yxx}^{(2)}$, with a linear dispersion in the THz frequency range, the second-order nonlinear THz polarization density induced in the sheet through the interpulse DFG between two x -polarized NIR pumps corresponds to a THz carrier modulated by the first-order temporal derivative of the product of the two input optical envelopes. Fig. 1b shows the analytic solution to this reference scenario for the case in which both input optical signals have the same Gaussian temporal profile. The assumed dispersion of the ideal $\chi_{yxx}^{(2)}$, which linearly

crosses its zero value at 4 THz, enables low-frequency filtering around such a THz carrier frequency, retaining only high-frequency components in which the event occurrence is encoded. As such, the induced THz polarization density, and thus, the radiated field peak at the instants when the optical envelopes' product undergoes the most rapid variation.

To showcase a more realistic scenario, an AlGaAs thin film is considered and the temporal edge detection experiment is numerically evaluated via finite-element method (FEM) simulations. Remarkably, the coupling of THz light to infrared-active transverse-optical phonons yields a highly dispersive bulk $\chi^{(2)}$ of polar semiconductors in the THz region, whose real part shows a quasi-linear dispersion at certain frequencies and thus makes these materials promising candidates for optical event detection. The simulation results are reported in Fig. 1c for a 400 nm thick [001]-cut AlGaAs slab (black curve) and an AlGaAs nanopillar metasurface of the same thickness (pink curve), both standing upon a [0001]-Al₂O₃ substrate. The input optical information signal is a rectangular pulse whose rising and falling edges are precisely highlighted by the nonlinearly reflected THz electric field, which shows a 2-fold enhancement in the case of the metasurface.

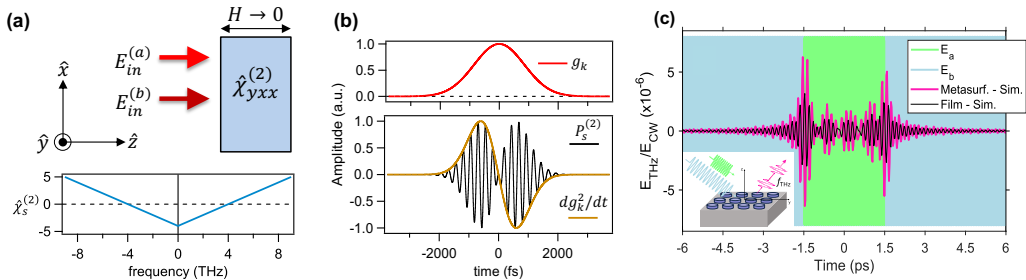


Fig. 1 | **a** Top: vanishing-thickness slab together with the wavevectors for the incident fields and the laboratory frame. Bottom: dispersion of the ideal sheet nonlinear susceptibility in the THz region. **b** Top: temporal envelope of the two input Gaussian optical pulses in the ideal reference scenario. Bottom: normalized THz polarization density resulting from DFG (the yellow curve represents its THz envelope). **c** Full-wave simulation results for edge detection in a 400 nm thick AlGaAs film and nanopillar metasurface (pillar radius of 160 nm and period of the square lattice of 400 nm), upon sapphire. The green and blue backgrounds represent the two TM-polarized optical input signals, i.e. a rectangular pulse and a continuous-wave pump, respectively (not on scale). The two optical carriers are separated by 5.6 THz, frequency around which the real part of AlGaAs' DFG- $\chi^{(2)}$ shows a linear dispersion around a zero-crossing point. Adapted from [2].

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