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# Production of THz Radiation from Mid- and Far-Infrared Two-Color Femtosecond Pulses in Air

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Terahertz (THz) science is attracting a broad interest as many molecular fingerprints belong to the THz range [1]. A well-known technique to create efficient THz emitters is to focus a two-color femtosecond light pulse into air [2] and create a plasma spot. Recent studies [3,4] showed that increasing the pump wavelength  $\lambda_0$  can enhance the laser-to-THz conversion efficiency which is usually limited to about  $10^{-4}$  for  $\lambda_0 = 0.8 \mu\text{m}$ . By means of local-current estimations [4], a gain of about two orders of magnitude can be expected in the THz energy yield with a 10.6- $\mu\text{m}$  pump compared with a near-IR pump [see Figs. 1(a,b)]. Moreover, the pump power contained in a filament is limited to a few times the critical power for self-focusing  $P_{\text{cr}}$  before undesired spatial breakup and multiple filamentation kicks in [5]. Because  $P_{\text{cr}} \propto \lambda_0^2$ , increasing  $\lambda_0$  makes filaments with much higher energies possible. Long laser wavelengths, *e.g.*, 3.9  $\mu\text{m}$ , are nowadays accessible in the femtosecond regime and energetic 100-fs CO<sub>2</sub> laser pulses operating at 10.6  $\mu\text{m}$  should be available in the coming years [6].

Using a three-dimensional unidirectional solver [4], we study intense broadband THz fields generation by such long-wavelength two-color 100-fs pulses ionizing air, with initial power  $P_{\text{in}} = 1.73P_{\text{cr}}$ . Peak intensities of  $\sim 200 \text{ TW}/\text{cm}^2$  are reached, producing electron densities above  $10^{17} \text{ cm}^{-3}$ . When increasing the pump wavelength and so the pump energy, longer filaments are promoted and start to self-focus earlier. Figure 1(c) illustrates the resulting THz energy yields below 10 THz that reach 0.11 mJ for  $\lambda_0 = 3.9 \mu\text{m}$  and 3.1 mJ for  $\lambda_0 = 10.6 \mu\text{m}$ . For this wavelength, we report much smaller angles of the conical THz emission and a better coupling between the two colors along extended propagation ranges.

Finally, we examine the role of many-body Coulomb ionization (MBI) [7] in THz generation. Under strong laser field irradiation, excited-state electrons from neighboring atoms are able to collide and thus increase the ionization rate. MBI becomes relevant for far-infrared pulses at early propagation distances, where multi-photon and tunnel ionizations remain minor players [see Fig. 1(d)]. With such plasma contribution, Fig. 1(e) show that THz emission starts at the very beginning of propagation, but saturates due to accumulated plasma defocusing actions.

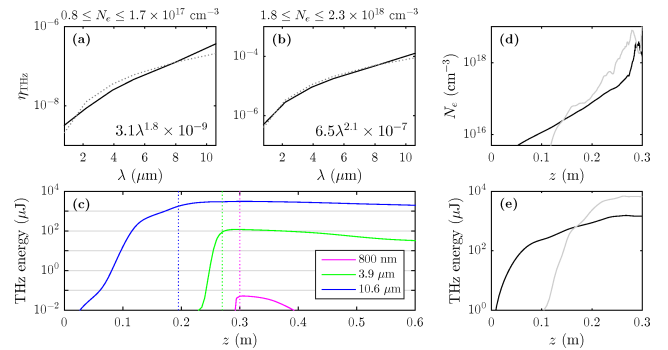


Figure 1: Laser-to-THz conversion efficiency from the local-current model using the two input fluences (a) 5 and (b) 10 J/cm<sup>2</sup>. Dotted gray curves are fits in  $\lambda_0^\alpha$ . (c) THz energies numerically computed for two-color 100-fs Gaussian pulses with  $\lambda_0 = 0.8, 3.9, 10.6 \mu\text{m}$ . (d) Peak electron density and (e) THz energy reached along propagation including (black) or not (gray lines) MBI

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