Phase-matched scalable THz generation in two-color filamentation

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Outline:

- Background
  - THz generation via two-color laser mixing
  - Plasma current model
- THz generation with high-power lasers
- THz phase matching in long filaments
- Summary
Two-color photoionization:
THz generation mechanism:

Current surge → THz generation

Directional quasi-DC current

BBO crystal
Tunneling ionization:

The nonlinearity arises from photoionization!

Multiphoton ionization

Over-the-barrier ionization

$I < 10^{12} \text{ W/cm}^2$

$I > 10^{14} \text{ W/cm}^2$

$I > 10^{16} \text{ W/cm}^2$

However, single-color photoionization can not effectively generate THz radiation.
Plasma current model I:

Laser field: \[ E_L(t) = E_\omega \cos(\omega t) + E_{2\omega} \cos(2\omega t + \theta) \]

\[ \theta \]: relative phase

Plasma current model II:

Tunneling ionization and subsequent classical electron motion in the laser field are considered.

\[ \theta = \pi/2 \]

Radiation spectrum

\[ I_\omega = 10^{14} \text{ W/cm}^2, \quad I_{2\omega} = \]  

Quasi-DC current

Strong field approximation; ignored rescattering, collisional processes, plasma oscillations.
Plasma current model III:

The nonlinearity arises from extremely nonlinear tunneling ionization localized near the laser peaks.*

* Laser field: \[ E_L(t) = E_\omega \cos \omega t + E_{2\omega} \cos(2\omega t + \theta) \]

* Ionization rate: \[ w(t) = 4\omega \left( \frac{E_a}{E_L(t)} \right) \exp \left( -2 \frac{E_a}{3 E_L(t)} \right) \]

* Plasma current: \[ J(t) = \langle eN_e(t)\nu(t) \rangle \]

* THz field: \[ E_{\text{THz}} \propto \frac{dJ(t)}{dt} \propto f(E_\omega) \cdot E_{2\omega} \cdot \sin \theta \]

\[ f(E_\omega) = \sqrt{\frac{E_a}{E_\omega}} \exp \left( -2 \frac{E_a}{3 E_\omega} - 3 \frac{E_\omega}{E_a} \right) \]

* \( f(E_\omega) \) is highly nonlinear, not necessarily quadratic dominant.
More effects to consider:

- **Ionization model:**
  Tunneling vs multiphoton ionization

- **Plasma current calculation:**
  Semiclassical vs quantum-mechanical calculation

- **Additional effects:**
  Plasma oscillations, collisional (electron-ion, electron-neutral) effects, rescattering with parents’ ions

- **Propagation effects:**
  Self- and cross-phase modulations, spectral shifting and broadening, Kerr-induced polarization rotation, phase- and group velocity walk-offs
Broadband EM generation & control:

- Plasma current
- Plasma oscillation & Collisional effects
- Spectral broadening (SPM & blue shift)
- Rescattering
- Ion current

Graphs showing:
- B-dot probe
- EFISH
- FTIR

- Frequency range:
  - 1 THz to 10 THz
  - 100 THz
  - 1 PHz to 10 PHz

- Time scale:
  - 0 to 3 ns

- Frequency scale:
  - 0 to 70 THz

- Power (arb. units) scale:
  - 10^-1 to 10^3

- Spectral power (arb. units) scale:
  - 0 to 0.8
Laser upgrade @ Kim Lab:

5 mJ, 25 fs, 1 kHz Ti:S laser

15 mJ, 1 kHz Ti:S laser
(Peak power ~0.6 TW)

New cryo-amplifier
New cryogenic amplifier:

Cryo-chamber

Beam profile

Ti:S crystal
15 mJ laser interaction with gaseous targets

Interaction with Ar cluster gas jets

Filamentation in air
THz generation with 15 W laser @1 kHz:

![Graph showing THz yield vs. laser energy](image-url)

- **Si**
- HDPE x2
- Teflon x15
THz generation with 20 TW laser

- Laser pulse
- Monomers or clusters
- BBO
- Lens
- Gas jet
- Parabolodal mirror
- Pyroelectric detector

In vacuum

20 TW laser
Experimental Result:

- Several microjoule THz radiation per pulse.
- THz energy saturation.
- Clusters provides less THz output.
Phase matching in THz generation:

Microscopic source

Macroscopic phase matching

Directional current surge

Gaseous medium
Dephasing between $\omega$ and $2\omega$:

This occurs due to different refractive indices at $\omega$ and $2\omega$ in air and plasma

$$\theta = \omega \left[ \left( n_{\text{air}, \omega} - n_{\text{air}, 2\omega} \right) L_1 + \left( n_{\text{filament}, \omega} - n_{\text{filament}, 2\omega} \right) L_2 \right] / c + \theta_0$$
Phase matching in a long filament:

Condition for constructive interference:

\[ \Delta l = P_3 - (P_1 + P_2) = (m + 1/2) \Gamma \]

\[ \cos \Theta \approx 1 - \Gamma/(2l_d) \]
THz phase matching:

Source:

\[ \tilde{P}(r', \Omega) \propto \tilde{A}(r', \Omega) \sin(\theta(z')) \exp \left( i n g k_{THz} z' - i \Omega t \right), \]

THz far field:

\[ E(r, \Omega) \propto \int_V d^3r' \ \frac{\tilde{P}(r', \Omega) e^{ik_{THz}|r-r'|}}{|r-r'|} \]

THz intensity:

\[ |E(r, \Theta, \Omega)|^2 \propto |\tilde{A}(r', \Omega)|^2 \frac{(\pi a^2)^2 l^2}{r^2} \left( \kappa_1^2 + \kappa_2^2 + 2\kappa_1\kappa_2 \cos(2\theta_0 + \pi) \right) \left( \frac{2J_1(\beta)}{\beta} \right)^2 \]

\[ \kappa_{1,2} = \frac{\sin(\alpha_{1,2})}{\alpha_{1,2}} \quad \alpha_{1,2} = \frac{k_{THz} l}{2} \left( n_g \pm \frac{\Gamma}{2l_d} - \cos(\Theta) \right) \quad \beta = \frac{2\pi a}{\lambda} \sin(\Theta) \]

\[ \cos(\Theta_p) = 1 - \frac{\lambda}{2l_d} \]
Simulated THz profiles:

Short (~1 cm) plasma

Long (~3 cm) plasma

$N_e \sim 3 \times 10^{16}$ cm$^{-3}$
THz radiation profile measurement:

- Laser pulse
- BBO
- Lens
- Filament
- THz
- Pyroelectric detector
- Raster scanning
- Teflon & Si filters or Ge filter
Measured THz profiles:

- **Low THz**
  - Short (<1 cm) plasma
  - [Graph showing low THz profiles for short plasma]

- **High THz**
  - Long (>3 cm) plasma
  - [Graph showing high THz profiles for long plasma]
Measured optical and THz profiles:

400 nm + 800 nm

~700 nm (blue-shifted 800 nm)
THz focusing issue:

~6 mm long filament

Focused THz profiles
THz yield vs filament length:

- BBO
- $\omega$
- Aperture
- $l_f$
- THz yield vs $l_{eff}$ (mm)
- $\theta_0 = 0$
- $\theta_0 = \pi/4$
- $\theta_0 = \pi/2$
THz yield vs filament length:

THz output increases almost linearly with the plasma length.
Summaries:

- **THz generation via two-color laser mixing:**
  - Ideal for broadband intense THz spectroscopy

- **High-energy THz generation:**
  - Used 15 W, 1 kHz and 20 TW, 10 Hz lasers
  - Produced several $\mu$J THz radiation but observed saturation

- **Scalable THz generation:**
  - Demonstrated THz phase matching in long filaments
  - THz output energy increases with the filament length
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