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# Studying Terahertz Conical Emission by a Two-color Laser-based Air Plasma

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**Abstract:** We characterize the frequency-resolved terahertz (THz) beam profile created by two-color air-plasmas in the broadband frequency range (1-15 THz). Far-field conical emission patterns are confronted with current models proposed in the literature. © 2022 The Author(s)

## 1. Production of THz radiation

Optical methods offer a promising way to enhance the laser-to-THz conversion yields and frequency ranges given by solid emitters, such as photoconductive antennas or quantum cascade lasers. We here study the production of THz pulses using an air-plasma driven by a two-color, ultrashort and intense laser beam [1]. One main feature of this method is the typical conical shape of the THz emission in the far-field. Several papers [2–4] previously addressed the question of modelling THz conical emission without receiving a clear confirmation of their accuracy through dedicated experiments. In the following, we bring some experimental evidence in favor of You et al. [3]. The experimental setup used for THz emission is illustrated in Fig. 1.a. We employ a Ti:Sa laser amplifier centered around 800 nm with 1 kHz repetition rate and  $\approx 40$  fs pulse duration. A  $\beta$ -barium borate (BBO) crystal creates its second harmonic (400 nm). The two colors are then focused by a 300 mm lens (L1) in a dinitrogen cell, creating a plasma by photo-ionization. The induced photo-currents generate THz pulses of  $\approx 0.2$   $\mu$ J. The resulting THz radiation is guided by four off-axis parabolic mirrors through collimation and focusing steps to a high-resistivity Si wafer filtering the optical components (photocurrent influence to the THz wave is negligible), then to a knife-edge measurement setup and a coherent detection zone, involving an Air-Biased Coherent Detection (ABCD) [5, 6]. We report off-axis emission of the THz pulses, shaped as cones, the aperture angles of which depend on the frequency of the radiation (Figs. 1.b and 1.c). The crescent moon-like shape of the THz far-field measurement is attributed to small spatial walkoff between the two optical colors and astigmatism of the laser pump [6, 7].

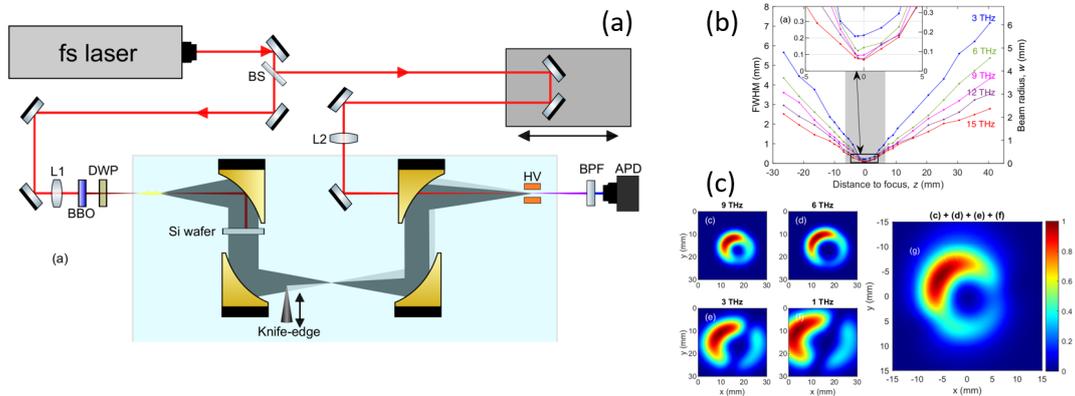


Fig. 1. (a) Experimental setup used to produce and detect THz radiation (see text). (b) Diameter of the produced THz frequency depending on its distance to focus. Lower parts of the THz spectrum tend to defocus faster. (c) THz far-field measured using the knife-edge method in a collimation step. The emission is a heterogeneous cone shaped as a crescent moon in the transverse plane.

## 2. Characterization of the THz conical emission

To understand the conical nature of the THz emission revealed by the experiment, one analytically evaluates the far-field intensity radiated by the local electron current. The model established by You et al. [3] predicts off-axis emission of the generated THz field due to the phase-mismatch between the two optical colors depending on their respective optical and plasma dispersion. This effect induces phase-matched, off-axis THz bursts along the propagation axis that result from interferences, forming a cone in the far-field. The two main parameters that affect the THz emission angle are the electron density  $N_e$  and the length of the emitting volume  $L$ . By admitting that the emitting volume is a cylinder of radius  $a$ , length  $L$  and with homogeneous electron density  $N_e$ , the angular-frequency dependency of the THz spectral power is given by :

$$P_r(\omega, \Theta) \propto L^2 a^4 |A(\omega)|^2 (\kappa_+^2 + \kappa_-^2 - 2\kappa_+ \kappa_- \cos(2\theta_0)) \left( \frac{J_1(\beta)}{\beta} \right)^2 \quad (1)$$

where  $A(\omega)$  is the THz spectrum emitted by the plasma,  $\kappa_{\pm} = \text{sinc}\left(\frac{1}{2}kL\left(1 - \cos\Theta \pm \frac{\lambda}{2l_d(N_e)}\right)\right)$ ,  $\theta_0$  an incident phase shift and  $\beta = ka \sin\Theta$ .  $\lambda = 2\pi/k$  is the THz wavelength and  $l_d$  is the  $N_e$ -dependent dephasing length, over which the two optical colors shift from 0 to  $\pi$ . Equation (1) implies that the privileged emission angle of the THz generated by a plasma is described by  $\cos\Theta = 1 - \lambda/(2l_d(N_e))$ , provided that the plasma length satisfies  $L > l_d$ . This condition is verified in the experimental setup of Fig. 1.a.

Figure 2.a shows the frequency-angular spectrum measured in the far-field. The spectral content is localized within a conical shape along 1-15 THz with a divergence (emission) angle from  $9^\circ$  to  $2^\circ$ . A pattern computed from Eq. (1) is depicted in Fig. 2.b where we chose  $N_e = 5 \times 10^{16} \text{ cm}^{-3}$ ,  $L = 2.5 \text{ cm}$  and  $a = 50 \mu\text{m}$ . The squared absolute value of the THz spectrum  $|A(\omega)|^2$  is obtained from the experimental measurements, including the ABCD contribution subject to temporal and spatial overlap between the THz pulse and the 800 nm probe, which leads to a frequential response up to 15 THz shown in Fig. 2.c. This semi-analytical calculation based on You et al.'s model gives a satisfactory reproduction of the measured conical THz spectrum. Alternative patterns provided by accounting for plasma opacity [2, 4] will also be addressed.

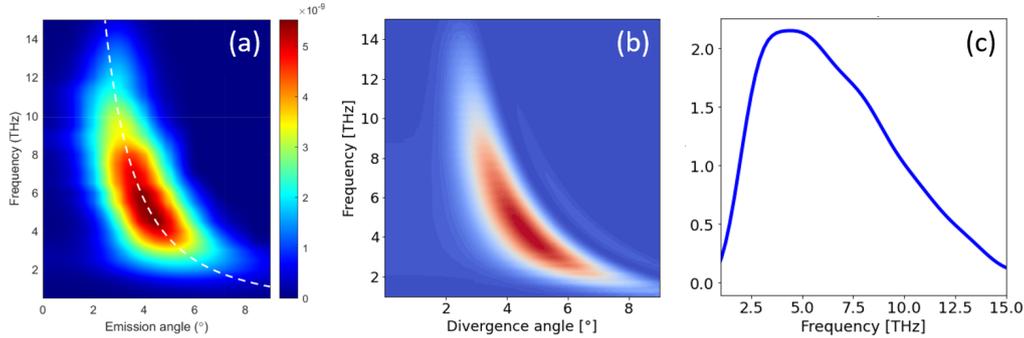


Fig. 2. (a) THz frequency-angular spectrum measured by the knife-edge setup in the far-field. The dashed line shows that the privileged emission angle roughly follows  $\Theta(v_{THz}) \propto 1/\sqrt{v_{THz}}$ . (b) Same figure obtained by integrating You et al.'s model using  $N_e = 5 \times 10^{16} \text{ cm}^{-3}$  and  $L = 2.5 \text{ cm}$ . (c)  $|A(\omega)|^2$  (y-axis in arbitrary unit) measured using the experimental setup in Fig. 1.a.

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