Near-field & far-field modelling of a sub-wavelength THz source

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***Abstract*—The THz emission point on a nonlinear electro-optical crystal for generating broadband THz radiation is modeled as a radiating Gaussian aperture. With the wavelengths of the infrared pump beam being much smaller than the wavelength components of the generated THz pulse, a THz sub-wavelength radiating aperture with Gaussian profile is effectively created. This paper investigates this general modelling approach for focused THz radiation generation in electro-optical crystals. Different implementations are employed for the near- and far-field regime. While a numerical approach is required to characterize near-field intensity distributions, a semi-analytical model is sufficient for far-field considerations. The near-field study has ramifications in THz near-field focused beam techniques while far-field investigations elucidate the radiation pattern shape and hence the detectable SNR.**

I. Introduction And Background

The Gaussian beam is a solution to the paraxial wave equation and is characterised by a Gaussian intensity distribution in any plane transverse to the direction of propagation [1]. The paraxial approximation can be considered approximately for a beam waist w_0 larger than 0.91λ with a divergence angle $\theta_0 < 20°$. For $w_0 < \lambda/5$ $\theta_0 \rightarrow 90°$, the paraxial theory completely breaks down and the radiation pattern converges to the well known obliquity factor pattern [2]. With THz wavelengths (100 µm to 3 mm) being orders of magnitude longer than wavelengths of the infrared pump beam (centred at 800 nm) the breakdown of paraxial theory for THz beams generated from electro-optical crystals pumped by an optical beam becomes increasingly relevant. These sub-wavelength THz sources are investigated in the near-field [3] and far-field regime [4] as a radiating aperture of Gaussian profile, using numerical and semi-analytical techniques respectively.

II. Near-Field Study

A THz hybrid setup that generates THz radiation by optical rectification and detection via a PCA is used in our experiment. An optical lens of 200 mm focal length is used to focus down the IR pump beam to a waist of 51 µm with a Rayleigh range of 10 mm, greater than the optical path length in the 1 mm thick ZnTe <110> crystal. Taking into consideration the beam divergence in the crystal, the effective IR pump beam waist is expected to be slightly larger than the theoretical value. A dual-axis (i.e. x and y-axis) knife-edge profile measurement is conducted on the generated THz beam at a distance of 150 µm, as determined from the tip of the knife-edge to the crystal surface. The generation of THz radiation with optical rectification in a nonlinear crystal is a square law process [5].

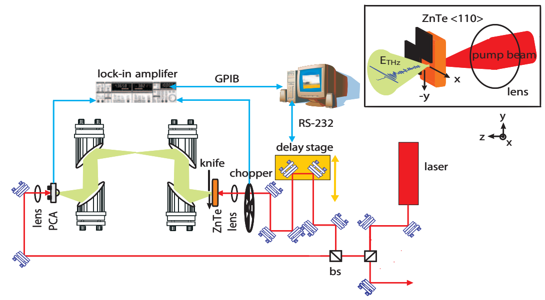

Figure 1 - The pump laser beam is focused into a 1 mm thick ZnTe crystal. The emitted THz radiation polarized parallel to the x-axis is sliced along the x-axis and y-axis respectively.

The square relationship between generated THz electric field to the optical electric field therefore implies a reduction factor of $\sqrt{2}$ in the radius of THz source. In the present model, the THz source is approximated as the radiation from an aperture with a Gaussian intensity profile, located inside the crystal. Near-field wave propagation in the knife-edge experiment is simulated with a full-wave electromagnetic simulation tool based on the Finite-Volume Time-Domain (FVTD) method [6, 7]. The application of this in-house developed code is motivated by the possibility of implementing a sub-wavelength Gaussian aperture source as demonstrated in [8]. This flexibility in implementation is not readily available in most commercial software. The volume is discretized with an inhomogeneous tetrahedron mesh [9] to resolve the geometry near the fine razor blade tip, and to refine the discretization in the crystal with a relative permittivity of 9. The Gaussian sub-wavelength source is excited with a sine-modulated Gaussian pulse, which covers the frequency spectrum from 300 GHz to 2.5 THz. The computational cost associated with modelling the full knife-edge experiment is relatively heavy considering the size of the computational domain in terms of wavelength, and the fact that a simulation has to be performed sequentially for each position of the blade. Also at every blade position, discrete Fourier transformations are performed on the fly during the time iteration of the FVTD simulation to obtain the equivalent frequency representations. Discrete implementation of the frequency domain near-to-far-field transformation is performed in accordance with [10] to simulate the radiation pattern relevant for far-field detection.

III. Far-Field Study

In the far-field investigation, a single-axis knife-edge profile measurement is conducted on the generated THz-TDS setup in Figure 1, at a distance of 0.75 mm away from the crystal surface. The IR pump beam waist is 100 µm. Terahertz radiation generation is modeled as an aperture with Gaussian intensity distribution and a beam waist determined by the IR pump beam. Using the equivalence principle, equivalent electric and magnetic current densities are introduced as equivalent radiating sources in the aperture [11].

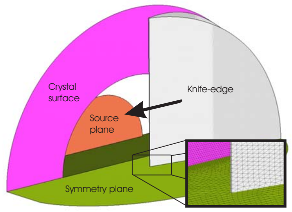

Figure 2 - Schematic of the numerical FVTD model. The inset shows the surface skin triangulation and illustrates the refinement of the mesh near the blade tip and on the crystal surface.

The aperture area is discretized with a regular rectangular mesh from which, a near-field to far-field transformation for computing the radiation integrals on the basis of the discretized source distribution are conducted. The far-field intensity distribution is projected onto a screen, taking into account the decay of intensity as a function of distance. The projection is truncated to the acceptance angle of the parabolic mirrors. A numerical knife-edge measurement on the field intensity projected on the screen is performed to obtain the resulting curve. It is noted that the sharp truncation of the acceptance angle neglects diffraction effects.

IV. Results

In order to validate the developed Gaussian aperture numerical model, the model is applied with estimated and measured experimental parameter values such as (i) IR pump beam waist, (ii) acceptance angle, (iii) knife to crystal surface distance and (iv) THz frequencies unaffected by water vapor.

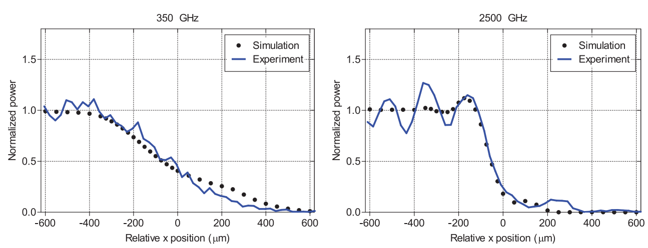

Figure 3 – Near-field experimental and simulated knife-edge profile of THz radiation at 150 μm from the crystal backside at 0.35 THz and 2.5 THz respectively.

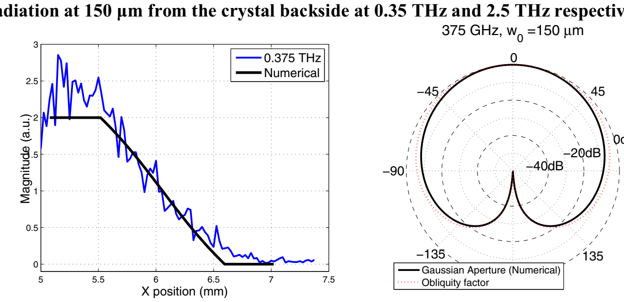

Figure 4 – Far-field experimental and numerical knife-edge profile and the radiation pattern at 0.375 THz. The beam waist w_0 is approximately λ/5 leading to a pattern resembling the obliquity factor.

The simulation results are normalized with respect to the full

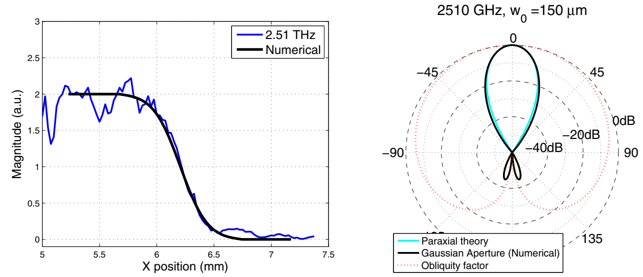

Figure 5 - Far-field experimental and numerical knife-edge profile and the radiation pattern at 2.51 THz. The beam waist w_0 is approximately 1.25λ leading to a pattern resembling the paraxial Gaussian pattern, except for the back lobes.

power, while the measurement is normalized for best visual fit as the full power is not measured in the experiments. The simulated knife-edge results closely match all the experimental results, both in near- and far-field, in terms of the integral function shape and slope.

V. Conclusion

We have modeled and validated THz radiation generation in a ZnTe electro-optical crystal as a radiating aperture with Gaussian intensity distribution in both near and far-field. The near-field numerical model elucidates the quantitative understanding of the performance parameters in the THz near-field focused beam technique. Far-field modelling illustrates that the shape of the radiation pattern broadens dramatically as the wavelength increases past the validity range of the paraxial Gaussian beam model. This causes a reduction in detectable THz radiation and hence contributes significantly to low SNR in focused THz radiation generation

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