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Phase-Sensitive THz Heterodyne Imaging Using Nonparaxial Structured Illumination

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Direct-power terahertz (THz) imaging offers poor contrast for weakly absorbing dielectric samples. Heterodyne detection overcomes this by preserving both amplitude and phase of the transmitted field, providing up to 43 dB higher dynamic range [1] and enabling phase-resolved imaging and computational refocusing [2]. Combined with nonparaxial structured illumination – Airy and Gaussian beams generated by compact silicon diffractive elements – this approach delivers simultaneously enhanced sensitivity, resolution, and phase contrast.

The demonstrated imaging system uses compact silicon nonparaxial diffractive optical elements and a broadband (0.3–2.2 THz) silicon CMOS FET detector with dual-substrate-lens coupling, routing the local-oscillator and RF beams to opposite sides of the chip and eliminating the beam-splitter [3]. Harmonic mixing (600 GHz – 600 GHz) achieves 57.8 dB SNR – 34 dB above direct detection – while sub-harmonic mixing (600 GHz – 300 GHz) yields 54.8 dB.

A multi-material sample (one to five layers of paper sheets, metallic foil, fabric, plastic, gauze) was raster-scanned in all three modes. Direct-power and heterodyne amplitude images show similar few-dB contrast; heterodyne phase images reveal sharp boundaries between all material zones invisible in amplitude data, with a phase range of 0.77π across the paper stack (Fig. 1). Modulation transfer function analysis on a Siemens star target confirms that heterodyne imaging reaches 2.55 cycles/mm – exceeding the 1.45–1.69 cycles/mm of direct detection – with mean squared error reduced from 0.19–0.21 to 0.11. Nonparaxial Airy-beam illumination further enhances SNR and phase sensitivity beyond conventional Gaussian beams [4].

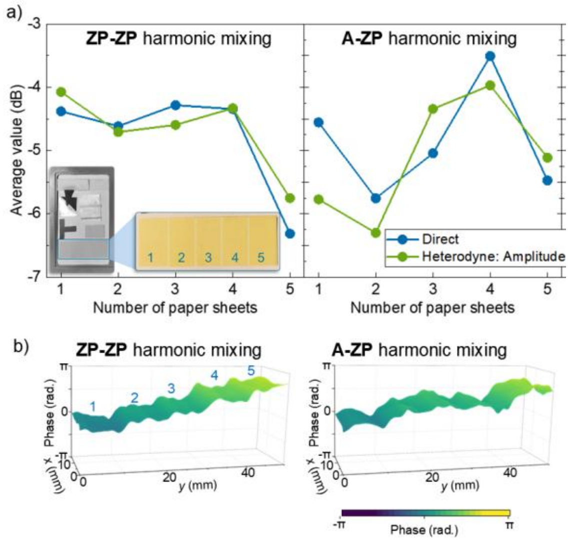

Fig. 1 Comparison of direct and heterodyne imaging results: amplitude (top) and phase (bottom) distributions for the zone plate–zone plate (a) and Airy lens–zone plate (b) configurations. The imaged sample consists of one to five layers of paper sheets.

REFERENCES

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