Terahertz imaging super-resolution

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Spatial resolution is the ability to distinguish the details of a physical object that an optical instrument can reproduce in an image. However, because of the wave nature of light, resolution is limited by diffraction, which hampers attempts to overcome the Abbe's limit [1]. This limit, the diffraction limit, defines the minimum distance between two features that can be resolved with a certain contrast by optical instruments and is a physical limit. It is expressed by the formula $dx = 2\,\lambda/(n\,\mathrm{NA}^2)$, where dx represents the smallest resolved feature in the lateral direction, meanwhile n is the refractive index of the medium between the objective lens and the sample, λ is the wavelength of radiation used, NA is the numerical aperture of the optical system.

The acquired image is always a blurred representation of the actual object under investigation. The so-called Point Spread Function (PSF) describes this blurring: the response of a camera system to a point source or an impulse. Indeed, for each single point in the object, the minimal size of its focal spot is never infinitely small, and the lateral and axial extents of the intensity distribution in the focal region represent the three-dimensional diffraction pattern of light emitted and transmitted to the image plane through a high Numerical Aperture (NA) objective. Moreover, since the image formation process is linear, the acquired image is a focused image, the sample, convolved with the PSF, i.e.: image = sample $\otimes$ PSF.

Methods such as super resolution can be utilized to alleviate the impact of a wide Point Spread Function (PSF), and they are particularly useful in the THz range where diffraction can significantly degrade imaging quality for details smaller than the order of millimeters. The exploration and advancement of super-resolution imaging have been ongoing since the 1980s and 1990s. Numerous optical imaging techniques, including both near-field (Fresnel regime) and far-field (Fraunhofer regime) approaches, have been devised, with the far-field methods based on structured-illumination gaining significant popularity in biological samples, primarily owing to their application of fluorescent dyes [2,3].

This work aims to develop a far-field super-resolution THz imaging system utilizing a freestanding knife-edge [4] within a confocal configuration, in transmission or reflection mode, of a THz-time domain spectroscopy (THz-TDS) system [5]. The intended application is for the examination of small-scale graphic details in planar samples, such as documents on paper substrates, typically featuring signs with lateral dimensions below 1 mm [6].

The THz super resolution set-up was implemented on a Menlo Systems (Germany) TERA K15 THz-TDS system [7]. The knife-edge was realized by a blade, which was put close to the object plane by distances shorter than that of THz wavelength. In practical terms, the conversion of evanescent-wave intensity scattered by the blade edge into newly formed propagating waves, enabling the reconstruction of super-resolved images in the far-field, involves subtracting the total far-field power collected at each blade position x from that collected at the previous position $x - dx$ for each pixel in the image. In Fig. 1 it is shown the improvement in spatial resolution of a sharp metallic edge imaged in transmission mode at 0.3 THz due to the knife-edge technique. The maximum slope of each profile was calculated between 0.1 and 0.9 of the maximum intensity finding that without the blade amounted to 0.44/mm, whereas with the blade, the slope reached 1/mm, with an enhancement of 2.3 times.

Super-risolution was also achieved in reflection mode in the THz imaging of graphic signs realized by several compounds on paper and on a real medieval manuscript.
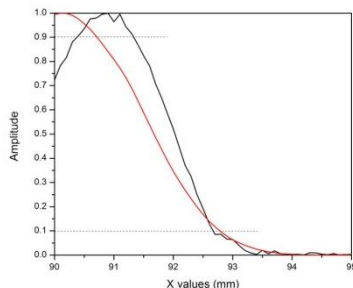
Figure 1. Intensity profiles along X of a sharp metallic edge imaged by using the THz-TDS transmission setup at 0.3 THz with (black curve) and without (red curve) the blade.

References

1. Fowler, G. R. *Introduction to Modern Optics*. Dover Publications, 1989.
2. Huang, B.; Babcock, H.; Zhuang, X. Breaking the diffraction barrier: Super-resolution imaging of cells. *Cell* **2010**, 143, 1047–1058.
3. Xin Chen, X.; Zhong, S.; Hou, Y.; Cao, R.; Wang, W.; Li, D.; Dai, Q.; Kim, D.; and Xi, P. Superresolution structured illumination microscopy reconstruction algorithms: a review. *Light Sci. Appl.* **2023**, 12, 172.
4. Flammini, M.; Pontecorvo, E.; Giliberti, V.; Rizza, C.; Ciattoni, A.; Ortolani, M.; and DelRe, E. Evanescent- Wave Filtering in Images Using Remote Terahertz Structured Illumination. *Phys. Rev. Appl.* **2017,** 8, 054019. DOI: 10.1103/PhysRevApplied.8.054019
5. Vazquez, D. A.; Pilozzi, L.; DelRe, E.; Conti, C.; Sotgiu, S.; Delia, F.; Missori, M. Terahertz imaging super-resolution for documental heritage. Proceedings of the 2023 *IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage*, Rome, Italy, October 19-21, 2023, pag. 554-558.
6. Fukunaga, K.; Ogawa, Y.; Hayashi, S.; Hosako, I. Application of terahertz spectroscopy for character recognition in a medieval manuscript. *IEICE Electron. Express* **2008**, 5, 223. DOI: 10.1587/elex.5.223
7. Missori, M.; Pilozzi, L.; Conti, C. Terahertz waves dynamic diffusion in 3D printed structures. *Sci. Rep.* **2022**, 12, 8613. https://doi.org/10.1038/s41598-022-12617-3
8. Author 1, A.B.; Author 2, C.D. Title of the article. *Abbreviated Journal Name* **Year**, *Volume*, page range.
9. Author 1, A.; Author 2, B. Title of the chapter. In *Book Title*, 2nd ed.; Editor 1, A., Editor 2, B., Eds.; Publisher: Publisher Location, Country, 2007; Volume 3, pp. 154–196.