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Terahertz imaging super-resolution for documental heritage

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Abstract – THz time-domain spectroscopy (THz-TDS) and pulsed imaging have been demonstrated to be able to provide a non-invasive examination of cultural heritage materials. However, the spatial resolution of THz pulsed imaging is of the order of 1 mm for THz waves, a value that is often not sufficient for the examination of small details on written heritage. This paper will focus on the development of a far-field super-resolution THz imaging system based on a free-standing knife edge and a reflective confocal configuration for the THz beamline. This system has been designed for the recognition of inks, pigments, and dyes used in graphic signs and for the detection of texts buried beneath graphical layers. To optimize the set-up preliminary experiments were realized by imaging the diffraction pattern of a slit, where the freestanding knife set-up showed an improved resolution. After, a reflective set-up was realized and tested on paper samples with graphite patterns. Results demonstrated the super-resolution of THz imaging by showing written features separated by less than the wavelength used. The future direction will be the application of the set-up to real ancient documents for their diagnostics.

I. INTRODUCTION

Electromagnetic waves are widely used in the nondestructive testing of cultural heritage [1,2]. The application of waves in the terahertz (THz) range, also called the far-infrared range, to diagnostics began about 15 years ago, with applications in spectroscopic imaging and material identification [3].

THz time-domain spectroscopy (THz-TDS) technology, developed in the 1990s [4], uses narrow pulses with pulse widths of the order of 1ps to obtain spectra in the frequency range of 0.2-4 THz [5]. Terahertz imaging has the potential to identify and decipher fragments of ancient writings that are invisible at infrared and visible wavelengths [6]. However, the spatial resolution of THz pulsed imaging is diffraction-limited to about the wavelength, which is of the order of 1 mm for commonly used THz waves.

This work will focus on the development of a far-field super-resolution THz imaging system based on a freestanding knife edge and a reflective confocal configuration for the THz beamline, like those employed in THz-TDS systems [7]. The super-resolution THz imaging system may be applied to the study of the text in ancient documents on paper or parchment substrates, where graphic signs with lateral sizes less than 1 mm are usually found [8].

II. EXPERIMENT PROCEDURE

The knife-edge scan is a super-resolution scheme operating with a structured illumination plane at a variable subwavelength distance from the reflecting surface. It achieves super-resolution in its most basic single-wavelength beam-profiling execution, in contrast to advanced super-resolution techniques that generally involve radiation delivery and collection at different wavelengths, deconvolution calculations, fluorescence phenomena, and/or nonlinear interactions with other light fields [9]. In the THz range, knife-edge scans have been implemented to greatly increase the spatial resolution of images of laser-induced broadband source points, and an optically induced virtual knife-edge technique was also demonstrated by structured illumination with a visible laser in the terahertz-emitting (object) plane [10].

Spatial resolution is the ability to distinguish objects that are separated in reality, in the sample, as separated from one another, in the image of the sample that is generated in the microscope. Indeed, the light collecting system convolves each point source in the sample with a point spread function (PSF) that represents the distribution of light within a blurry circle, so that :

$$sample \otimes PSF = image$$

The shape of the PSF depends on the type of microscope and its parameters. A theoretical approximation is given by a symmetric Gaussian function that in 2D reads as:

$$PSF(x,y,z) = \frac{1}{\pi\sigma_X(z_0)\sigma_Y(z_0)} exp\left(-\frac{(x-x_0)^2}{2\sigma_X(z_0)^2} - \frac{(y-y_0)^2}{2\sigma_Y(z_0)^2}\right)$$

Here x_0, y_0, and z_0 are the true spatial coordinates of the emitter, and $\sigma_X(z_0)$ and $\sigma_Y(z_0)$ represent the widths of the Gaussian function along the two perpendicular x and y-axes at z_0.

To simplify our analysis, we consider as the object plane a sample surface at z = 0 emitting or reflecting radiation in the direction z > 0, with subwavelength spatial features. We implement the mechanism for super-resolution with a blade in the plane z = 0, covering the optical field on $x' > 0$.

If $\int_R O(u, z, x')PSF(x - u)du$ is the convolution of the intensity distribution, $O(u,z,x')$, immediately after the blade with the microscope *PSF*, its collection for several positions of the blade edge $x' \int_R \int_R O(u, z, x')PSF(x - u)du$, after differentiation provides the scattered intensity distribution.

$$I_S(x',z) \quad = -\frac{d}{dx'}\int_{\mathbb{R}} dx \int_{\mathbb{R}} O(u,z,x')\mathrm{PSF}\,(x-u)du$$

Given that $O(u,z,x') = I(u,z)\theta(u - x')$ and making use of the normalization of the PSF, we obtain

$$I_S(x',z) = -\int_{\mathbb{R}} I(u,z)\frac{d}{dx'}\theta(u-x')du = I(x',z)$$

so that the high spatial frequencies of the spectrum of $I(x', z)$ will be fully transferred to the reconstructed far-field image $I_S(x', z)$ which is, therefore, no longer limited by diffraction and is a remotely super-resolved image [11] .

Practically, the scattering of the evanescent-wave intensity by the blade edge into propagating waves newly formed at z > 0, allowing super-resolved image reconstruction in the far-field, is achieved by subtracting, for each pixel in the image, the total far-field power collected at each blade position x' from that collected at a previous position $x' - dx'$.

The first experiment was the study of the diffraction effect and super-resolution in a metal slit composed of two blades. These blades were separated first at a distance of 5.0 mm (Fig. 1), and later by 1.5 mm. It was analyzed the behavior of the diffraction pattern with the knife-edge placed at different distances from the slit (150, 250, 350 and 500 μm) in a THz-TDS transmission setup.

We assembled the reflective confocal microscope shown in Fig. 2, with one added knife-edge profiling system and a high numerical aperture (0.45) parabolic mirror. According to the Rayleigh criterion,the diffraction-limited resolution indicates that two linear image details are resolved if they are more than Δx= λ/2NA apart in one-directional scans of the sample in the focal spot [12].

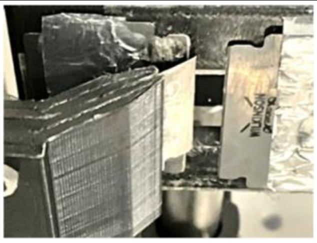	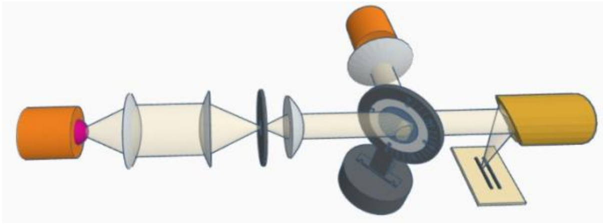	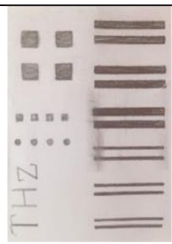
Figure 1:Metal slit with 5mm of separation at 0.5mm from the blade	*Figure 2: Reflective confocal configuration for the THz-TDS set-up with a beam splitter. The blades are placed close to the surface of the sample.*	*Figure 3. Mock-up targets made up of graphite stripes on paper.*

Mock-up targets for super-resolution testing were realized on a paper substrate. Paper is typically made from cellulose fibers derived from plants or wood and possesses a low refractive index and low absorption in the THz frequency range [13]. Meanwhile, graphite is a reflective material in the THz range due to its high electrical conductivity. For that reason, a mock-up target was prepared on modern paper with a handmade graphite design of vertical lines parallel to the blade (Fig. 3), separated by 1.5 mm, to study the super-resolution of the knife edge in the reflective set-up.

III. RESULTS

First, we tested the diffraction effect and super-resolution by using the THz-TDS transmission set-up with the metal slit composed of two blades. There were studied the effect of the blade in the near-field (~150μm from the slit) of one single aperture of 5mm, analyzing the Fresnel-Fraunhofer diffraction patterns and the behavior of the super-resolution at different frequencies (Fig.4), observing the Fraunhofer pattern when no blade is used and, on the other hand, the increase of the resolution with the blade at bigger frequencies.

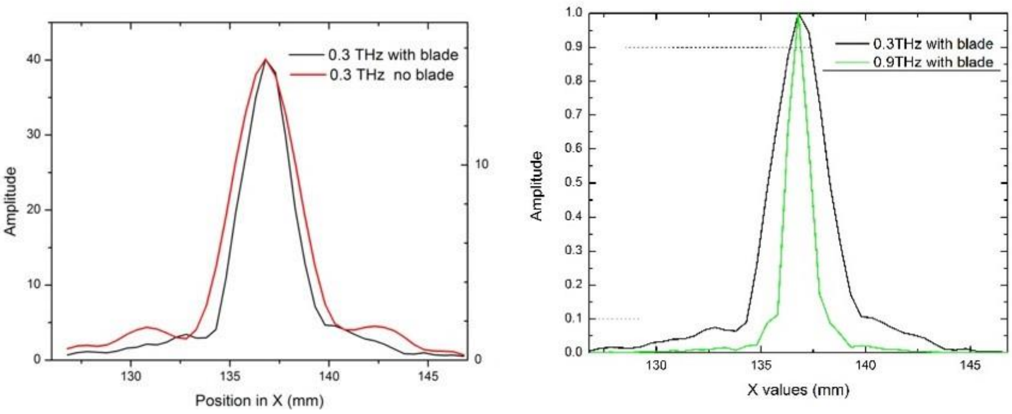

Figure 4: Intensity profiles along the direction X at different frequencies with THz-TDS transmission setup.

The confocal microscopy image in Fig. 5a shows a single broad feature when no knife-edge scan is used. The two stripes are too close and cannot be separated. When the knife-edge scan reconstruction method is applied, the two reflecting stripes are visible (Fig. 5b, 5c). We can observe also in Fig.5d the behavior of the super-resolution at different wavelengths, obtaining an increase of the super-resolution at smaller wavelengths, for example, the profile at 0.9THz (λ=0.33mm) shows better the small features than theTime Domain or at 0.3THz (λ=1mm).

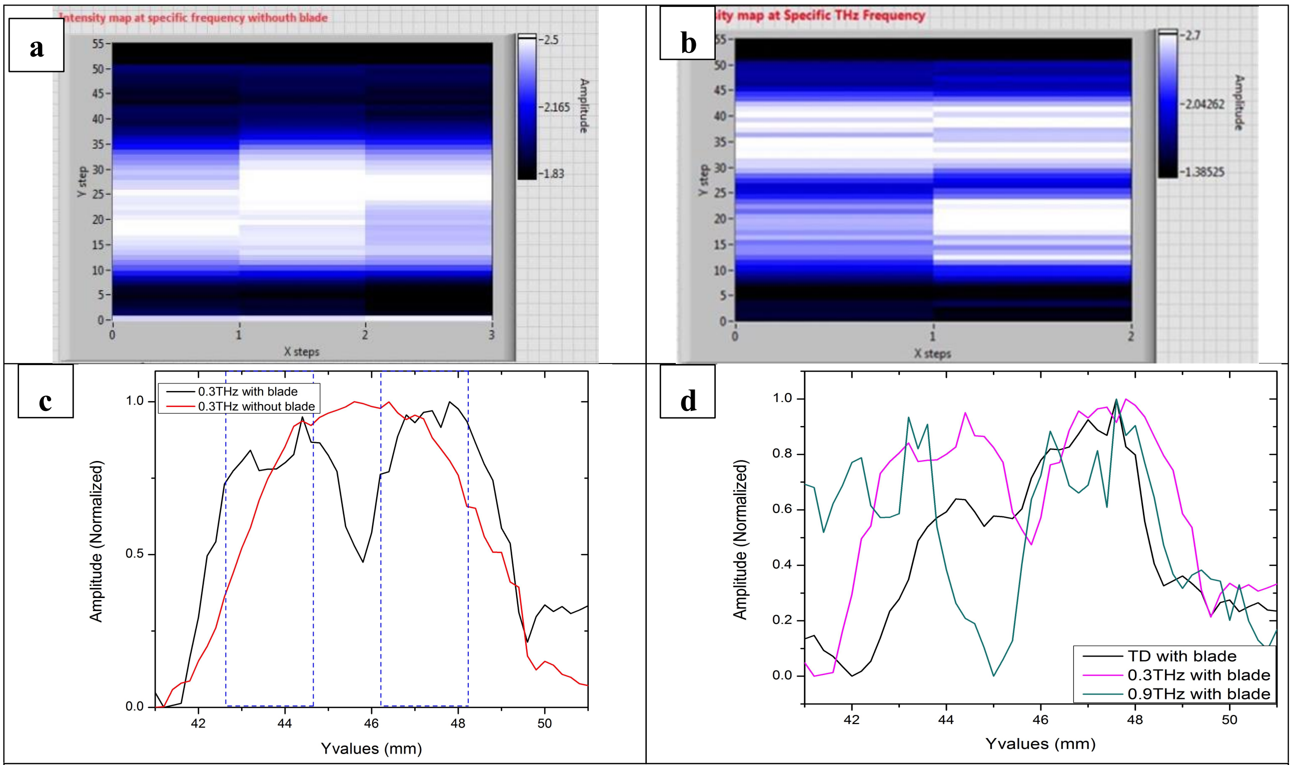

Figure 5: THz image of 2 stripes of graphite on paper separated by 1.5mm obtained with the scanning THz confocal microscope at λ = 1 mm. a) Imaging at 0.3THz without the knife-edge. b) Imaging at 0.3THz with a blade in contact with the target. c) Intensity profiles along the Y axis show the increase of super-resolution. d) Profiles at different wavelengths.

The violation of the Rayleigh principle appears evident in the images and intensity profiles shown in Fig. 5, which conceptually demonstrates how knife-edge super-resolved imaging works. The knife-edge scan plane is in contact with the target at an angle of 45° with respect the object plane. Two parallel graphite stripes of 2 mm in width and separated by a distance of 1.5mm are imaged by the reflective THz-TDS set-up. The distance between the stripes lies well below the limit set by the Rayleigh criterion $\Delta x \sim 2.3$ *mm*.

IV. CONCLUSIONS

We report a super-resolved THz-TDS reflective set-up that is able to image structures below the Rayleigh resolution limit when a structured-illumination plane is put close to the object plane by distances on the order of one wavelength. The effect is attributed to an evanescent wave, and it is detected using a remote mechanical knife-edge scan technique in a confocal THz imaging system. The size of the focal spot depends on the wavelength, as specified by the Rayleigh criterion. In broadband set-ups such as THz-TDS, greater wavelengths produce larger spots. In order to get spectroscopic data from the same spot super-resolution is important. In this way, the focal spot of the longer wavelength will have a comparable size with those at shorter wavelengths, making easier the spectroscopic diagnostics of artworks. These findings have an immediate impact on the development of super-resolved THz imaging for documents and for THz imaging of buried structures, and also for super-resolution THz imaging in general in the cases of cultural heritage.