THz holography in reflection using a high resolution microbolometer array

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Abstract: We demonstrate a digital holographic setup for Terahertz imaging of surfaces in reflection. The set-up is based on a high-power continuous wave (CW) THz laser and a high-resolution (640 × 480 pixel) bolometer detector array. Wave propagation to non-parallel planes is used to reconstruct the object surface that is rotated relative to the detector plane. In addition we implement synthetic aperture methods for resolution enhancement and compare Fourier transform phase retrieval to phase stepping methods. A lateral resolution of 200 µm and a relative phase sensitivity of about 0.4 rad corresponding to a depth resolution of 6 µm are estimated from reconstructed images of two specially prepared test targets, respectively. We highlight the use of digital THz holography for surface profilometry as well as its potential for video-rate imaging.

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1. Introduction

The use of coherent THz radiation for imaging is becoming a powerful tool for material science and mechanical engineering. Over the past two decades research in Terahertz (THz) technology has shown potential for practical applications due to the ability of THz radiation to penetrate various non-conducting materials, that are opaque for visible light [1]. THz waves are of interest for imaging applications with a resolution similar to that of the human eye [2].

Of particular interest are holographic methods. Digital holography is well established at optical wavelengths [3, 4]. Although its implementation in the Terahertz region is methodically straightforward [5], the holographic recording and image reconstruction of many recent realizations suffer from either the low power of the Terahertz sources or the small detectors, which make data collection often a time consuming task. Ding et al. [6] report a lateral resolution of about 400 µm with a classical optics setup and a data collection time of about two hours for one image.

The simplest interferometric set-up is inline holography, where the sample is measured in transmission, for which a lateral resolution of 200 µm is reported [7]. Rong et al. [8] show a resolution of 120-240 µm and claim to observe traces of features as small as 35 µm. Wang et al. [9] report THz phase imaging using a Michelson interferometer for depth profiling with a lateral resolution down to 200 µm and depth standard deviation of 5-7 µm with an imaging speed of about 10 pixels per second.

In visible light, holographic imaging in reflection is used in digital holographic microscopy (DHM) [10]. The Twyman-Green-interferometer applied in reflection DHM is not ideal for THz applications. But the long wavelength of coherent THz radiation enables the use of off-axis reference beam illumination and off-centre object reflection. In a general reflection holography set-up the backward propagation from the detector plane must be made to a non-parallel object plane. This necessitates propagation of wave-fields between arbitrarily oriented planes for which Fourier transform methods have been developed [11, 12] and the procedure has been implemented for holographic problems [13, 14].

To overcome the limitations of digital holographic resolution due to the detector size the use of object rotation [15], several detectors [16] or the use of a single detector in different positions has been reported [17]. These synthetic aperture approaches cover a larger frequency spectrum
and thus improve resolution as is known from combining multiple off-axis holograms [18]. Although this approach seems straight-forward, care must be taken in the stitching process to obtain both a continuous intensity map and a continuous phase map [19]. Due to the long wavelength of THz radiation as compared to visible light, the phase problem is less severe, since the phase error due to an out of plane camera misalignment is two orders of magnitude smaller. In addition to the lateral resolution, the phase resolution is also an important issue in digital holography. Depending on the application the phase of the diffracted object wave contains information of the optical thickness of the sample in a transmission measurement or the depth resolution in surface profiling applications. In contrast to optical methods such as projection moiré THz reflection holography has the potential to be extended to samples hidden behind materials transparent to THz but opaque in the visual range such as polypropylene, teflon and other plastic materials. In a recent study on THz transmission holography we have experimentally verified that due to phase information a depth resolution well below the wavelength can be reached [20, 21].

In this paper we demonstrate camera based THz holography in reflection using reconstruction to a tilted plane. In the methodology section the basics for phase retrieval, image reconstruction and synthetic aperture are described. Experiments were carried out to explore two opposing aspects of potential applications: The first is the suitability for real time imaging. The use of a high power monochromatic source in combination with a high resolution area detector allows to circumvent the time consuming scanning method. The second is the improvement of the lateral resolution using a synthetic aperture method. In the last part the results are presented and all relevant aspects are discussed.

2. Methodology

2.1. Phase determination

After subtraction of the thermal background the interferometric signal recorded by the camera is

\[ I = I_{ref} + I_{obj} + 2\sqrt{I_{ref}I_{obj}}\cos(\phi_{ref} - \phi_{obj} + \delta\phi), \]  

where subscripts \( ref \) and \( obj \) refer to the THz reference beam and the object beam, respectively. \( \phi \) is the respective phase of the waves, while \( \delta\phi \) denotes a phase step controlled by mirror translation. In order to reconstruct the object, knowledge of the amplitude and the phase of the object wave is a prerequisite.

While its amplitude is readily available from the diffraction pattern (taking the square root of the intensity of the object wave measured without reference beam), the phase of the object wave is retrieved either using phase stepping algorithms (PSA) or applying the Fourier transform method (FTM) to the carrier frequency frames [22]. PSA retrieve the phase in every image pixel individually by using a set of images each with a varied optical path difference between the object and reference wave. FTM uses a single interference image with a carrier fringe induced by an off-axis reference beam and retrieves the phase from its Fourier transform. Phase resolution of the FTM is related to the number of pixels and the size of the filter around the satellite peak corresponding to the carrier frequency. Note that all phase images shown in this paper are relative to the phase image of a flat sample at the same position.

2.2. Image reconstruction

The reconstruction method is based on evaluating the Rayleigh-Sommerfeld diffraction integral by use of the fast Fourier transform with a special transformation to handle tilts and offsets of planes that was first described by Delen et. al. [11]. Our implementation bases on a more recent formulation for arbitrary rotations given by Matsushima [12]. The reconstructed complex field
at the object plane is obtained in two steps. First the field is backpropagated to a plane parallel to the detector plane at a distance $z_0$. In a second step the field is propagated to a plane tilted by an angle $\psi$ around the $y$-axis.

**Propagation to a parallel plane.** When a wave field $f(x,y,0)$ with wavelength $\lambda$ is given in a source plane, the field in a parallel plane $(x,y,z_0)$ with a positive offset $z_0$ is [12, 23]

$$f(x,y,z_0) = \mathcal{F}^{-1} \{ F(u,v)e^{2\pi i w(u,v)z_0} \}$$  \hspace{1cm} (2)

$$w(u,v) = \sqrt{\lambda^{-2} - u^2 - v^2}$$  \hspace{1cm} (3)

where $F(u,v) = \mathcal{F} \{ f(x,y) \}$ is the two-dimensional Fourier spectrum and $[u,v,w(u,v)]$ are the Fourier frequencies for $(x,y,z)$. Back propagation from a given diffraction field to a source field can be obtained by changing the sign of the exponent in Eq. (2).

**Propagation to a tilted plane.** A wave field is initially given in the plane $(x,y,0)$. Let us now use rotated coordinates $(\hat{x}, \hat{y}, \hat{z})$ in which a wave field is calculated by rotational transformation in the plane $(\hat{x},\hat{y},0)$. Both coordinate systems share the origin. Position vectors $\mathbf{r} = (x,y,z)$ and $\hat{\mathbf{r}} = (\hat{x},\hat{y},\hat{z})$ can be rotated by $\hat{\mathbf{r}} = \mathbf{R}\mathbf{r}$ using

$$\mathbf{R} = \begin{bmatrix} a_1 & a_4 & a_7 \\ a_2 & a_5 & a_8 \\ a_3 & a_6 & a_9 \end{bmatrix}, \quad \mathbf{R}^{-1} = \mathbf{R}^T = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix}$$  \hspace{1cm} (4)

The same rotation $\hat{\mathbf{f}} = \mathbf{R}\mathbf{f}$ can be applied to the Fourier frequencies $\mathbf{f} = (u,v,w)$ and $\hat{\mathbf{f}} = (\hat{u},\hat{v},\hat{w})$. Thus the Fourier coefficients $u$ and $v$ are related to the coefficients $\hat{u}$ and $\hat{v}$ by

$$u = a_1\hat{u} + a_2\hat{v} + a_3\hat{w}$$  \hspace{1cm} (5)

$$v = a_4\hat{u} + a_5\hat{v} + a_6\hat{w}$$  \hspace{1cm} (6)

Following the derivation in [12] we use their equations (14) - (16):

$$\hat{f}(\hat{x},\hat{y},0) = \int \int \hat{F}(\hat{u},\hat{v})e^{2\pi i (\hat{u}\hat{\hat{u}} + \hat{v}\hat{\hat{v}})} d\hat{u}d\hat{v} = \mathcal{F}^{-1} \{ \hat{F}(\hat{u},\hat{v}) \}$$  \hspace{1cm} (7)

where $\hat{F}(\hat{u},\hat{v})$ is

$$\hat{F}(\hat{u},\hat{v}) = F(a_1\hat{u} + a_2\hat{v} + a_3\hat{w}(\hat{u},\hat{v}), a_4\hat{u} + a_5\hat{v} + a_6\hat{w}(\hat{u},\hat{v}))|J(\hat{u},\hat{v})|$$  \hspace{1cm} (8)

$$J(\hat{u},\hat{v}) = (a_2a_6 - a_3a_5)\frac{\hat{u}}{\hat{w}(\hat{u},\hat{v})} + (a_3a_4 - a_1a_6)\frac{\hat{v}}{\hat{w}(\hat{u},\hat{v})} + (a_1a_5 - a_2a_4)$$  \hspace{1cm} (9)

Using a rotation by an angle $\psi$ around axis $y$ the rotation matrix $\mathbf{R}$ is

$$\mathbf{R}_y(\psi) = \begin{bmatrix} \cos \psi & 0 & -\sin \psi \\ 0 & 1 & 0 \\ \sin \psi & 0 & \cos \psi \end{bmatrix}$$  \hspace{1cm} (10)

The formulas Eq. (8) and Eq. (9) can be combined and simplify to

$$\hat{F}(\hat{u},\hat{v}) = F(\cos \psi \hat{u} + \sin \psi \hat{w}(\hat{u},\hat{v}), \hat{v}) \left| \cos \psi + \sin \psi \frac{\hat{u}}{\hat{w}(\hat{u},\hat{v})} \right|$$  \hspace{1cm} (11)

Since the complex amplitude for the spatial frequencies $(u,v)$ to be transformed are known only at a set of discrete points, interpolation is needed to find the complex amplitude $(\hat{u},\hat{v})$ at intermediate points. We used linear interpolation as proposed by Delen et al. [11].

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2.3. Synthetic aperture

To increase the lateral resolution the numerical aperture is increased using a synthetic aperture. Overlapping frames are collected in a hexagonal grid. A typical tiling is shown in Fig. 1(a). For every single frame amplitude and phase are determined separately using either phase stepping or the Fourier transform method. Starting with the central frame new frames are stitched one by one in order to synthetically increase the aperture. A typical example of two stitched frames is given in Fig. 1(c). To allow correct registration of the images the shift is determined using cross correlation. Furthermore an intensity scale and offset as well as an overall phase shift is determined from the overlap area of the new frame and the already accumulated image (rectangles in Fig. 1(b)).

Fig. 1. (a) Tiling of frames for synthetic aperture. Frame centers are shown with red circles and the sequence of stitching is marked with arrows. (b) Two single frames from different camera positions with overlap area marked. (c) Stitched frames of (b), for a final stitched image see also Fig. 3, top left.

3. Experimental

We use a Far Infrared laser FIRL100 (Edinburgh Instruments) capable of producing monochromatic lines in the range of $60 - 500 \, \mu m$ with a CW power of up to 150 mW. We work with one of the strongest available lines at 118.8 $\mu m$ (corresponding to 2.52 THz) of methanol (CH$_3$O).

The detector is an uncooled vanadium oxide micro-bolometer array (DelMar Photonics, San Diego, USA) with $640 \times 480$ pixels on a pitch of 25 $\mu m$. Images are recorded through a CameraLink interface with a frame rate of up to 16 frames/s.

The off-axis digital holography set-up is described in Fig. 2. A beam splitter at the exit of the laser reflects about 10% of the beam to monitor the laser intensity with a pyrometer. With the use of two off-axis parabolic mirrors the beam from the FIR-laser with a diameter of about 10 mm is slightly expanded in order to assure a good illumination of the sample as well as the reference mirror. A shutter at the focal point between the parabolic mirrors allows fast laser on-off measurements. The reference mirror can be moved along the $z$-axis in small steps for phase stepping measurements or moved out of the beam for measurements without reference beam. The camera is moved along the $x$- as well as the $y$-axis for synthetic aperture operation. The sample is positioned at an angle of about 45° with respect to the laser beam in order to capture the direct reflected intensity by the camera. The angle of the reference beam with respect to the detector plane was around 50°. For the Fourier transform method a large angle is essential to separate the carrier peak in the Fourier plane from the zero order peak. Note that with a THz wavelength of 118 $\mu m$ and a 25 $\mu m$ detector pitch the interference fringes can be resolved at very large angles without risk of undersampling.
Three different samples were measured in order to test the performance and resolution of the THz reflection holography set-up.

1. A Siemens star with an outer diameter of 12 mm was used to determine the spatial resolution. The sample was fabricated from a metal sheet of 100 μm thickness using laser ablation.

2. To determine the phase resolution a stainless steel disk of 13.9 mm diameter with seven hollows of 4 mm diameter and depths in the range of 15 – 350 μm was used. The hollows were again structured using laser ablation.

3. A Swiss five cent piece with a diameter of 17.15 mm was used to demonstrate surface profiling.

The first two samples were specifically designed to assess the lateral and depth resolution, respectively. The use of a Siemens star for lateral resolution simplifies a comparison with other published work, while the use of structures with known depths allows for quantitative comparisons with the real structure dimensions. The third sample was chosen to demonstrate the suitability of the method for profilometry.

Projection moiré [24] with two sensitivities was applied for an independent absolute measurement of the surface profiles. A chrome-on-glass grating with 20 line pairs per millimetre was used in the moiré projector and moiré viewer (MP-1000, Newport Corp, Fountain Valley, USA) together with a pair of Micro-Nikkor 60 mm f/2.8 lenses (Nikon Corp., Tokyo, JP). A triangulation angle of 30° was used. A PSA with 5 frames was used to obtain the phase images of the surface profiles. The set-up was calibrated by translating a reference plane, resulting in a sensitivity of 50.6 rad/mm (or 124 μm per moiré fringe) and 16.7 rad/mm (376 μm per moiré fringe) in the object centre, respectively.

4. Results and discussion

4.1. Lateral resolution

Reconstruction results for sample 1 are shown in Fig. 3. The hologram was compiled using 19 overlapping frames leading to a fused image of up to 1120 vertical and 960 horizontal pixels.
The phase information at the hologram plane was determined with phase shifting (PSA) or Fourier transforms method (FTM). Note, that in the central part where the hologram has the highest intensity variation the phase varies relatively slowly, whereas in the outer part where the intensities fall off the phase varies in a circular structure, which originates from the diffraction at the circular border of the sample.

In order to test the dependency of the resolution on the numerical aperture, reconstructions were performed using different masks applied to the holographic data. The size of the masks and the obtained resolutions for PSA and FTM are shown in Table 1.

| Mask          | NA (µm) | PSA (µm) | FTM (µm) |
|---------------|---------|----------|----------|
| 480 circular  | 0.28    | 400      | 385      |
| 640 × 480     | 0.35    | 305      | 325      |
| 640 circular  | 0.36    | 305      | 325      |
| 800 circular  | 0.44    | 240      | 255      |
| 960 circular  | 0.51    | 200      | 245      |
| All data      | 0.57    | 190      | 240      |

Table 1. Lateral resolution as a function of the effective Numerical Aperture (NA) for experimental data (PSA and FTM).

The lateral resolution of the reconstructed object is estimated from the Modulation Transfer Function around concentric circles with decreasing diameter intersecting the spokes of the Siemens star [25]. The 10% modulation level was used to define resolution. For the full data set using PSA a resolution better than 200 µm was obtained. From the experimental setup a distance of about 20 mm from the sample center to the detector plane can be estimated. An effective reconstruction distance of 20.5 mm was determined to yield the highest resolution.

For the full data set and non circular masks an effective Numerical Aperture (NA) was calculated corresponding to the radius of a circle with the equivalent number of pixels. The results were compared to simulations of an ideal sample using forward propagation to the detector plane for a 0° and a 45° geometry (see Fig. 4). For the simulations it was assumed, that the
Fig. 4. Lateral resolution as a function of the effective Numerical Aperture (NA) for simulations (0° and 45° geometry) and experimental data (PSA and FTM).

phase at the detector plane is known, thus ignoring effects of the phase retrieval method. It is interesting to compare the 45° geometry with the 0° geometry, which from a resolution aspect is more favorable, but experimentally difficult to realize. The simulation results show that the expected resolution of a sample tilted by 45° is only about 15% worse than for a 0° geometry. The simulations have the same qualitative behavior as reported earlier [21] and show nicely the inverse relationship of numerical aperture and resolution. The experimental resolutions obtained using the phase shifting method follow the same trend. Thus for PSA the numerical aperture seems to be a limiting factor for the resolution. For the FTM the resolution levels off for NA > 0.5, indicating that the Fourier masking process rather than the NA limits the lateral resolution.

For potential measurements at video rate neither a synthetic aperture method nor phase shifting are suitable. Therefore we also reconstructed the object using only one frame (640 × 480 pixel) and the Fourier transform method (see Fig. 3, right images). In this case the resolution drops to about 325 µm (see Table 1), still enough for many applications. To extract the object wave amplitude we used two images, one with and one without reference beam. Note that the image without reference beam could also be replaced by an image without sample for computation of the intensity. Such a reference image needs only to be measured once, and further frames can be recorded at video speed (16 frames/s). Even when using phase shifting and synthetic aperture the data collection time is much shorter than with scanning methods which use typically 2 hours [6]. With 20 camera positions for synthetic aperture and five phase shift exposures total data collection can be accomplished within a few minutes, provided that camera positioning and mirror shift are fully automated.

4.2. Depth resolution

The holographic reconstruction results for sample 2 are shown in the bottom row of Fig. 5. The hologram was obtained from 23 frames leading to a stitched image of up to 1120 vertical and 1080 horizontal pixels. For the phase determination we have used synthetic aperture and phase stepping. Using the phase information the depth of the hollows was determined and compared to optical measurements. Phase difference values were estimated from averaging the phases in three concentric rings, one in the center, one at the deepest position and one surrounding the hollow. From these phase difference values a relative phase sensitivity of 0.4 rad corresponding
Fig. 5. Sample 2: Comparison of THz and projection moiré topography. Photo (top left), moiré phase image (top middle), moiré profile (top right), THz intensity (bottom left), THz phase (bottom middle), THz profile (bottom right), scale for profile images (far right). The numbers on the photo identify the hollows for depth measurements.

to a depth resolution of 6 \( \mu \text{m} \) could be estimated. With a THz wavelength of 118.8 \( \mu \text{m} \) and a 45\(^{\circ}\) geometry a \( 2\pi \) phase shift corresponds to a depth of 84 \( \mu \text{m} \). Note that for conversion of phase differences to depth values prior knowledge of the approximate depth was used for the phase unwrapping. Measurements using dual wavelengths [26] could resolve phase ambiguity. Table 2 compares these values with the depths obtained from optical measurements and phase-stepping projection moiré.

Table 2. Depth determination of sample 2 compared with optical measurement. Numbers in parentheses are estimated standard deviation in units of the last digit. For hollow numbering see Fig. 5.

| hollow nr | optical \( \mu \text{m} \) | moiré \( \mu \text{m} \) | THz holography \( \mu \text{m} \) |
|-----------|----------------|----------------|----------------|
| 1         | 17(1)          | 18(3)          | 14(2)          |
| 2         | 34(1)          | 38(3)          | 32(5)          |
| 3         | 51(1)          | 52(3)          | 47(4)          |
| 4         | 84(2)          | 89(3)          | 78(6)          |
| 5         | 134(2)         | 137(3)         | 125(6)         |
| 6         | 216(2)         | 227(4)         | 207(4)         |
| 7         | 354(2)         | 369(5)         | 339(5)         |

Table 2. Depth determination of sample 2 compared with optical measurement. Numbers in parentheses are estimated standard deviation in units of the last digit. For hollow numbering see Fig. 5.

First, a microscope was focused on the top and bottom surface of each hollow, and its depth was obtained from the difference of the z-stage readings. Second, projection moiré was used to obtain the profile of the plate. Both phase based measurements show a quite good agreement with the microscopic depth determination. Differences in the depth measurements are shown in Fig. 6. There is a systematic deviation in the order of 5%. In the moiré case the depth values are
too high probably due to the limitation of the calibration. For the THz measurement a deviation from the assumed 45° reflection angle may have caused a systematic error. Furthermore the estimated depths may be too small due to the restricted lateral resolution which leads to an underestimation of the depths.

4.3. Application to surface profilometry

The reconstruction results for the coin (sample 3) are shown in the bottom row of Fig. 7. The hologram was constructed using 30 frames with nominal frame offsets of 4 mm horizontally and 2 mm vertically, leading to a fused image of up to 1120 vertical and 1280 horizontal pixels. For the phase determination we have used synthetic aperture and phase stepping. The result is again compared to the profile obtained by projection moiré.

Note that the appearance of the reconstructed THz intensity image is very similar to that of the photograph which was taken under similar illumination conditions. The embossed letters and numbers in the intensity image are mostly readable. Only letters which where farthest away from the detector are illegible. This trend is consistent with the fact that resolution depends on the reconstruction distance. There is potential to increase the lateral resolution if synthetic aperture is increased by collecting more frames, or if the sample can be placed closer to the detector which however would require a different camera.

The profiles obtained by the two methods (see Fig. 7 right) are very similar. The THz-profile cannot resolve features as small as the letters, however the head is reproduced very well. Even if resolution does not fully reach that of the optical method, note that the potential of the method lies in the fact that THz reflection holography can be extended to samples hidden behind materials transparent to THz but opaque in the visual range.

5. Conclusion

We have implemented a reflective digital holography set-up for high-resolution THz imaging of amplitude and phase objects. With the current setup we reached a lateral resolution of 200 µm and a relative phase sensitivity of about 0.4 rad corresponding to a depth resolution of 6 µm. It was shown that the depth resolution of the profiles is comparable to classical profilometry using projection moiré. Both the reconstruction from synthetic aperture measurements using phase shifting as well as from a single frame hologram using the Fourier transform method
have been demonstrated. On one hand the synthetic aperture approach has a potential to push the resolution limits even further. On the other hand with the use of the Fourier transform method the way is opened to true real-time, viz. video-rate THz imaging. Overall this new level of image quality for the intensity as well as the phase images for short acquisition times opens new opportunities towards applications in material characterization and dynamic nondestructive testing.

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