Surface profile measurement by terahertz interferometric phase imaging

Yingxin Wang¹,², Ziran Zhao³, Zhiqiang Chen³, Li Zhang² and Jingkang Deng¹

¹ Department of Physics, Tsinghua University, Beijing, 100084, China
² Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Department of Engineering Physics, Tsinghua University, Beijing, 100084, China

E-mail: wangyingxin2000@tsinghua.org.cn

Abstract. We demonstrate an interferometric phase imaging technique by using a continuous-wave terahertz system with a far-infrared gas laser as the radiation source. A terahertz Michelson interferometer is constructed based on a reflection imaging system. By analyzing the measured fringe patterns, the phase distribution information can be obtained and then used to reconstruct the profile of the object surface under test. We also show that, for imaging a nearly transparent object with terahertz radiation, our technique can provide a high contrast image which would be quite valuable for accurate identification of the examined object.

1. Introduction

Non-contact and non-destructive characterization of the surface topography of an object plays an important role in a wide range of fields, such as industrial inspection, quality control, optical component testing and biomedical engineering. One common means to achieve this task involves determining the wavefront distortion of an illumination light beam induced by the surface under test. In visible and infrared regions, many interferometric techniques have been developed to detect the spatial phase variation of the optical beam and have been widely used for surface profile measurement, including holographic [1], moiré [2], speckle [3], and fringe projection [4] interferometry. However, these optical techniques encounter problems for the surface with roughness on the order of the wavelength or more. Due to the longer wavelength of terahertz radiation, it is insensitive to this roughness. Also terahertz radiation can penetrate most non-metallic and non-polar materials, which enables the surface of a concealed object to be measured. Consequently, sensing with terahertz waves can serve as a complementary tool to conventional optical techniques for surface profilometry.

At terahertz frequencies, phase-shift interferometry for few-cycle optical pulses has been demonstrated to enhance the depth resolution dramatically in tomographic measurements [5]. Recently, continuous-wave (CW) terahertz heterodyne profilometry [6] and fiber-endoscopy [7] based on interferometric imaging systems have been reported to reconstruct the object surface profile. Using CW terahertz interferometer, noncontact sensing vibrations of macroscopic objects behind optically opaque barriers is also possible [8]. These investigations indicate that terahertz interferometric imaging has a variety of valuable applications. But the above-mentioned CW systems worked in the submillimeter region (below 1 THz). This limits the lateral spatial resolution of imaging. In this report, we present a terahertz interferometric phase imaging (TIPI) technique that can be used to determine
the object surface profile as well as image a weak absorption or nearly transparent object. The phase measurement is performed by a Michelson interferometer that is constructed from a CW reflection imaging system employing a far-infrared gas laser as the source of 2.52-THz radiation. We show that TIPI could reveal the surface profile with a high sensitivity and give a good contrast for the weak absorption object compared with the conventional terahertz absorption imaging so as to obtain its true material distribution.

2. Experimental setup

The schematic diagram of the TIPI experimental system is shown in figure 1(a). The interferometer operates in a Michelson configuration for reflection imaging. An optically-pumped far-infrared laser (FIRL 100, Edinburgh Instruments Ltd., UK) is employed for terahertz generation. Its output power can reach approximately 150 mW at 2.52 THz (corresponding to a wavelength of $\lambda=118.8$ µm). To address the problem of beam divergence, the terahertz beam is first focused by a gold-coated off-axis parabolic mirror and then collimated by a high-density polyethylene lens. After a beam splitter (a high resistivity silicon wafer), one part of the terahertz radiation is incident on a flat mirror M1 mounted on a linear translation stage, serving as the reference beam. Another part is guided to the sample under test at normal incidence by a focusing element. The reference beam and the object beam are recombined to produce interference and the interference signal is recorded via a Golay cell detector. The optical path difference (OPD) between these two beams is adjusted by translating the flat mirror in the reference arm. In order to obtain the two-dimensional surface profile of the sample, it is located at the focus of the object beam and raster scanned in a plane perpendicular to the beam axis. For measuring transparent object, an additional flat mirror M2 is placed behind the object to retroreflect the transmitted terahertz radiation. An optical chopper and a lock-in amplifier are used to improve the signal-to-noise ratio (SNR) of the system. Meanwhile, the chopper creates a modulated radiation input (with a frequency of 25 Hz) for the Golay cell. In addition, an attenuator set with four transmission levels (30%, 10%, 3%, and 1%) is inserted into the beam path to avoid saturation of the detector.

![Figure 1. (a) Schematic diagram of the TIPI system. C, chopper; A, attenuator; PM, parabolic mirror; L, lens; BS, beam splitter; M, mirror. (b) Measurement of the interference intensity variation with respect to the OPD (square points) and the corresponding cosine fit curve (solid line).](image)

By blocking the terahertz radiation in the reference and sample arm, respectively, we evaluated the light intensity ratio of the reference and sample beam. It was measured to be 1.24, close to unity, which satisfies the basic requirement that the interferometer has a high fringe contrast (i.e., high...
sensitivity). Figure 1(b) displays the measurement result of the interference intensity variation with respect to the OPD of the two beams. The measurement was performed by scanning the reference mirror M1 with a step size of 5 µm (corresponding to an OPD of 10 µm). Fitting the raw data points to a cosine function will yield an estimate of the wavelength of the CW terahertz radiation. It was obtained to be 127.5 µm, having a relative error of 7.3% compared to the theoretical value (118.8 µm). This slight inconsistency may arise from the position error of M1 and misalignment of the optical elements. The fringe contrast was calculated to be about 40%, which is sufficient for further analysis. Consequently, performance evaluation for the interferometer demonstrates the successful construction of our TIPi system.

3. Results and discussion

We select a plastic sample and a reflective metal surface as the test objects to illustrate how to image the weak absorption material as well as reconstruct the surface profile by using the TIPi technique. The weak absorption sample is a plastic sheet cut into the shape of character “T” [see region A in Figure 2(a)] and has a generally uniform thickness of 0.6 mm. The sample was held in a rectangular aperture [not shown in Figure 2(a) except for one boundary marked with C] by a layer of adhesive tape and then mounted on a metal plate (region B). In the imaging experiment, we first blocked the reference beam and performed the conventional terahertz reflection imaging for the sample. The time constant of the lock-in amplifier was set to be 30 ms. The sample was raster scanned over an area of 37×45 mm² with a step size of 0.5 mm and a speed of approximately 10 pixels per second. Mirror M2 was fixed during the scan. Figure 2(a) shows the resulting terahertz image of the plastic sample and the metal plate. We can see that only the shape of the plastic sample is visible owing to the scattering effect occurring at the sample edge. Because of the high transmittance of plastic to terahertz radiation, no obvious intensity difference emerges between the sample region and the background region. Thus obtaining the true material distribution information for transparent object is impossible through such common absorption imaging. In other words, one could not distinguish which region in the image is plastic. Since the metal plate is covered with a layer of adhesive, it exhibits nonuniform gray level. The weak signal intensity around the aperture boundary originates from the strong attenuation of the sample holder.

Figure 2. (a) Conventional terahertz reflection imaging result. A represents a plastic sheet; B represents a metal plate; C represents the edge of the sample holder. (b) Terahertz interferometric imaging result. The red line indicates the data adopted for surface profile reconstruction.
With the reference beam block removed, we acquired an interferometric image, as shown in Figure 2(b). The scanning parameters were the same as above. It is clear that fringe patterns appear both in the plastic sheet and the metal plate region. Note that if the plastic sheet has an absolutely uniform thickness, it will exhibit an almost constant difference in intensity compared with the background signal, which could help recognize the sample distribution. This difference is determined by the phase shift $\Delta \varphi$ of terahertz radiation induced by the sample and becomes more notable when $\Delta \varphi$ approaches $\pi$, considering the $2\pi$ ambiguity of $\Delta \varphi$. Assuming the refractive index and thickness of the sample are $n$ and $d$, respectively, the phase shift can be expressed as $\Delta \varphi = 4\pi(n-1)d/\lambda$. We substitute the measured values, $n = 1.5$, and $d = 0.6 \text{ mm}$, into the above relation and get $\Delta \varphi \approx 10\pi$. However, the existence of fringes shows that the plastic sheet has a varied thickness. In another aspect, reflections from the sample interfaces may also lead to such interference fringes [9]. It is difficult to separate these two contributions accurately. Anyway, compared with the conventional terahertz imaging, interferometric imaging for weak absorption materials can provide an image with a high contrast, from which we can obtain the information about the exact material distribution.

The fringe patterns in the metal plate region are generated from inclination of the plate plane, i.e., not perpendicular to the incident beam. The degree of inclination or, equivalently, the surface profile can be evaluated by demodulating this fringe pattern. We used the Fourier transform technique [10] for this purpose. The data along a horizontal line [as indicated by the red line in Figure 2(b)] were extracted for analysis. Figure 3(a) plots the signal amplitude variation along this line. After a filtering procedure in the spatial frequency domain, the phase distribution was calculated, as shown in Figure 3(b). Finally, the object surface profile could be formed with a phase unwrapping algorithm, as shown in Figure 3(c). Owing to the low SNR of the system, the measured profile looks less smooth. From this reconstruction result, we know that the plate surface has a maximum height of about one wavelength in the observation direction. In other words, the inclination angle of the metal plate along this direction is only about $3.2 \times 10^{-3}$ rad.

![Figure 3.](image)

**Figure 3.** (a) Signal amplitude variation of the fringe pattern in the metal plate region along a horizontal direction indicated by the red line in Figure 2(b). (b) Phase distribution obtained by the Fourier transform method. (c) Reconstructed surface profile along the observation line.

### 4. Conclusion

In conclusion, we have presented an interferometric phase imaging technique at terahertz frequencies. An interferometric imaging setup based on a CW terahertz system has been constructed successfully. Experimental results show that our method can not only produce an image with a higher contrast for transparent objects compared to that acquired from the conventional absorption imaging, but also provide the surface profile information of the sample. Therefore, our method has a promising application potential in the fields of industrial inspection, quality control, etc.
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