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Continuous-wave off-axis and in-line terahertz digital holography with phase unwrapping and phase autofocusing

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ABSTRACT

Continuous-wave terahertz digital holography is a practical tool to obtain the complete wave-front information of a sample in the terahertz region that has offered unique advantages in various fields. The propagation distance plays a decisive role in the numerical reconstruction of both in-line and off-axis digital holograms. Only when a terahertz hologram is propagated back to a focal object plane can the authentic amplitude and phase distribution be reconstructed, which is actually a troublesome task. In this manuscript, the combination of hologram enhancement, spectrum filtering, phase retrieval and phase unwrapping algorithms is illustrated and organized to benefit the decision-making process of the autofocusing method not only for the amplitude distribution but also for the phase image. To guarantee the accuracy of the autofocusing results, the noise of the hologram, the intrinsic twin image in the amplitude and phase results and the wrapped ambiguity in the phase distribution are suppressed or lessened by using the four techniques stated above. The focused amplitude and unwrapped phase distributions of the sample are reconstructed, and experimental verification confirms that the present hybrid autofocusing method is a feasible, effective and promising technology with broad application prospects.

1. Introduction

The terahertz imaging method based on terahertz sources whose frequency ranges from approximately 0.1 THz to 10 THz has broad applications in the field of biomedical observation, non-destructive testing and security monitoring. This novel detection technique can fully exploit the characteristics of terahertz radiation, like its ability to penetrate through non-metal and non-polar materials, similar to microwave and X-rays only without their adverse effects [1,2]. In addition, the original benefits of conventional imaging approaches, such as high-resolution imaging and phase-contrast imaging, can be integrated. The current typical terahertz imaging methods are terahertz tomography which can obtain the inner tomographic slices [3,4], terahertz near-field probe imaging in which the sub-wavelength resolution can be achieved [5], terahertz point scanning imaging with a stable process [6], and terahertz focal plane amplitude imaging [7]. These methods along with the diversity of imaging systems have their own strengths and weaknesses, thus they can be utilized to support various specific applications. Terahertz phase-contrast imaging approaches are promising because the phase information of an object in the terahertz frequency range is as significant as its amplitude distribution.

Terahertz digital holography (TDH) is derived from traditional digital holography in visible light, infrared, electron wave, and other wavebands [8–13]. As an advanced terahertz imaging method, it can offer the amplitude and phase-contrast results simultaneously by using different types of terahertz sources, such as a continuous-wave source or a pulsed-wave source. TDH is a full-field and lens-less imaging approach without an extra point-scanning mode included in the system; thus, real-time detection based on a simple experimental setup can be conducted. Moreover, this technique can suppress the inherent drawbacks of terahertz imaging as, for example, it can reduce the propagation attenuation of the terahertz wave and improve the theoretical resolution as much as possible.

The first terahertz hologram was recorded by Mahon's group in 2006 who carried out millimeter-wave Fresnel off-axis digital holographic experiments based on a 100 GHz Gunn diode oscillator [14]. After that, progress in TDH with different instruments, configurations and applications was gradually reported. The early experimental results were

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obtained with time-consuming equipment and simple data processing. Tamminen et al. [15] studied the terahertz indirect holographic imaging technique at 310 GHz and resolved the details of an aluminum target down to 2 mm. Heimbeck et al. [16] reconstructed the amplitude and phase objects by using the dual wavelength method to achieve the phase unwrapping and developed this technology to provide sub-millimeter resolution images of voids within visually opaque three-dimensional printed structures. With the development of terahertz devices and the related imaging components, more and more imaging schemes and optimization algorithms for TDH were explored. Hu et al. [17] studied continuous-wave terahertz digital holography based on a pyroelectric array detector and successfully applied various improved methods to the data analysis. The terahertz quantum cascade laser (QCL) as a source for a wide variety of imaging applications was employed by Hack et al. [18], to perform digital holographic measurements using an off-axis recording setup to detect hidden objects with multi-beam interferences [19]. Also, working with a terahertz QCL, Locatelli et al. [20] demonstrated for the first time real-time terahertz digital holographic imaging for reflection-type and transmission-type samples in a one-shot exposure. Around the same period, Rong et al. [21,22] focused on the continuous-wave in-line TDH in which the source is an optically pumped laser, and Huang et al. [23–26] studied the same scheme with a terahertz QCL. The reconstructed resolution and quality of the experimental results were improved via innovations in both the hardware and software, and the proposed method was applied to biomedical observation for the first time. Besides using continuous-wave sources, some researchers also considered pulsed-wave TDH. For example, Petrov et al. [27] experimentally demonstrated the ability of terahertz pulsed-wave time-domain holography for phase imaging and reconstructed the relief features of an object [28]. Zhang et al. utilized a pulsed-wave terahertz digital holographic imaging system to investigate the natural dehydration processes in three types of biological tissues [29].

The data processing algorithm used in TDH has extensive applications in both industry and scientific research due to its convenience, reliability and low cost. The algorithm also plays a vital role in TDH, making it adjustable and flexible, especially in the numerical reconstruction procedure. The propagated distance in the digital reconstruction of digital holography is a key parameter necessary to guarantee the reconstruction of a sample's complex amplitude distributions in the focal plane. A sharp image can be obtained when the reconstructed distance is equal to the actual space between the sample and detector. However, the precise value is difficult to measure in some circumstances. Usually, the in-focus reconstructed complex amplitude distributions are searched and estimated according to observations made with the naked eye and subjective intervention. The autofocusing method is an effective and simple tool to solve this issue without any additional hardware. It can provide a quantitative evaluation curve to determine the parameters of a focal position using one hologram. Many new critical functions have been invented in the past decade, and their relevant applications have also been reported, such as tracking label-free live cells [30].

In this manuscript, the autofocusing method is applied to off-axis and in-line terahertz digital holographic imaging processes in which a frequency spectrum filtering method and phase retrieval algorithm are utilized to avoid the inaccuracies inherent in the judgment. More importantly, the autofocusing critical functions offer the calculated data and curves not only for the amplitude images but also for the phase distributions. It is noted that the wrapped phase ambiguity leads to failure in locating the focal plane due to the influence of the background noise and the twin image. In response to this problem, the autofocusing results of the original phase and the unwrapped phase distributions are displayed separately, and the phase unwrapping algorithms which prove to be effective in the reconstruction of information are discussed. Finally, after completing the data acquisition and data processing, the focused amplitude and phase distributions of the sample are reconstructed.

The manuscript is arranged as follows: Section 2 describes the experimental setup and samples, and Section 3 discusses the details of all the methods used in this study. The results and conclusion are presented in Sections 4 and 5, respectively.

2. Experimental setup and samples

Due to the long wavelength and lossy nature of the terahertz wave, a complex system with too many optical elements should be avoided. Consequently, a triangular simplified off-axis scheme and Gabor in-line scheme for continuous-wave TDH without a visible guiding light device have been designed. Schematic diagrams of the off-axis and in-line schemes are shown in Fig. 1(a) and (b), respectively.

In both of these systems, the core experimental unit was a commercial terahertz laser, model FIRL100 from Edinburgh Instruments Limited. The source was an integrated CO_2 and far infrared laser system which could generate a monochromatic terahertz beam with different wavelengths by changing the gas. In the proposed work, for the generation of a high and stable output power up to ~100 mW, methanol was used to produce a continuous wave with a frequency of 2.52 THz corresponding to a wavelength of 118.8 μm. A couple of gold-coated off-axis parabolic mirrors were added to the system with the ratio of their effective focal lengths equal to 1:2. They were placed separately at a distance of 228.6 mm to expand the diameter of the terahertz beam and improve the quality of the beam profile; thus, the size of the illuminated beam covered the whole target.

In the off-axis scheme, a high-resistivity float zone silicon (HRFZ-Si) plano-plano wafer was utilized as a single-pass beam splitter which provided a transmittance/reflectance ratio of 54/46. The specifications of the wafer were 150 mm in diameter and 3.5 mm in thickness. After that, the resized beam was divided into two parts: the transmitted part reached a sample to form the object wave and the reflected part arrived at a gold-coated reflecting mirror. The diameter of the reflecting mirror was 50 mm, and its position was adjusted to change the angle of the reflecting beam to make it overlap with the object wave in the detection plane.

In the in-line scheme, the resized and collimated terahertz wave reached a sample directly and the transmitted wave was regarded as the reference wave. Then the pyroelectric array detector (Pyrocam III and IV, Ophir-Spiricon, Inc.) connected to a computer was used to record and transfer the signal of the terahertz hologram. The captured hologram had 124 pixels in the horizontal and vertical directions with pixel pitches of 100 μm (Pyrocam III), which were equal to the physical parameters of the detector (Pyrocam IV: 320 pixels and 80 μm). Two types of samples were used in the experiments, shown in Fig. 2. The transmission-type sample was an artificial metal square plate with the hollowed-out shape of a capitalized letter "T" with a line width of 1.5 mm. The terahertz wave could only penetrate the hollow part containing air, so this sample was available for the off-axis scheme. The absorption type sample was a branch of a natural asparagus fern which had a complicated appearance. It was suitable for both the off-axis and in-line layouts because the plant parts which contained moisture could absorb the terahertz waves and the remaining parts had a high transparency ratio.

3. Methods

In the study, a total of five algorithms were used in the data processing, all of which are introduced in this section. The reconstructed flow charts of the off-axis and in-line holograms are depicted in Fig. 3. First of all, the signal-to-noise ratio and quality of the terahertz holograms were improved by using the accumulation enhancement pre-process. In addition, the common frequency spectrum filtering method was applied to the off-axis hologram, and the phase retrieval method with the constraint conditions was used for the in-line hologram. Then the amplitude and unwrapped phase distribution were reconstructed in dozens of sequential planes by using the propagation algorithm. All of the images were calculated by the autofocusing critical functions and the best propagation distance could then be determined. Eventually, the results were accurately reconstructed in the focal plane. The procedure and principle for each algorithm are detailed below.