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Application of autofocusing methods in continuous-wave terahertz in-line digital holography

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ABSTRACT

Terahertz digital holography is a combination of terahertz imaging and digital holography. During reconstruction, the key point is to find accurately the propagation distance from which the distribution of focused samples can be reconstructed. In this paper, we use a continuous-wave terahertz in-line digital holographic imaging system to record holograms. Moreover, the autofocusing algorithms through which the reconstructed distance can be calculated are applied to the reconstruction. The in-line schematic is beneficial to the terahertz wave imaging, which, however, inevitably produces the object's twin image. In the refocusing process, both the reconstructed image with low signal-to-noise ratio and contrast and the twin image induce the formation of false peaks corresponding to improper distances on the autofocusing curves. To restrain the disturbance factors and improve the accuracy of the judgment, a phase retrieval method is implemented in the reconstruction. The results demonstrate the feasibility of the autofocusing method with phase retrieval in terahertz in-line digital holographic imaging system. The proposed method provides an automated and efficient evaluation which helps to obtain the optimized propagation distance.

1. Introduction

Due to its characteristic of penetration in non-conducting material and non-contact with the samples, terahertz (THz) imaging, with its potential benefits, is an advanced technique that can be applied in various fields such as non-destructive component analysis, the pharmaceutical industry, photovoltaic material inspection, historic object detection, and observation of the internal structure of artworks [1–3]. The image aquired by terahertz digital holography is a combination of terahertz imaging and digital holography which can reconstruct the quantitative distribution of amplitude and phase of the sample. Compared with the detectors which obtain phase and amplitude simultaneously, terahertz digital holography is a full-field phase-contrast method without scanning. In the past decade, many researchers have explored and demonstrated the imaging technology of terahertz digital holography with different schematics like millimeter-wave Fresnel off-axis digital holography [4], pulsed terahertz digital holography [5], tunable terahertz source holographic imaging [6], continuous-wave terahertz digital holography based on thermal sensors [7–15] including Gabor in-line digital holography [7–12], phase retrieval for terahertz digital holography [9], biological specimen detection [10–12], and reconstruction research on terahertz off-axis digital holography [12–15].

Compared with other modalities, in-line digital holography has many merits such as compactness and better utilization of the detector's spatial bandwidth [16]. These advantages make it suitable for terahertz holographic imaging. In the reconstruction, the propagation distance is a key parameter which indicates the in-focus plane where the information of samples can be reconstructed accurately. In terahertz digital holographic imaging, the chip is placed inside the detector for recording an image, which leads to problems in accurately measuring the recording distance between sample and chip. Especially in the biological detection field, it is particularly difficult to acquire precise values

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from observations because living specimens can change position. Additionally, the reconstructed image needs to be artificially estimated in the reconstruction process and the reconstructed distance is approximated. Hence, the previous methods lack precision and are influenced by the environmental conditions. A digital holographic autofocusing algorithm makes it possible to make an automated evaluation without any mechanical components. And an in-focus plane can be obtained via searching for the optimized distance based on the intensity gradient, amplitude analysis, spectral norms and some other criterions [17–20]. Nevertheless, the autofocusing method has not been utilized in terahertz in-line digital holography experiments due to the low signal-to-noise ratio of the reconstructed image and the disturbance of twin image in the reconstruction.

In this paper, we use a continuous-wave terahertz in-line digital holographic imaging system to record holograms and introduce the autofocusing algorithms with the phase retrieval method to reconstruct the object's focused distribution. The existence of noise and a twin image in the reconstruction causes false peaks on the autofocusing curve corresponding to the defocused distances. In order to increase the veracity and accuracy of the method, a pre-experimental analysis such as the phase retrieval algorithm is applied to eliminate the twin image, and then the autofocusing method is used to obtain the accurate propagated distance in order to reconstruct the focused information of the object [21–25].

2. Recording principle

In continuous-wave terahertz in-line digital holography, the object beam and reference beam propagate from the object plane ($z=0$) and interference on the recording plane ($z=d$, where d is the propagation distance), as shown in Fig. 1.

The complex amplitude distribution $U_d(x, y)$ at the recording plane can be expressed as

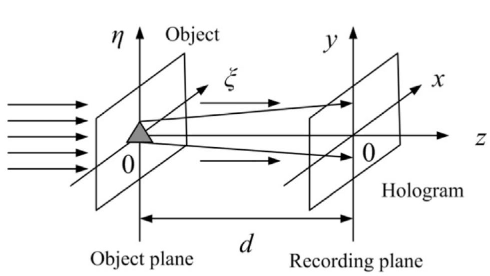

Fig. 1. Schematic of the recording process of in-line digital holography.

$$U_d(x, y) = \exp(jkd) + \mathrm{FT}^{-1}\left\{\mathrm{FT}[1 + O(\xi, \eta)] \exp\left[jkd\sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2}\right]\right\}, \quad (1)$$

where (x, y) and (ξ, η) denote the coordinates of the recording plane and the object plane respectively, FT and FT^{-1} represent Fourier and inverse Fourier transform, j is used as the root of (-1) and $O(\xi, \eta)$ is the complex function of the object wave in the object plane, in which $f_x = x/(N_x\Delta x)$ and $f_y = y/(N_y\Delta y)$ are the object frequencies, N_x and N_y are the numbers of pixels along the x and y directions, and Δx and Δy are the horizontal and vertical pixel pitches at the recording plane.

3. Reconstruction: autofocusing method and phase retrieval

To determine the focused propagated distance, four typical derivatives-based autofocusing criteria functions depending on the sharpness analysis are applied to the continuous-wave terahertz in-line digital holographic imaging. They are, respectively, the Tenenbaum gradient criterion function (TEG) [26,27], of which the evaluation function is

$$F_{TEG} = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}\{[2I(m, n+1) - 2I(m, n-1) + I(m-1, n+1) - I(m-1, n-1) + I(m+1, n+1) - I(m+1, n-1)]^2 + [2I(m-1, n) - 2I(m+1, n) + I(m-1, n-1) - I(m+1, n-1) + I(m-1, n+1) - I(m+1, n+1)]^2\}, \quad (2)$$

the Prewitt gradient criterion function (PRG) [26,28], of which the evaluation function is

$$F_{PRG} = \sum_{m=1}^{M}\sum_{n=1}^{N}\{[I(m+1, n-1) + I(m+1, n) + I(m+1, n+1) - I(m-1, n-1) - I(m-1, n) - I(m-1, n+1)]^2 + [I(m-1, n+1) + I(m, n+1) + I(m+1, n+1) - I(m-1, n-1) - I(m, n-1) - I(m-1, n-1)]^2\}, \quad (3)$$

the Square grade gradient criterion function (SQG) [26,27], of which the evaluation function is

$$F_{SQG} = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}[8I(m, n) - I(m, n-1) - I(m, n+1) - I(m-1, n) - I(m+1, n) - I(m-1, n-1) - I(m-1, n+1) - I(m+1, n-1) - I(m+1, n+1)]^2, \quad (4)$$

and the Square Laplace criterion function (SML) [20,26], of which the evaluation function is

$$F_{SML} = \sum_{m=1}^{M}\sum_{n=1}^{N}\frac{[|2I(m, n) - I(m-1, n) - I(m+1, n)| - }{|2I(m, n) - I(m, n-1) - I(m, n+1)|]^2}. \quad (5)$$

In the formulation, (m, n) represents the pixel coordinate position in the reconstructed image and F is the quantitative description of the image's sharpness calculated by the respective functions. The reconstructed images, which propagate over different distances, are evaluated by the autofocusing algorithms. The functions calculate the value of F corresponding to each distance and draw the correlation curves. During reconstruction, the