

Imaging quality and resolution enhancement by iterative phase retrieval in THz off-axis digital holography

Yuchen Zhao^a, Jean-François Vandenrijt^a, Murielle Kirkove^a, Marc P. Georges^{a,*}

Centre Spatial de Liège, STAR Research Unit, Université de Liège, Liège Science Park, B-4031 Angleur, Belgium

Author e-mail address: mgeorges@uliege.be

Abstract: The intrinsic resolution of 2.52 THz off-axis digital holography system is known to be diffraction limited. However, in practical recording condition, reference wavefront would inevitably suffer excessive diffraction or obstruction with large off-axis angle. Consequently, the theoretical resolution cannot be achieved, and the imaging quality is degraded. We propose a phase-retrieval-assisted solution to correct the errors caused by inaccurate reference wave. Experimental results demonstrate enhanced imaging quality and recovered lateral resolution. © 2019 The Author(s)
OCIS codes: (090.1995) Digital holography; (100.5070) Phase retrieval; (110.6795) Terahertz imaging

1. Introduction

Terahertz (THz) waves refer to electromagnetic radiations that locate between the infrared and microwave. This band has unique ability to penetrate non-polar materials without ionization damage and thus has great potential for non-destructive testing (NDT) applications. As diffraction-limited imaging technique, digital holography (DH) has been successfully implemented with continuous wave (CW) THz sources and array detectors [1-3]. Thus, for a typical detector, the recording distance should be minimized to tens of millimeters to get a hundreds of micrometers resolution. Gabor in-line configuration is a compact solution sparse object [2]. For larger object, an additional off-axis reference beam should be introduced [1, 3]. Large off-axis angles can be used since the wavelength is much larger than the pixel size of microbolometer. However, when using a large off-axis angle at a short recording distance, the reference beam will be obstructed by the housing or the sample border under investigation. The imaging quality will perform be degraded. The attainable resolution is always larger than the intrinsic resolution. In visible DH, attempts have been made to combine off-axis DH with phase retrieval techniques to optimize the final results [4, 5]. In this contribution, we propose to apply an iterative phase retrieval algorithm to eliminate the errors resulted from inaccurate reference beam and hence, reconstructed image is improved.

2. Experimental setup and Principle

The experimental setup for the proposed method is shown in Fig. 1(a). A CW laser working at 2.52 THz provides a maximum power of 500 mW. The diameter of the beam waist is 11 mm. After power adjustment through an attenuator (not depicted), the laser beam is divided into object beam and reference beam. The object beam passes through a pupil of 8 mm diameter and illuminates the sample situated 10 mm in front of the camera. The reference beam is injected to interfere with the object wave. The hologram is recorded by uncooled micro-bolometer camera with 640×480 pixels on a 17 μm pitch. Figure 1(b) shows a typical hologram when the reference beam is partially obstructed. A diffraction pattern of object should also be recorded in order to apply phase retrieval. Thus a shutter is used to block the reference wave during this acquisition.

The proposed reconstruction method is as follows: firstly, we reconstruct the object field distribution from the off-axis hologram. Hologram is padded to better sample the spectrum on the Fourier domain. Then, we use the reconstruction result as an initial estimation at the object plane and the recorded diffraction pattern at the detector plane to perform Gerchberg–Saxton phase retrieval. The object wave is propagated back and forth between the object plane and the detector plane. Each time the amplitude distribution at the detector plane is replaced by the measured value. The iterations stop once convergence is reached.

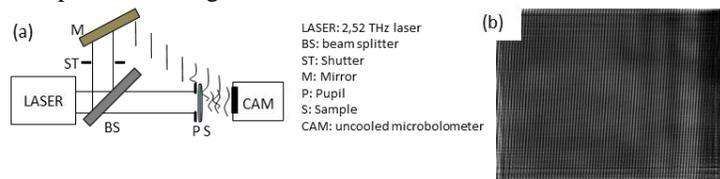


Fig. 1. (a) Schematic of THz off-axis DH; (b) typical hologram when the reference wave is obstructed.

3. Results

We performed numerical simulations to validate the proposed method. The results are shown in Fig. 2. A hologram (c) is simulated with an obstructed reference wave (k) and, an object with known amplitude (a) and phase (b). The

line pairs in the red rectangle are 8lp/mm which correspond to the intrinsic resolution. The line pairs in (e)-(f) become blurred after the conventional reconstruction from hologram (c). Then, iterative phase retrieval is conducted using (e)-(f) as initial guess and the simulated diffraction pattern (d). After 200 iterations, the imaging quality is improved. The line pairs become resolvable again.

The laboratory experiment is then carried out on two samples (1 cm^2), shown in Fig. 3. Both PET and HDPE samples used hereby are THz-transparent and visible-opaque. The convex logo patterns are hidden. The sample is placed 10.5 mm in front of the camera. The reconstruction result of the PET sample (c)-(f) shows an improvement on imaging quality. The first two '9's on the left are distorted and illegible on (c) but clear on (d). In (e) and (f), the phase map of the first '9' on the left is also improved. The reconstruction result of the HDPE sample (g)-(k) shows the recovery of intrinsic resolution. The line width of the letters corresponds to the intrinsic resolution on the vertical direction. The horizontal lines in 'H' and 'E', which cannot be resolved in (j), become resolvable in (k) after 200 iterations. The letters become more recognizable on (h) and (k).

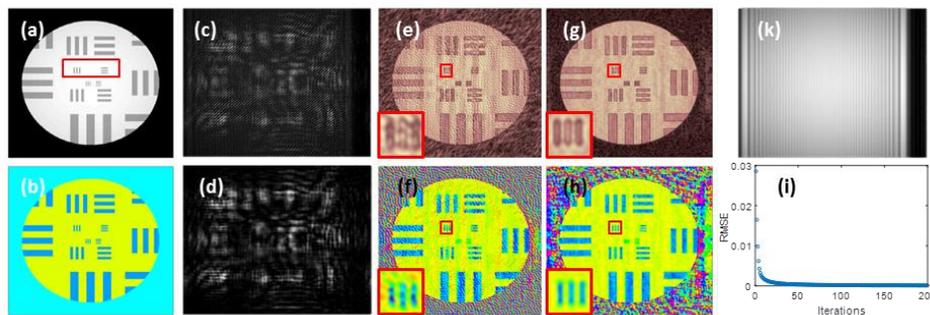


Fig. 2. Simulations: (a) amplitude and (b) phase of object; (c) hologram recorded with sheltered reference beam (k); (d) diffraction pattern of object; amplitude (e) and phase (f) reconstructed from (c); (g) amplitude and (h) phase after 200 iterations; (i) standard deviation plot.

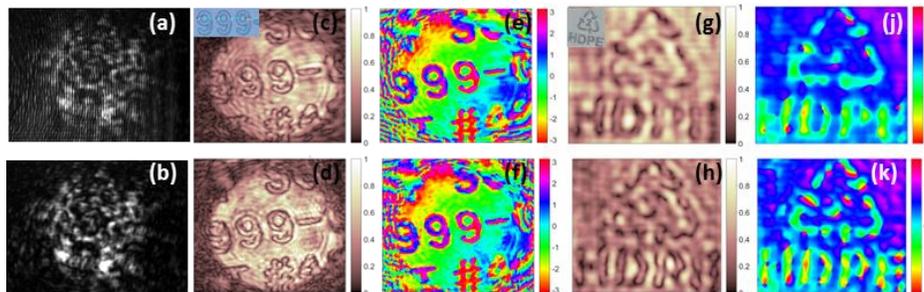


Fig. 3. Experimental results: (a)-(f) PET sample with hidden convex pattern "999" (width: $350 \mu\text{m}$, height: $130 \mu\text{m}$, see inset in (c)); (a) the hologram and (b) the diffraction pattern without reference wave; (c) amplitude and (e) phase from conventional reconstruction; (d) amplitude and (f) phase after 200 iterations. (g)-(k) HDPE sample with hidden convex recycle logo (width: $152 \mu\text{m}$, comparable to intrinsic resolution; height: $70 \mu\text{m}$, see inset in (g)); (g) amplitude and (j) phase from conventional reconstruction; (h) amplitude and (k) phase after 200 iteration.

4. Conclusion

We have demonstrated that, with only one additional acquisition, iterative phase retrieval method can be combined with off-axis holography to eliminate the degradations caused by obstructed reference wave. Both numerical simulations and experimental results showed enhancement in imaging quality and compensation in resolution loss. The proposed method offers an efficient solution for situations where the reference wave distortion is inevitable. Further investigation should be carried out on the choice of different phase retrieval algorithms.

5. References

- [1] S.-H. Ding, Q. Li, Y.-D. Li, and Q. Wang, "Continuous-wave terahertz digital holography by use of a pyroelectric array camera," *Opt. Lett.* **36**(11), 1993 (2011).
- [2] L. Rong, T. Latychevskaia, D. Wang, X. Zhou, H. Huang, Z. Li, and Y. Wang, "Terahertz in-line digital holography of dragonfly hindwing: amplitude and phase reconstruction at enhanced resolution by extrapolation," *Opt. Express* **22**(14), 17236 (2014).
- [3] E. Hack, L. Valzania, G. Gümamm, M. Shalaby, C. P. Hauri, and P. Zolliker, "Comparison of thermal detector arrays for off-axis THz holography and real-time THz imaging," *Sensors (Switzerland)* **16**(2), 1–11 (2016).
- [4] F. Wang, D. Wang, L. Rong, Y. Wang, and J. Zhao, "Single-shot dual-wavelength in-line and off-axis hybrid digital holography," *Appl. Phys. Lett.* **112**(9), (2018).
- [5] L. Orz , "High speed phase retrieval of in-line holograms by the assistance of corresponding off-axis holograms," *Opt. Express* **23**(13), 16638 (2015).