An ADMM-inspired image reconstruction for Terahertz off-axis digital holography

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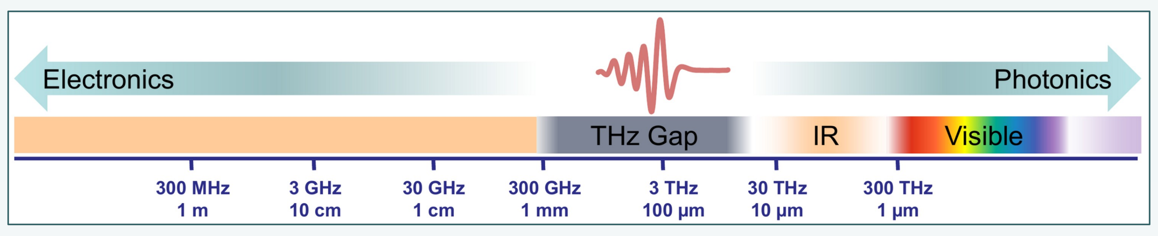
ABSTRACT

We propose a reconstruction technique to off-axis Terahertz digital holography that jointly reconstructs the object field and the reference amplitude. The objective function combining data-fidelity and wavelet-based regularization terms is optimized with an ADMM-inspired approach.

Keywords: Terahertz imaging, digital holography, computational imaging, inverse problems, wavelets, phase retrieval

TERAHERTZ IMAGING

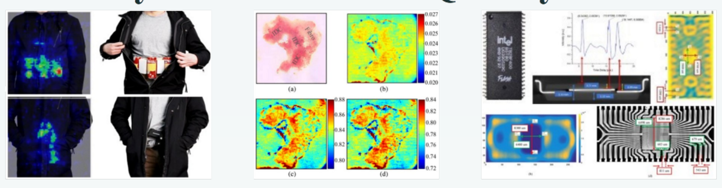
Terahertz (THz) wave range



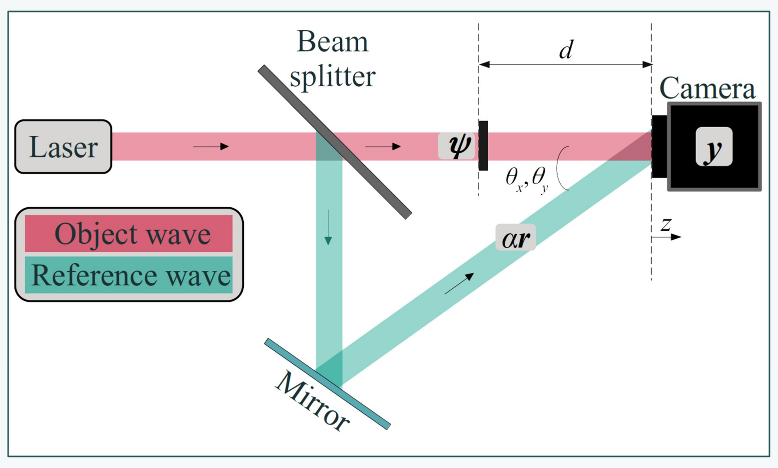
Unique properties
- Penetrating non-polar materials
- No ionization damage

Applications

Security – Biomedical - Quality Control



Imaging technique
- Off-axis digital holography (DH)



Challenges
- Small recording distance
  → excessive diffraction effect
  → perturbation of reference wave uniformity
- Lower resolution of cameras

FORWARD MODEL

$$y = |A_d\,\psi + \alpha r|^2 + n$$

Known
- y: noisy intensity measurements
- A_d: instrumental PSF associated with light propagation at distance d
- r: unit reference field

Unknown
- ψ: complex object field
- α: reference field amplitude

Phase retrieval
Interference pattern recorded by digital image sensor → object field ψ and reference field amplitude α

INVERSE PROBLEM

$$(\tilde{c}_\psi, \tilde{\alpha}) \in \underset{(c_\psi,\,\alpha)}{\operatorname{argmin}} \| y - |A_d W^{-1} c_\psi + \alpha r|^2 \|_2^2 + \lambda \| c_\psi \|_1$$

Non-convex problem → many local minima

Problem ill-posed → wavelet regularization
- c_ψ: wavelet coefficients of ψ
- W: (orthonormal) discrete wavelet transform matrix
- λ: regularization strength

Algorithm
- Based on Alternating Direction Method of Multipliers (ADMM) method
- Alternating optimization steps (with respect to c_ψ and α)
- Use of projection operator based on the one of [2] for minimization of data-fidelity term

Pre-processing
- Periodic boundary condition (BC) + frame truncation by camera → artifacts
- Alleviation of artifacts: pre-processing by apodization (2D Tukey window)

OTHER METHODS (for comparison)

Direct Fourier method (classical approach)
- Removal of 0 and -1 order terms of spectral information → recovery of object field ψ
- Filtering in Fourier domain → loss of high-frequency components → ringing artifacts
- No estimation of α

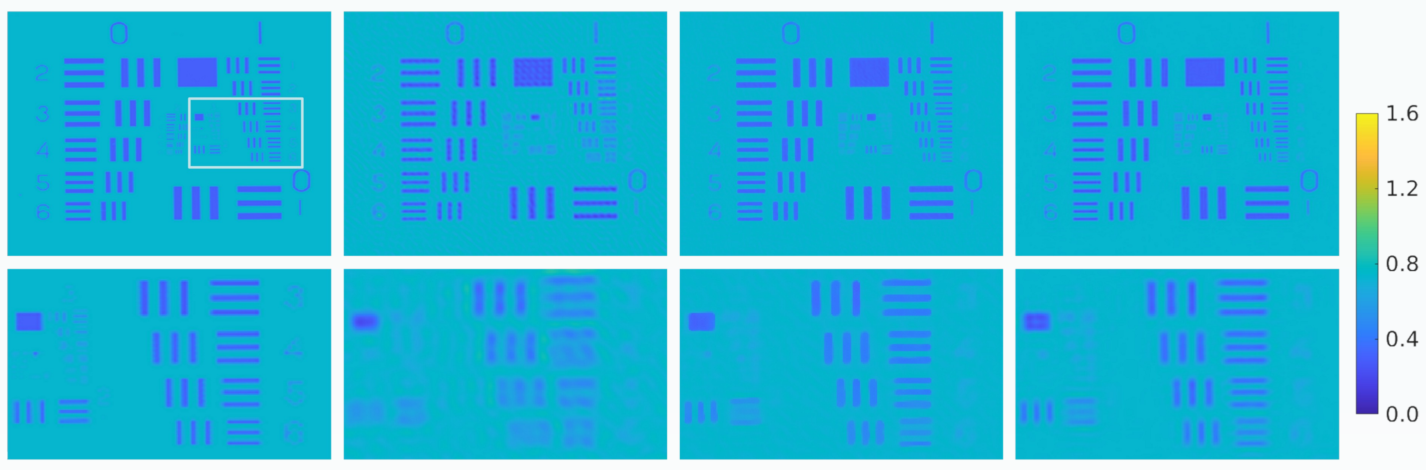
Constrained TV regularized method [1]
- IP-based reconstruction (Total Variation (TV) regularization)
- Estimation of ψ and α (pixel-dependent, same sampled 2-D pixel grid)

RESULTS on SYNTHETIC DATA

Data
- Highly transparent phase object (from USAF resolution target)
- $\theta_x, \theta_y = 45°$, $d = 8.5$ mm

Performance measures
- Signal-to-Noise Ratio (SNR)
- Structural Similarity Index Measure (SSIM)

Noiseless reconstruction



Simulation	Direct Fourier	Constrained TV [1]	Ours
	SNR: 24.27	SNR: 28.23	SNR: **28.90**
	SSIM: 0.67	SSIM: 0.82	SSIM: **0.90**

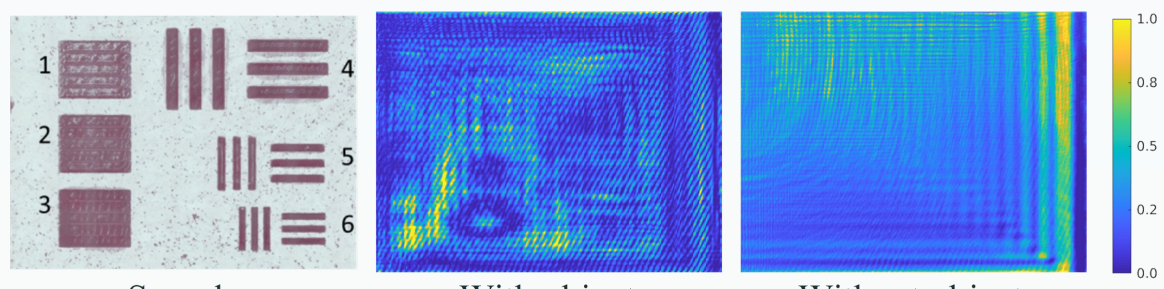
COMPARISON WITH 2 OTHER METHODS

- Direct Fourier method: loss of high-frequency components → ringing artifacts
- Direct Fourier and constrained TV regularized methods: fringe artifacts
- Ours: better SNR and SSIM, more signal details, better visibility of the patterns, absence of fringe and ringing effects, faintly visible blocky artifacts

➡ Our method outperforms the 2 other methods on real and synthetic data

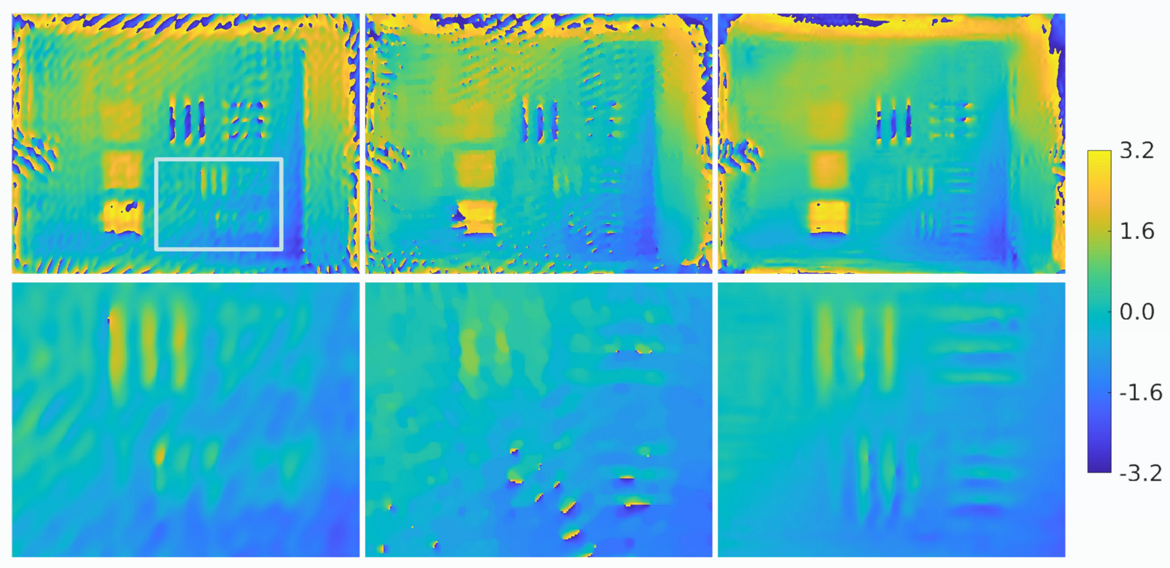
RESULTS on REAL DATA

Data
- Sample: visibly opaque 550 µm-thick polypropylene (PPP) slab with different engraved patterns
- $\theta_x = 41°$, $\theta_y = 21°$, $d = 9.5$ mm



Sample | With object | Without object
Holograms

Reconstruction with pre-processing



Direct Fourier | Constrained TV [1] | Ours

CONCLUSIONS

Our method provides joint reconstruction of object field and the reference field amplitude. For application in real situations, a pre-processing by apodization reduces the artifacts due to camera frame truncation. Experiments demonstrate improvements in terms of image quality compared to two other reconstruction methods. The pre-processing produces intensity decrease in the border area. A better solution would be to consider an unknown BC. Some other future works will concern improvements for a better separation of object and reference field amplitude solutions.

FUNDING/ACKNOWLEDGMENTS

The research was funded by project TERA4ALL in the frame of 2014-2020 ERDF/Wallonia region ”En Mieux” program and supported by the "Fonds de la Recherche Scientifique – FNRS" under Grant T.0136.20 (Project Learn2Sense). It could not have been accomplished without the work provided by two students, H. Blaschyk and L. Barriol, for their master internships.

REFERENCES

[1] A. A. Bourquard, N. Pavillon, E. Bostan, C. Depeursinge, and M. Unser, “A practical inverse-problem approach to digital holographic reconstruction,” Opt. Express 21, 3417 (2013)
[2] C. Schretter, D. Blinder, S. Bettens, H. Ottevaere, and P. Schelkens, “Regularized non-convex image reconstruction in digital holographic microscopy,” Opt. Express 25, 16491 (2017)