Study and development of Terahertz coherent imaging techniques

PhD Defense

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Context

- Imaging with THz radiation

  -Seeing through the opaque

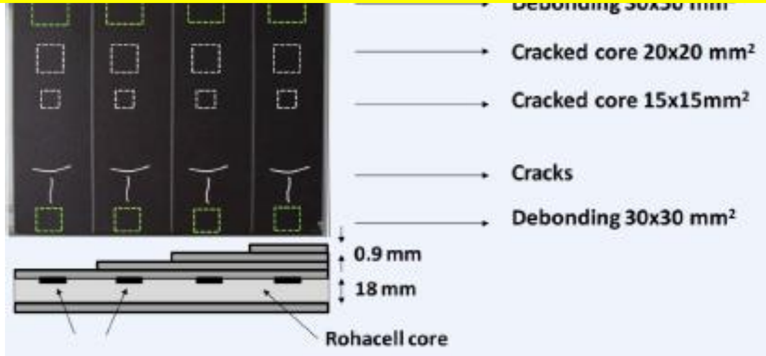
- Space Shuttle Columbia disaster
- Insulation foam failure

THz digital holography for composite NDT applications?

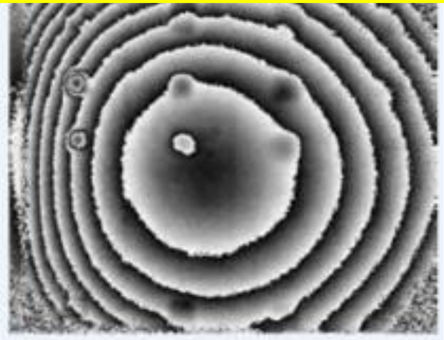
ERDF/Wallonia region project TERA4ALL:

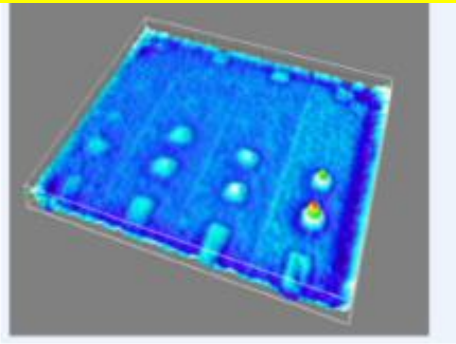
-implementing innovative THz imaging techniques

-promoting THz technologies for industrial applications



(Georges et al., 2012)





Objective of this thesis

My thesis=Our very first experience with THz radiation in CSL

- Understand different **THz science and technology** (Chapter 2)
- Evaluate the **feasibility** of our THz system for **composite NDT applications** (Chapter 2)
- Developing **coherent lensless imaging** techniques with THz radiation (Chapter 3)
    - Interferometric method: **digital holography** (Chapter 4)
    - Other non-interferometric methods: such as iterative **phase retrieval** and **ptychography** (Chapter 5-6)

Plan of presentation

Part 1: Overview of the THz technologies

- Key points about THz radiation
- THz generation and detection
- Material characterization with THz-TDS

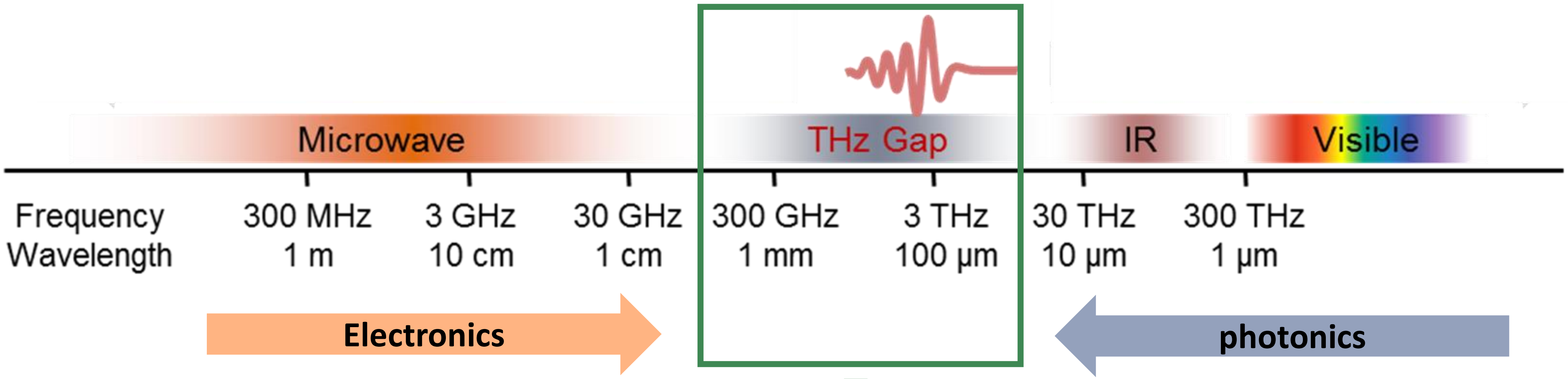
Part 2: Overview of coherent lensless imaging techniques

Part 3: Developing THz digital holography

Part 4: Developing THz ptychography

Part 5: Conclusions and perspectives

Key points about THz radiation



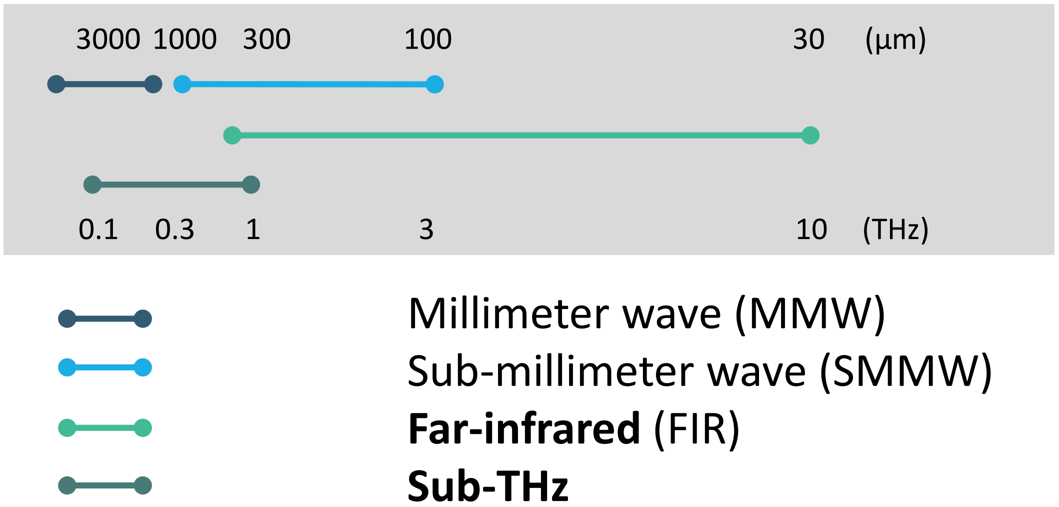
Terahertz wave range:

- Frequency: 0.1-10 THz (1THz=10^{12} Hz)
- Wavelength: 30-3000 µm
- 1 THz↔33.3 cm^{-1}↔300 µm↔4.1 meV

THz Gap:

- Lack of generating and detecting technologies
- Least explored

Subdivision of THz band:



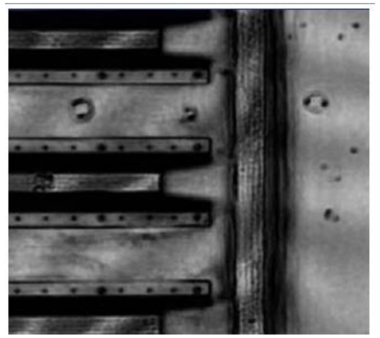
Similar behavior to their neighboring band

Key points about THz radiation

Unique characteristics

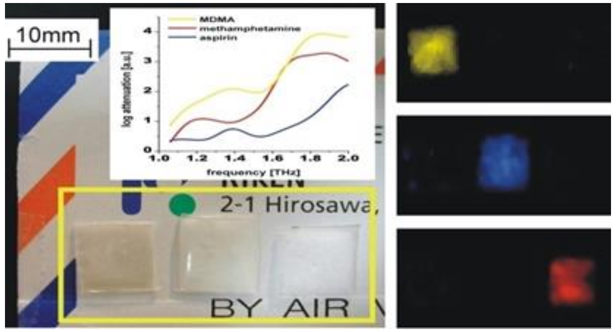
Material penetration · Non ionizing · Spectroscopic fingerprints · Water absorption

Various applications

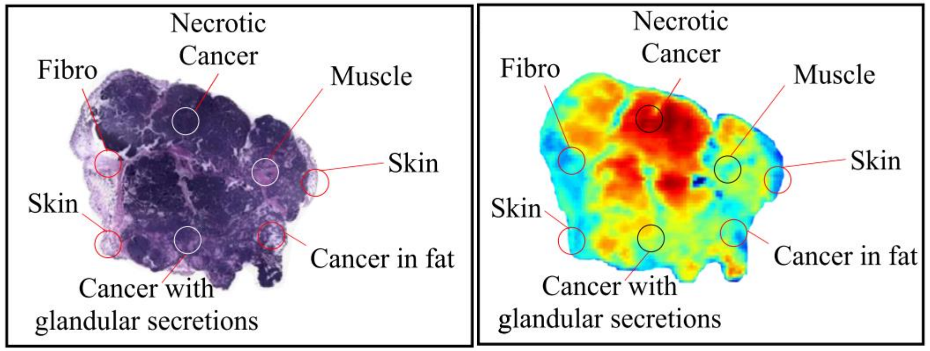


(Redo-Sanchez et al., 2006)

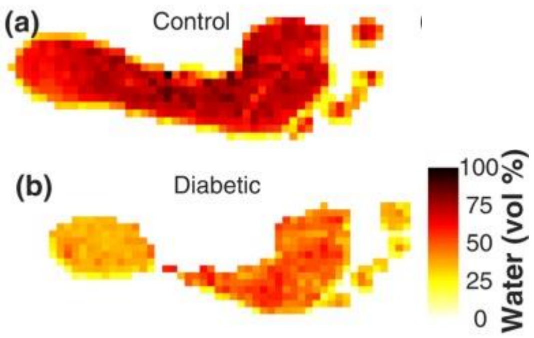
(Kramer, 2020)



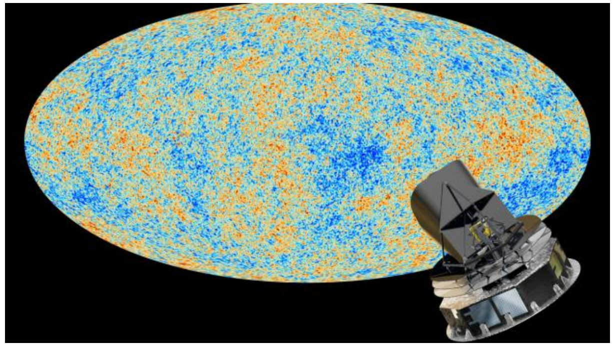
(Kawase et al. ,2003)



(El-Shenawee et al., 2019)

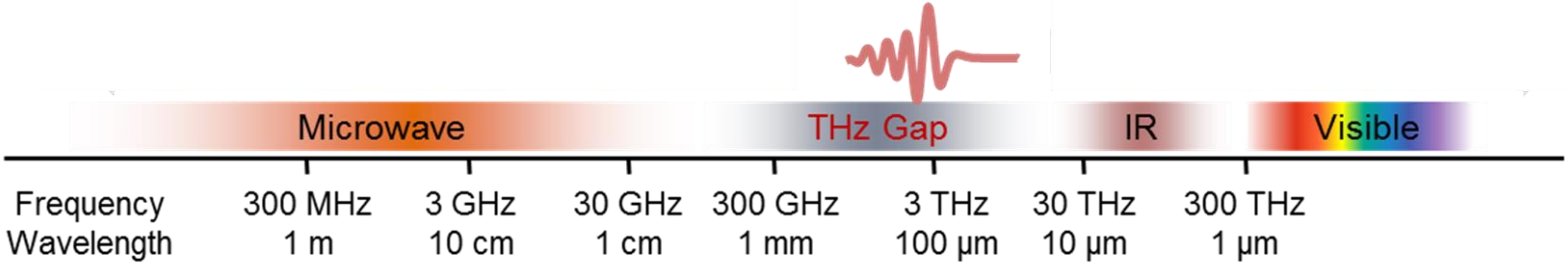


(Hernandez-Cardoso et al., 2017)



Planck and the cosmic microwave background,
HFI : 100 and 857 GHz (www.esa.int)

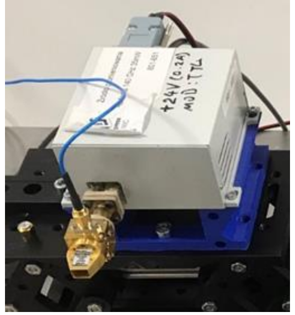
Continuous-wave (CW) THz generation



Vacuum electronics and solid state electronics

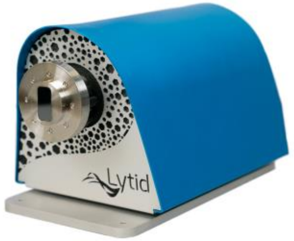
- Gunn diodes, IMPATT diodes and Frequency Multipliers

(http://terasense.com)



photonics

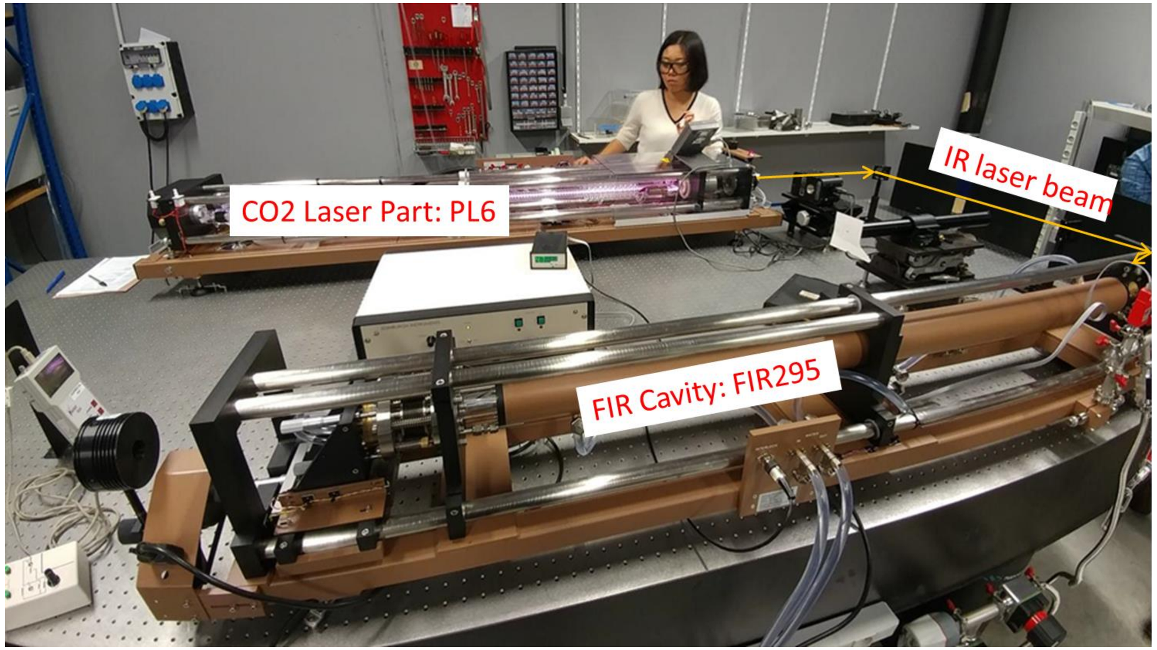
- Quantum cascade lasers (QCL)

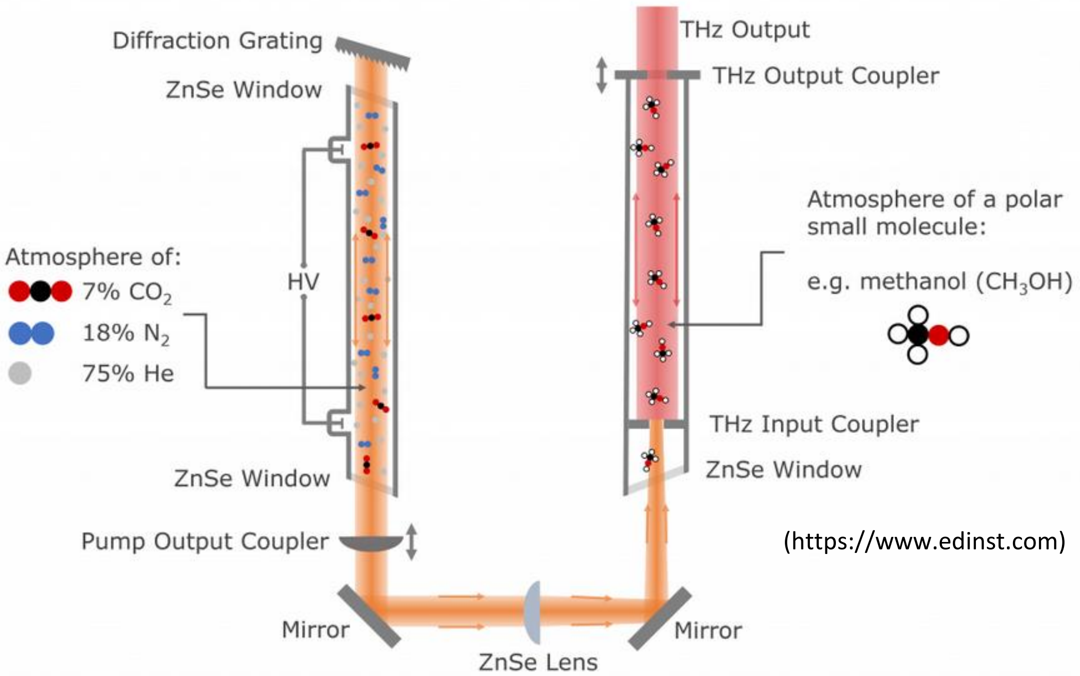


(https://lytid.com)

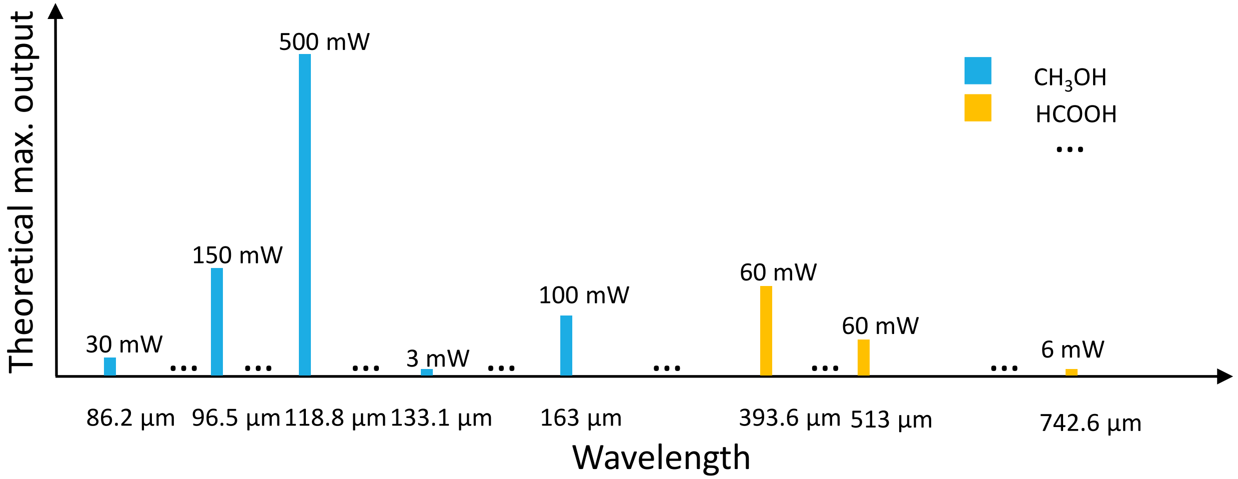
- Optically pumped FIR lasers :
  The source at CSL

THz source at CSL: Optically pumped FIR lasers





(https://www.edinst.com)



- Monochromatic
- Continuous wave
- Strongest lines: 2.52 THz, 3.1 THz

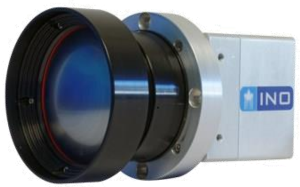
CW THz Room Temperature Detectors and Arrays (Incoherent detection)

- Focal plane arrays (FPA): Uncooled thermal detectors (mainly for > 1 THz)

Uncooled Microbolometers

NEC

- SiN
- 320x240
- Pitch 23.5 μm
- NEP < 100 pW @ 3 THz



INO

- VOx
- 384x288
- Pitch 35 μm
- NEP < 35 pW @ 2.5 THz

cea

- VOx
- 320x240
- Pitch 50 μm
- NEP < 30pW @ 2.5 THz

Swiss Terahertz

- VOx
- 160 × 120
- Pitch 25 μm
- NEP <1.5 pW @ 4.6 THz

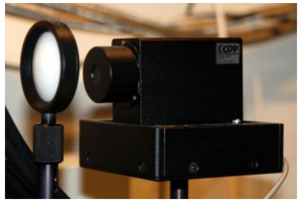
(Zolliker et al, 2021)

Xenics

- a-Si, LWIR camera
- 640 x 480
- Pitch 17 μm

- Other single-point detectors

Golay cells



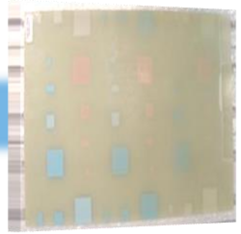
Diode detectors

FET-based THz detector

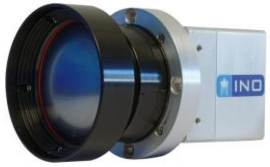
Can we see through the composites with our systems?

Very first experiment:

2.52 THz, 500 mW



GFRP



THz cam

No signal detected

FIR band cannot see through the composite materials.

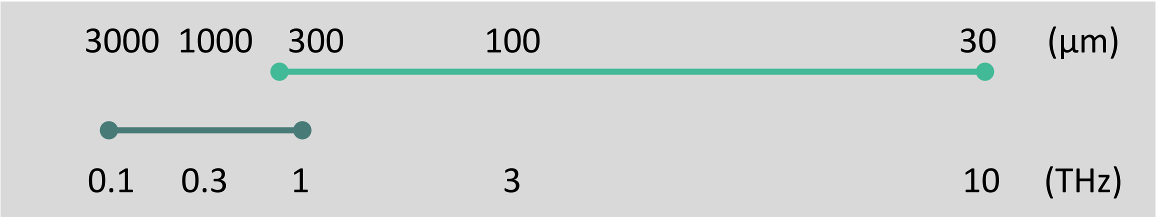
- Good transparency at deep sub-THz: 0.1 up to 0.6 THz

(Strom, 1977)

- Transparent materials at >1 THz:

  polypropylene (PP), polyethylene (PE), dehydrated tissues

Conclusions on the overview of the THz technologies



FIR band:

+ : Higher TRL for imaging application

+ : Higher resolution

+ : Equipment at CSL

- : Very selective penetration ability

Sub-THz band:

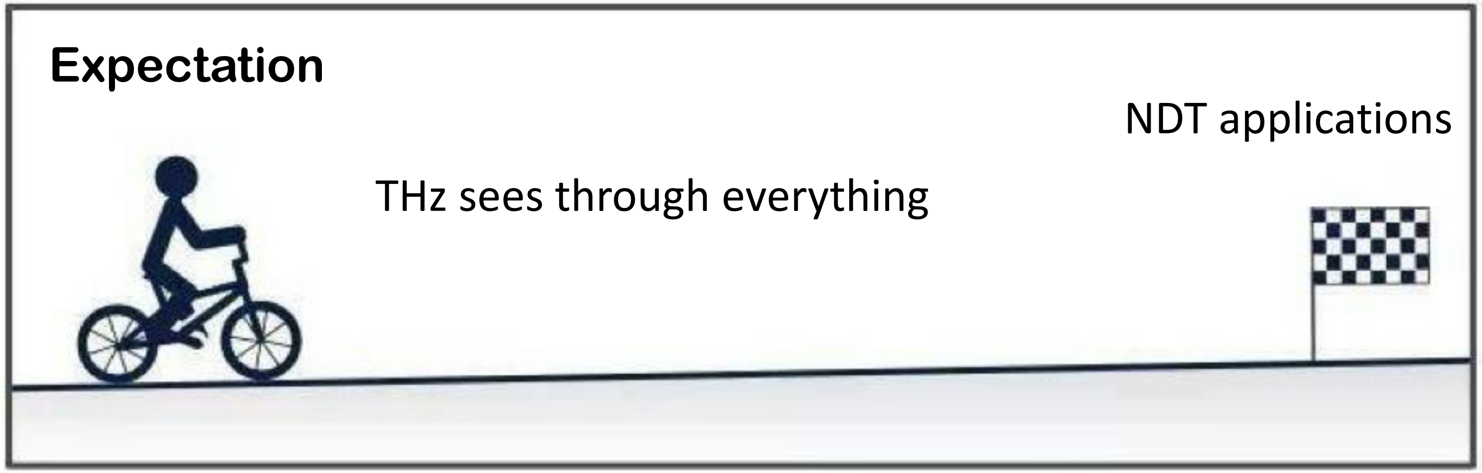
+: Penetration ability

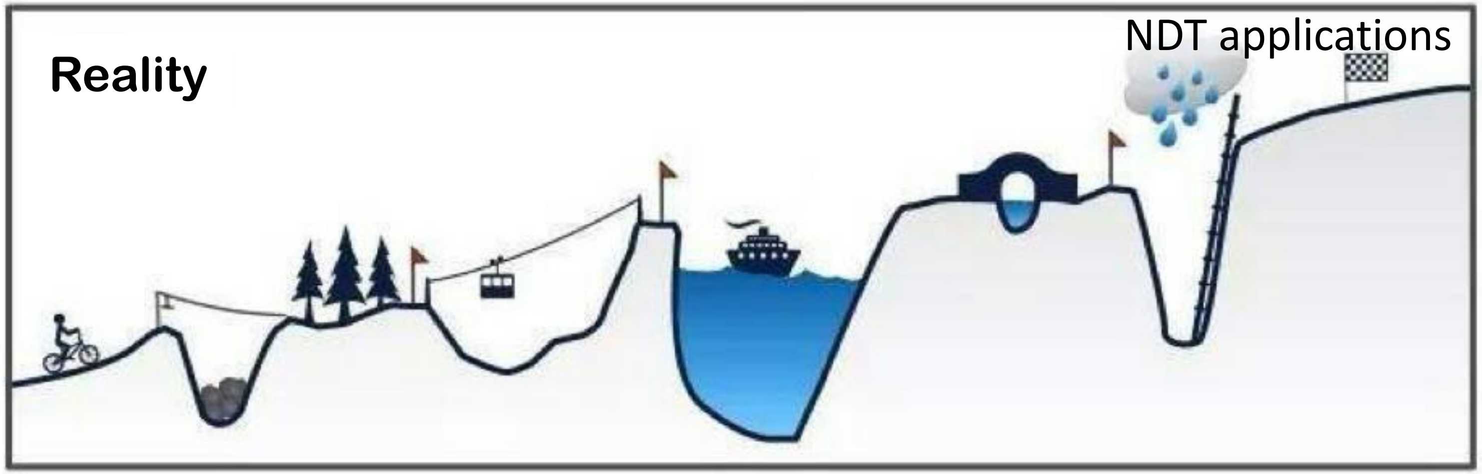
-: Lack of large array detectors

-: large wavelength

-: No equipment in our lab

Conclusions on the overview of the THz technologies





Plan of presentation

Part 1: Overview of the THz technologies

Part 2: Overview of coherent lensless imaging techniques

- General concept of coherent lensless imaging
- holography
- phase retrieval

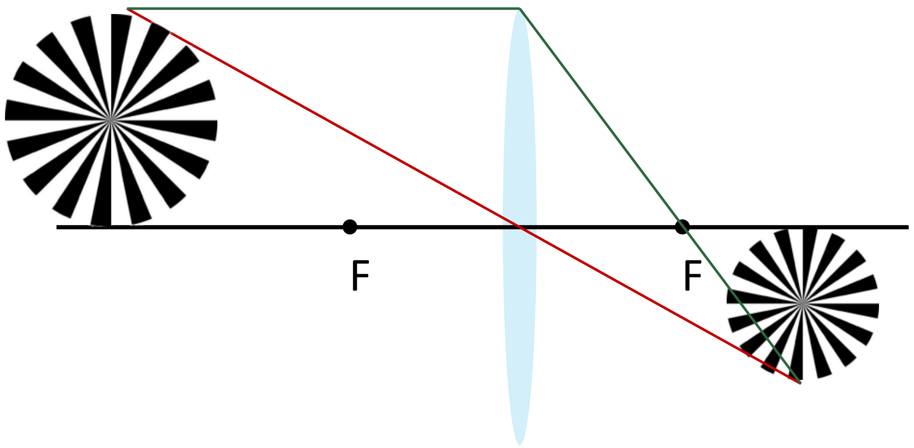
Part 3: Developing THz digital holography

Part 4: Developing THz ptychography

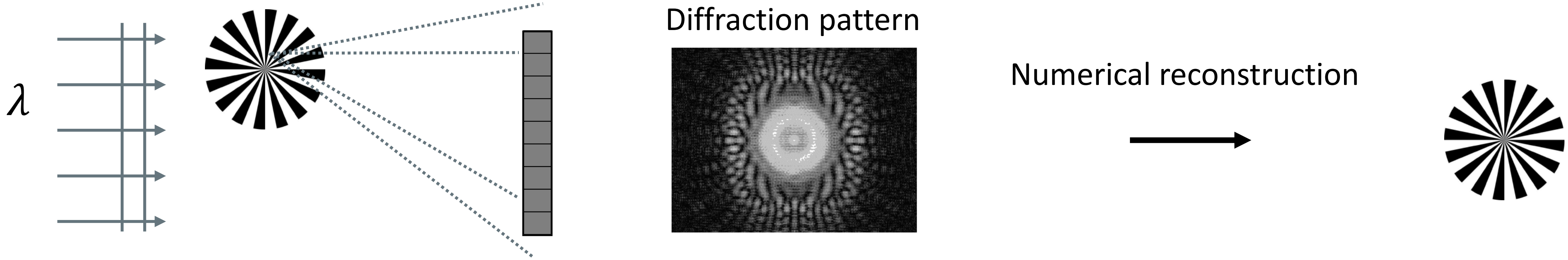
Part 5: Conclusions and perspectives

General concept of coherent lensless imaging

Imaging with a lens

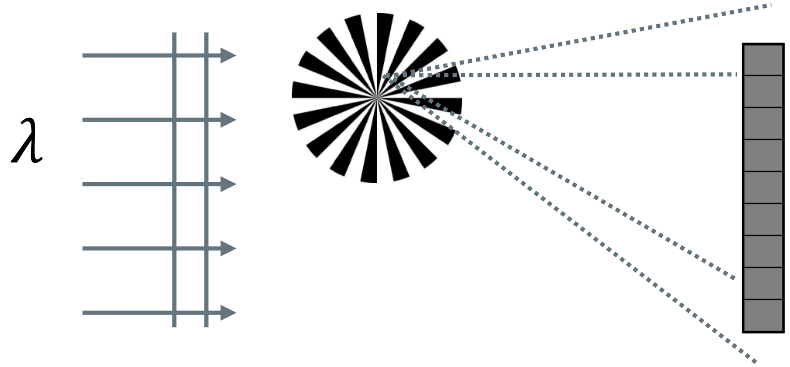


Coherent lensless imaging



General concept of coherent lensless imaging

Coherent lensless imaging ↔ the phase problem

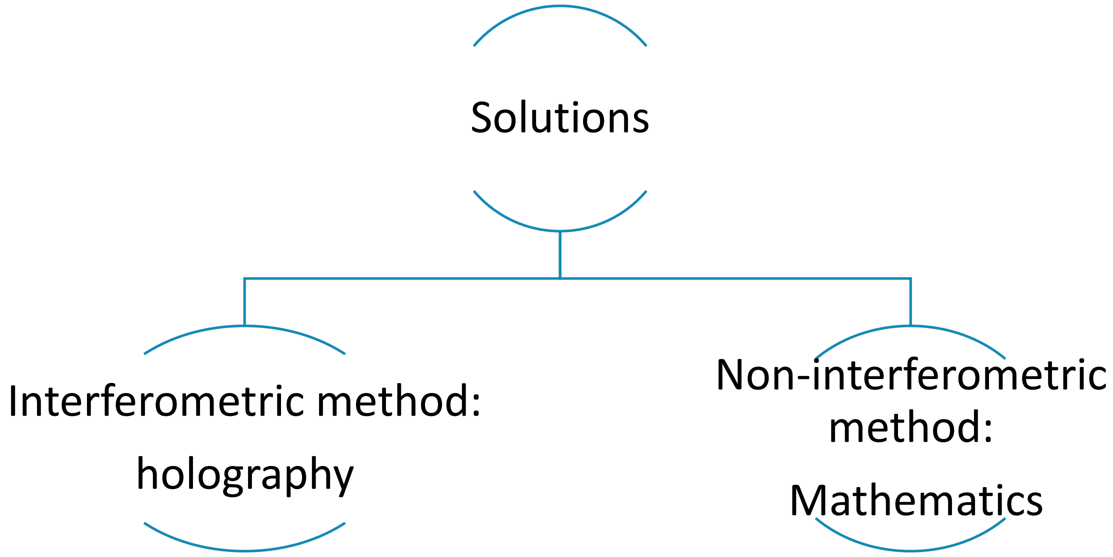


Diffraction formula: $\widetilde{\Psi}(x,y,0) \overset{\text{FFT}}{\Longleftrightarrow} \widetilde{\Psi}(x,y,d)$

Measured diffraction pattern: Intensity

$$\left|\widetilde{\Psi}(x,y,d)\right|^2$$

Phase information is lost!

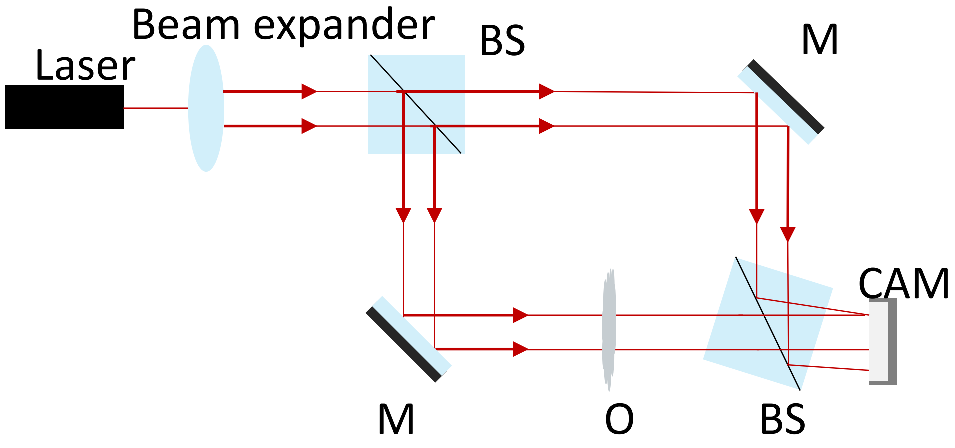


- Optics communities: retrieving the phase information of the object field
- Electron, X-ray communities: imaging without optics

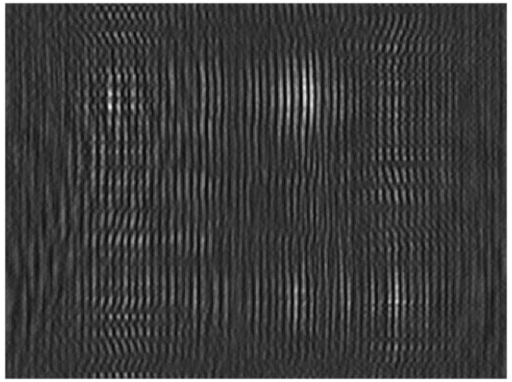
Holography

Holo: whole $H = |R + O|^2 = \underbrace{|O|^2 + |R|^2}_{\text{0 order}} + \underbrace{R^*O}_{\text{+1 order}} + \underbrace{O^*R}_{\text{-1 order}}$

R: reference wave (known wavefront)

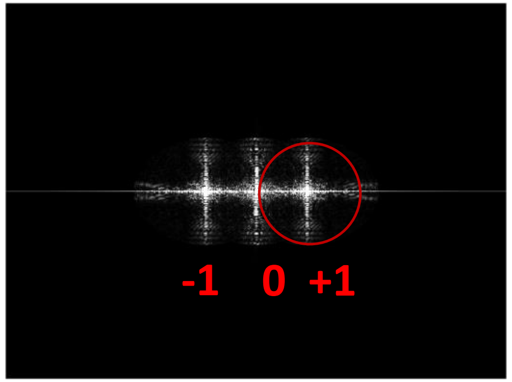


Hologram



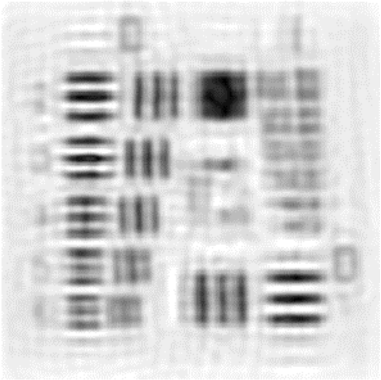
FFT ⟺

Fourier spectrum

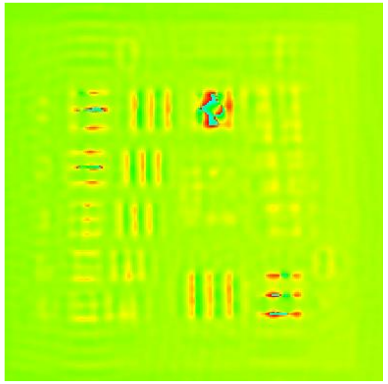


⇒

Amplitude



Phase



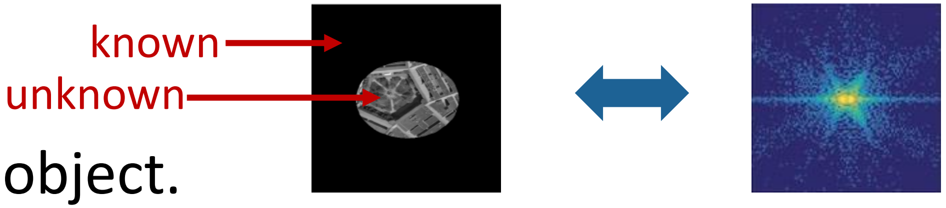
Non-interferometric methods

- Object : M^2pixels, $2M^2$ unknown values (amplitude+ phase)
- Measured intensity: N^2 pixels
- Oversampling ratio σ:

$$\sigma = \frac{\text{total number of measured pixels}}{\text{total number of unknown pixels to solve}} = \frac{N^2}{M^2}$$ (Miao, 1998)

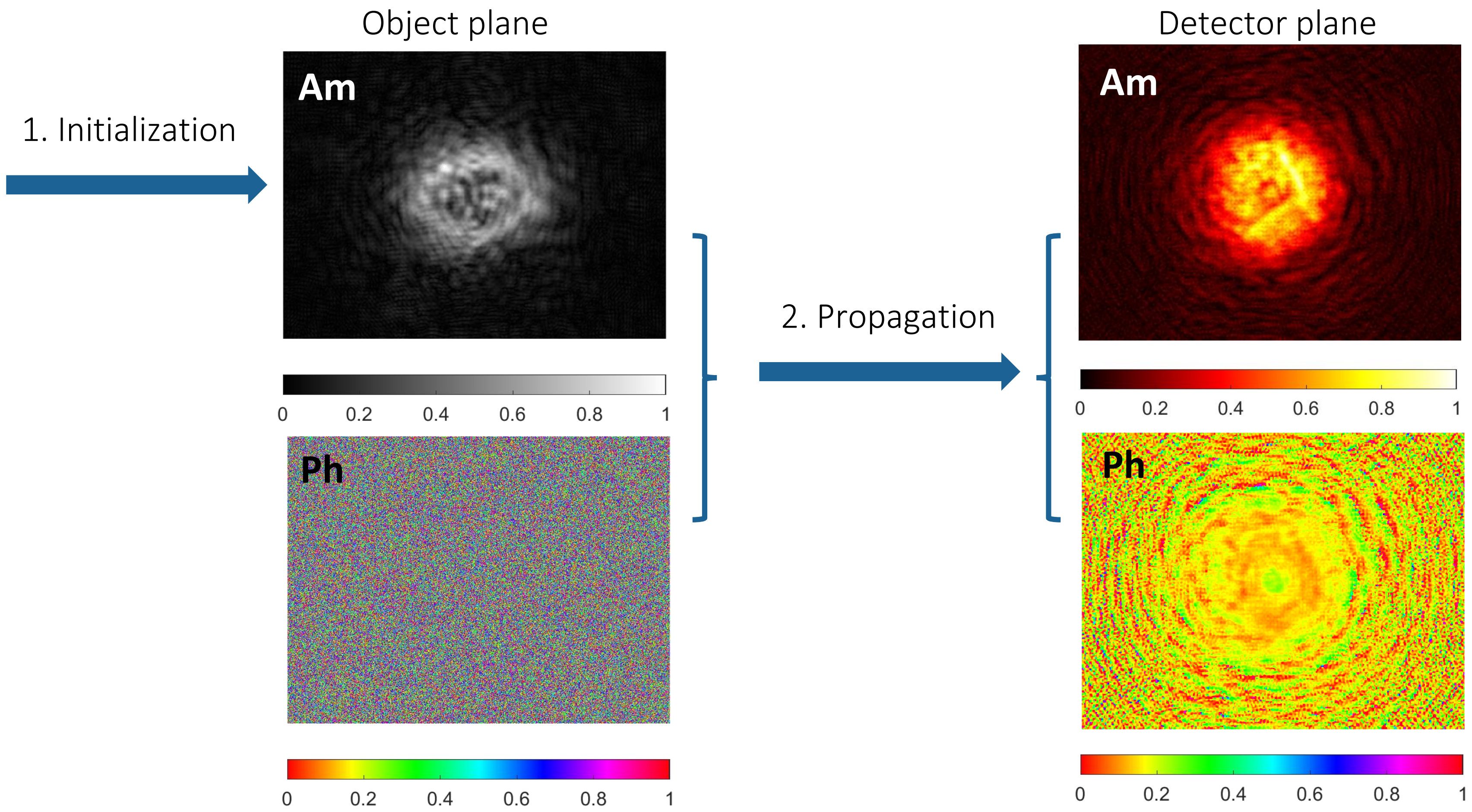
$\sigma \geq 2$ for a unique solution (with the presence of noise, $\sigma \gg 2$)

- How to get $\sigma > 2$?

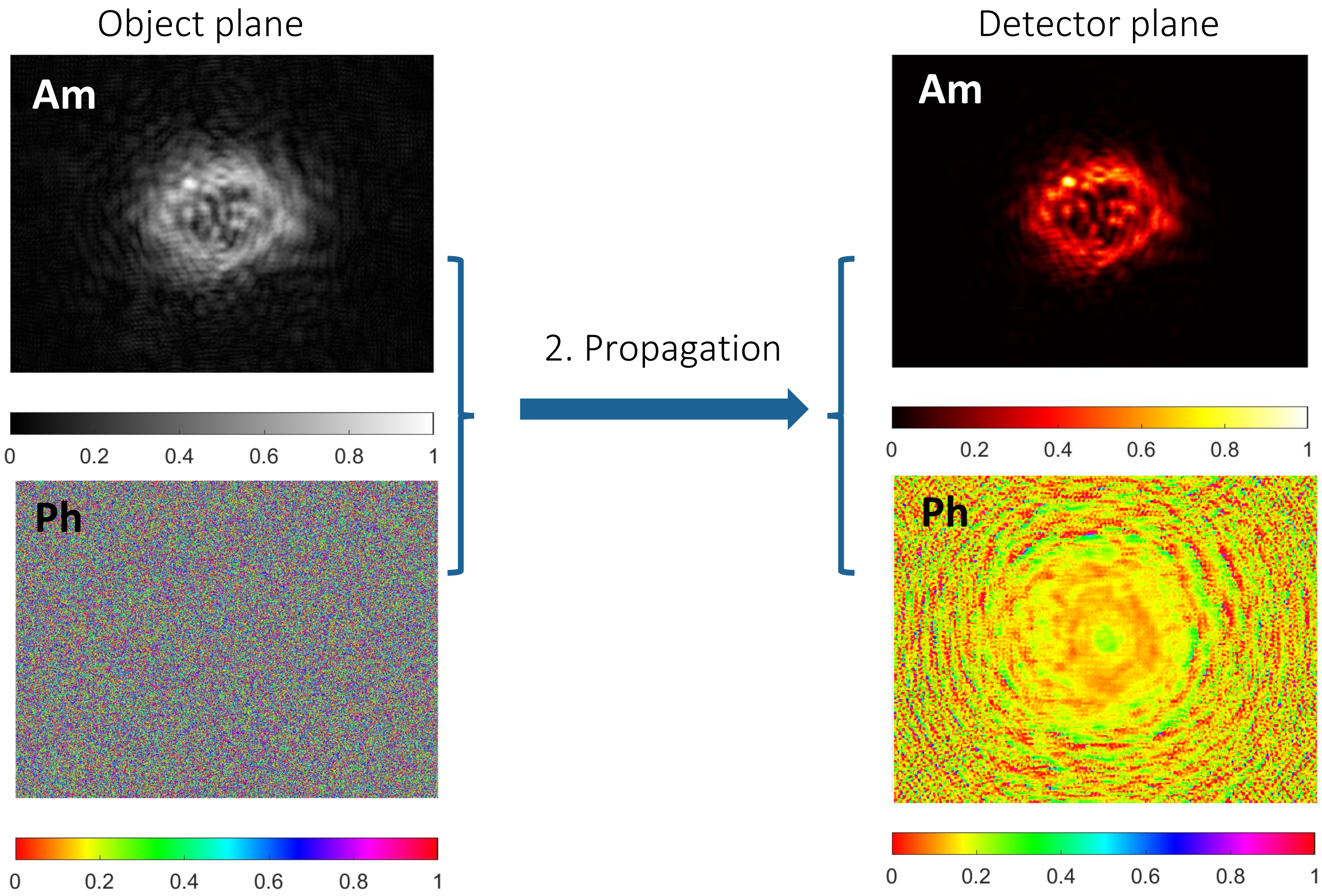


- Reduce $M^2 \leftrightarrow$ *A priori* support constraint of object.
- Increase $N^2 \leftrightarrow$ More intensity measurements (different z, λ... etc.), ptychography.

Iterative phase retrieval: basic routine (1/3)



Iterative phase retrieval: basic routine (2/3)



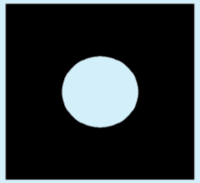
3. intensity constraints
(measured intensity)

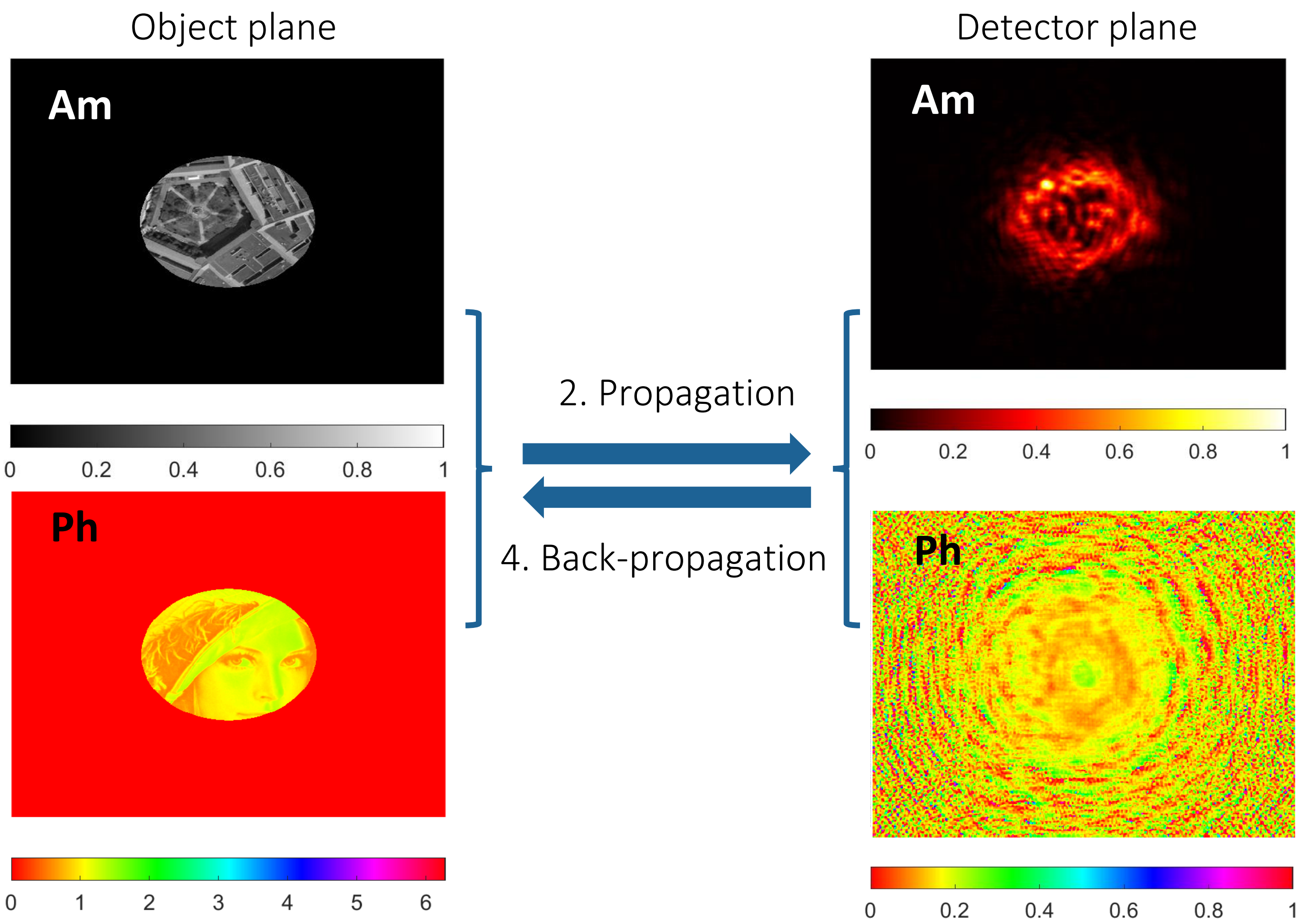
$$\sqrt{I_0}$$

Iterative phase retrieval: basic routine (3/3)

5. Update the object estimation

- Support
- Positive absorption
- Sparsity
- …





3. intensity constraints (measured intensity)

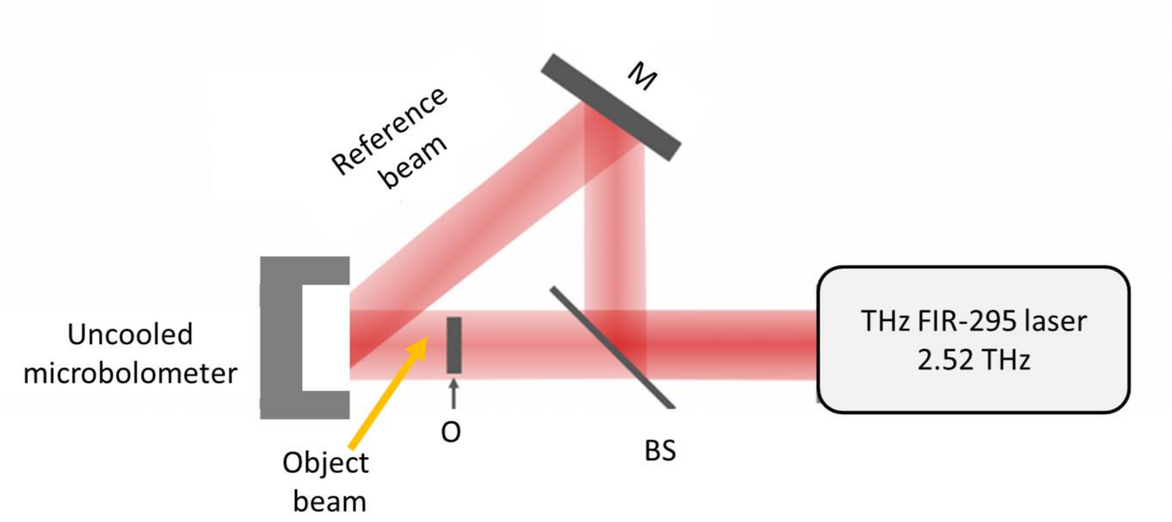
$\sqrt{I_0}$

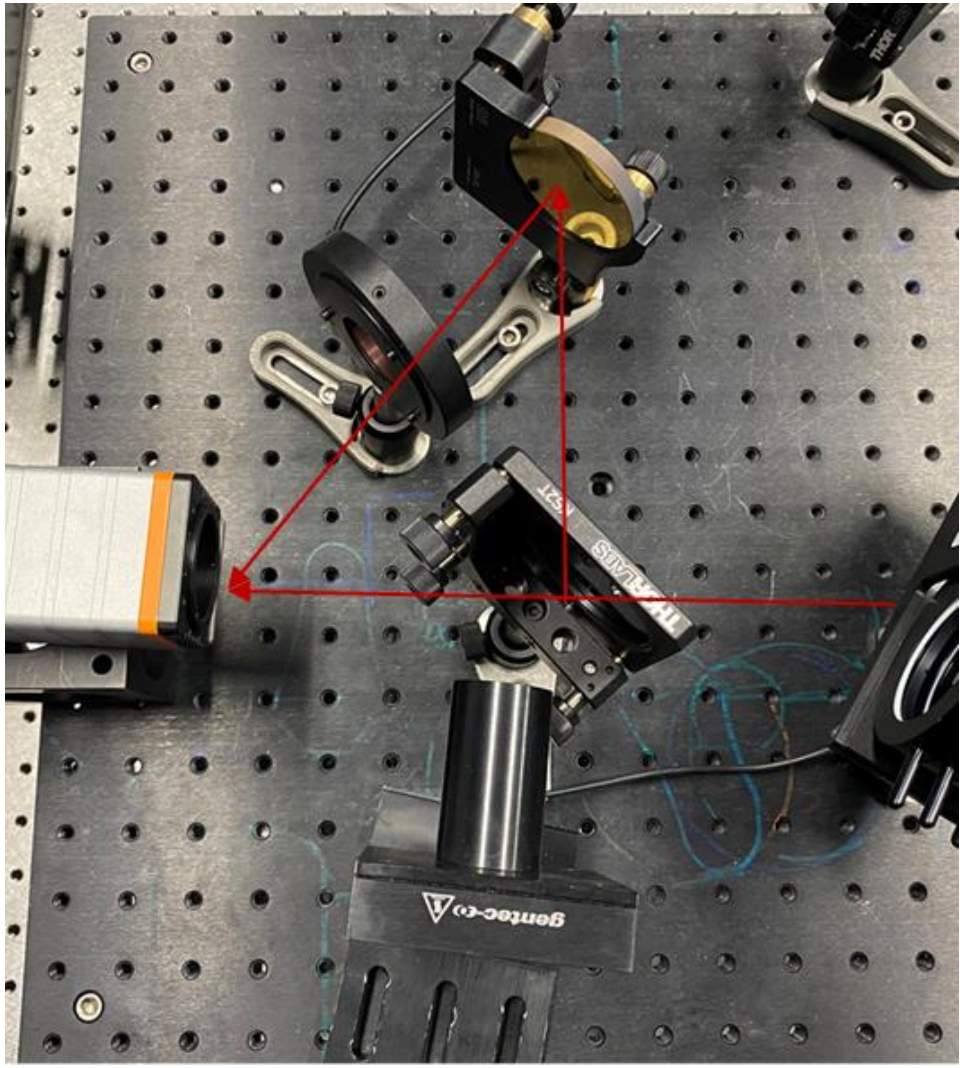
Plan of presentation

Experimental setup at 2.52 THz

- Camera: Gobi LWIR camera, 640 x 480, pitch 17 µm
- Working wavelength: 118.83 µm
- Minimize object-detector distance: 9.5 mm

  (pursue λ level resolution)
- Off-axis angle: 45°
- Sample: PP slab with patterns

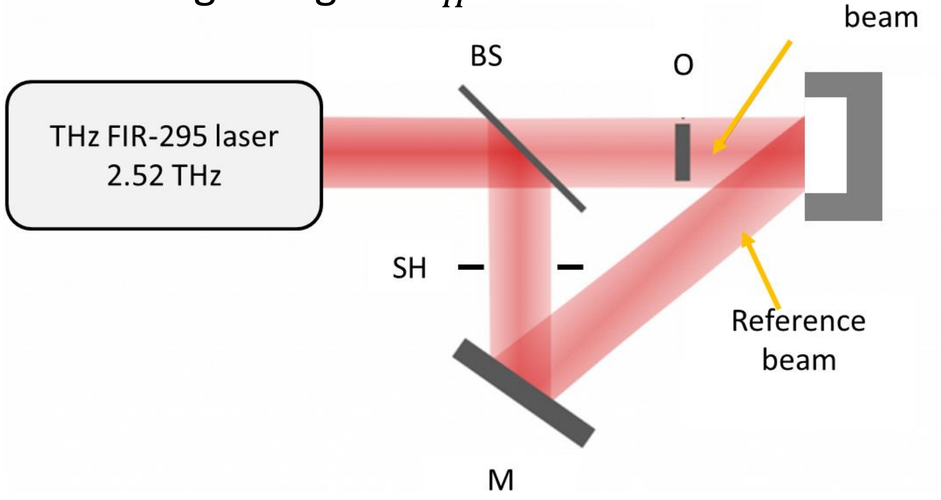




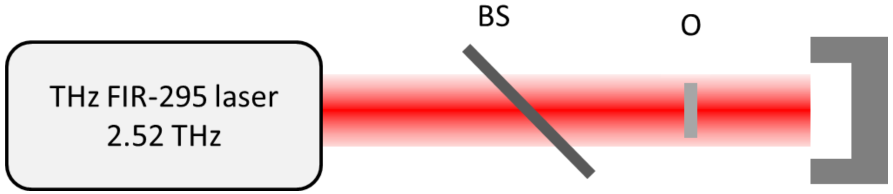
Zhao, Y., Vandenrijt, J. F., Kirkove, M., & Georges, M. (2019). Iterative phase-retrieval-assisted off-axis terahertz digital holography. *Applied Optics*, *58*(33), 9208-9216.

Recording the object intensity to help the reconstruction

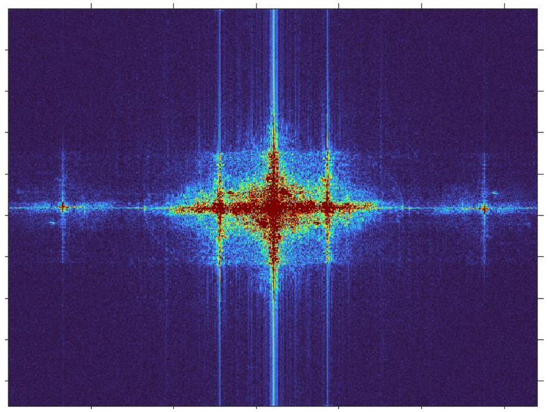
Recording hologram I_H



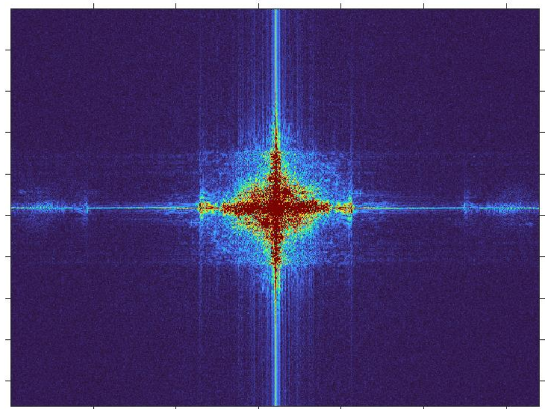
Recording object intensity I_O



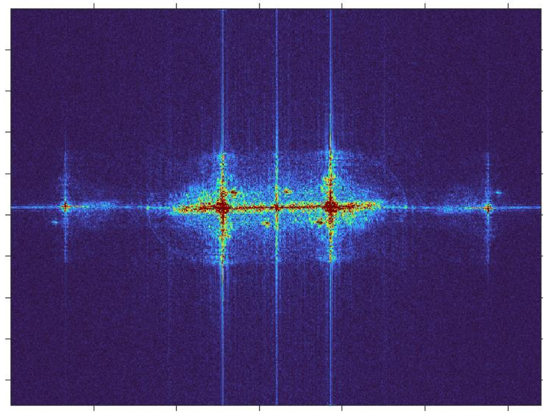
$\mathcal{F}\{I_H\}$



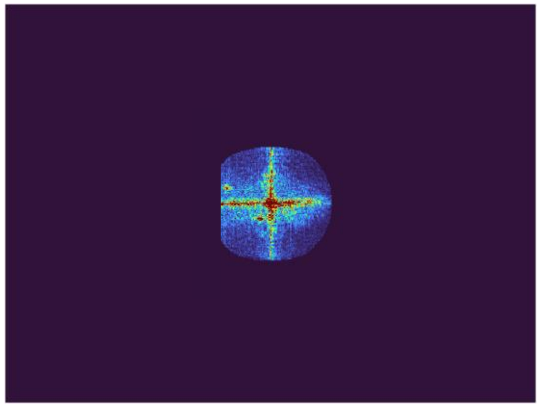
$\mathcal{F}\{I_O\}$



$\mathcal{F}\{I_H - I_O\}$



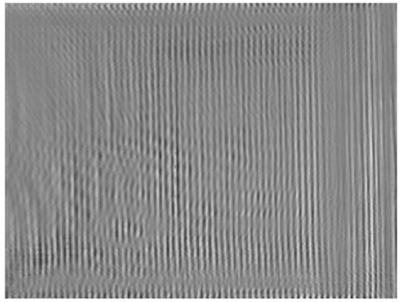
Filtered +1 order



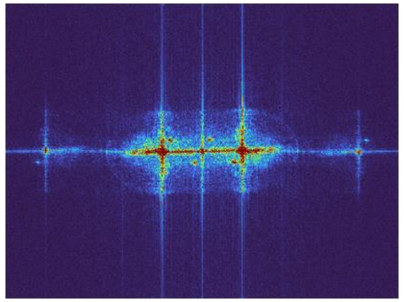
Phase retrieval assisted off-axis DH reconstruction

Off-axis reconstruction

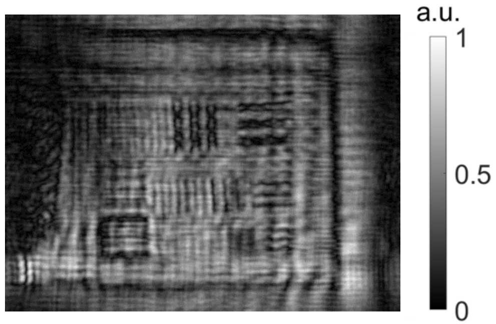
Hologram



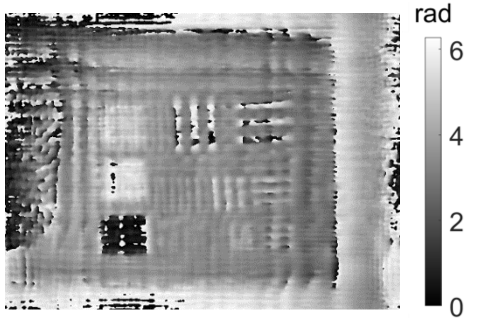
Fourier spectrum



Amplitude

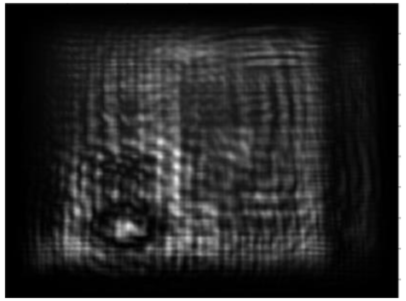


Phase

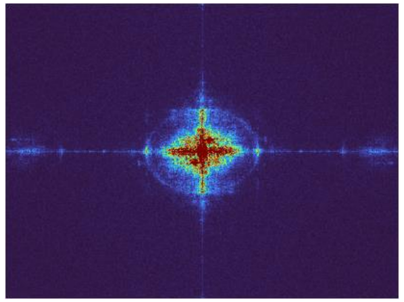


Off-axis +PR reconstruction (Apodized object intensity)

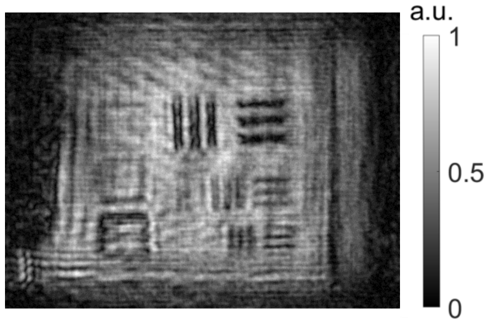
Apodized object intensity



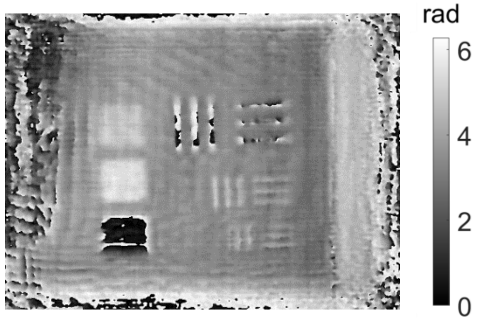
Fourier spectrum



Amplitude

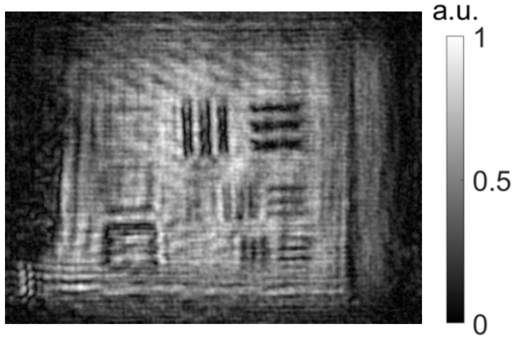


Phase

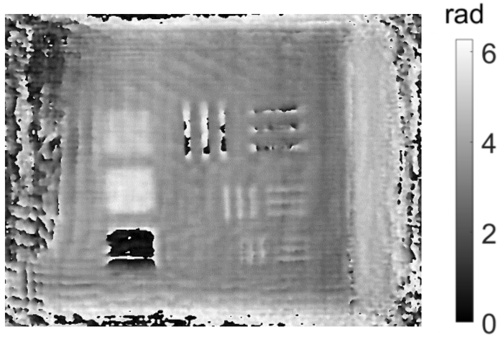


Phase retrieval assisted off-axis DH reconstruction

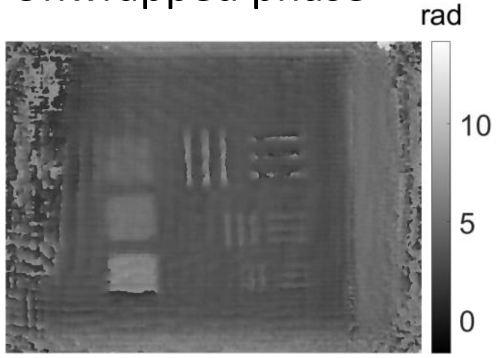
Off-axis +PR reconstruction

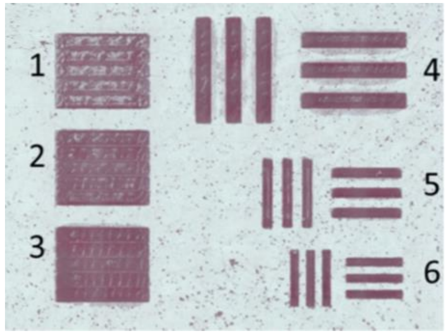


Wrapped phase



Unwrapped phase





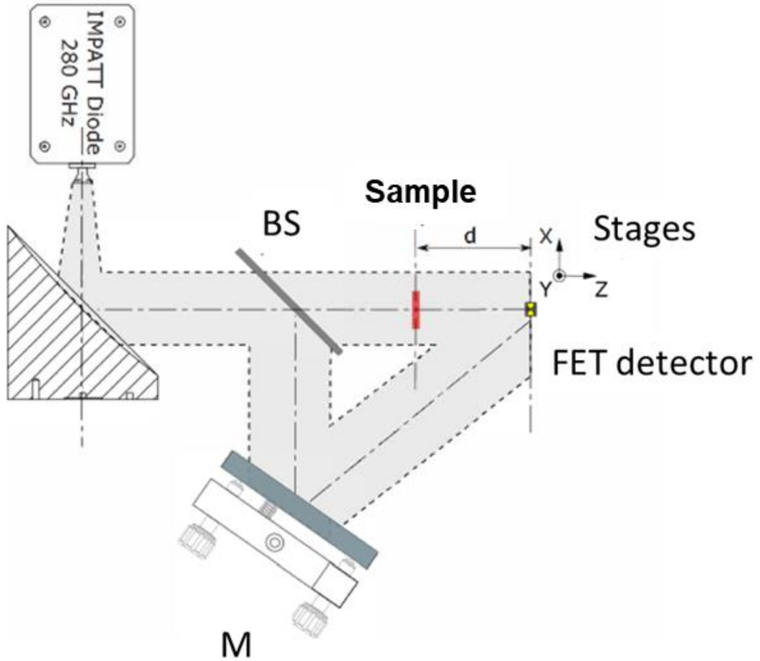
Zone	Depth (µm)	Calculated phase (rad)	measured phase (rad)	Measurement std (rad)
Pattern 1	44	1.14	1.13	0.21
Pattern 2	72	1.87	1.88	0.14
Pattern 3	105	2.72	2.95	0.14

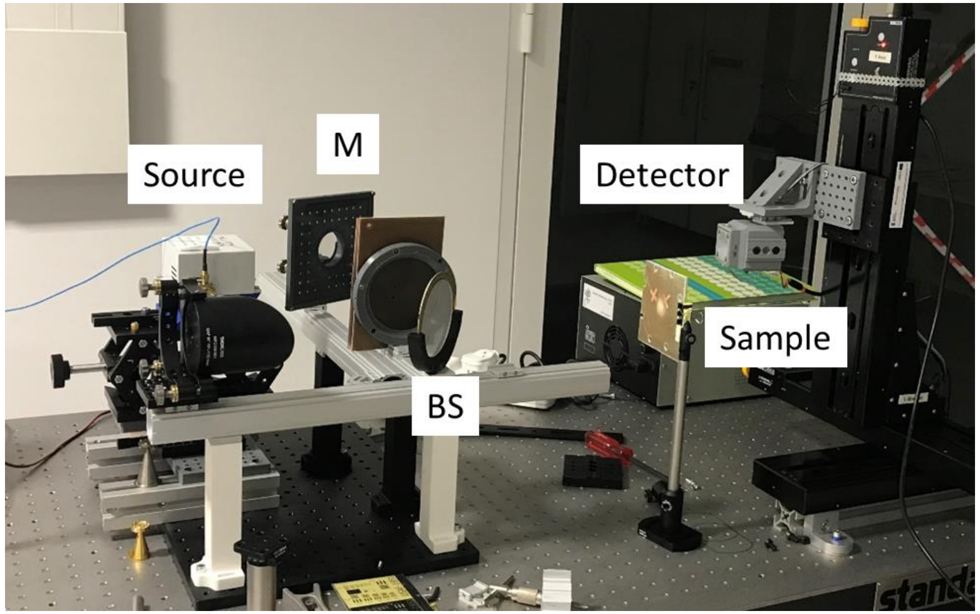
$$\varphi(x,y) = \frac{2\pi\,(n_{pp} - 1)\,d(x,y)}{\lambda}$$

Lateral resolution:

Pattern 6 resolvable ↔ 140 µm (1.17 λ)

Experimental setup at 280 GHz



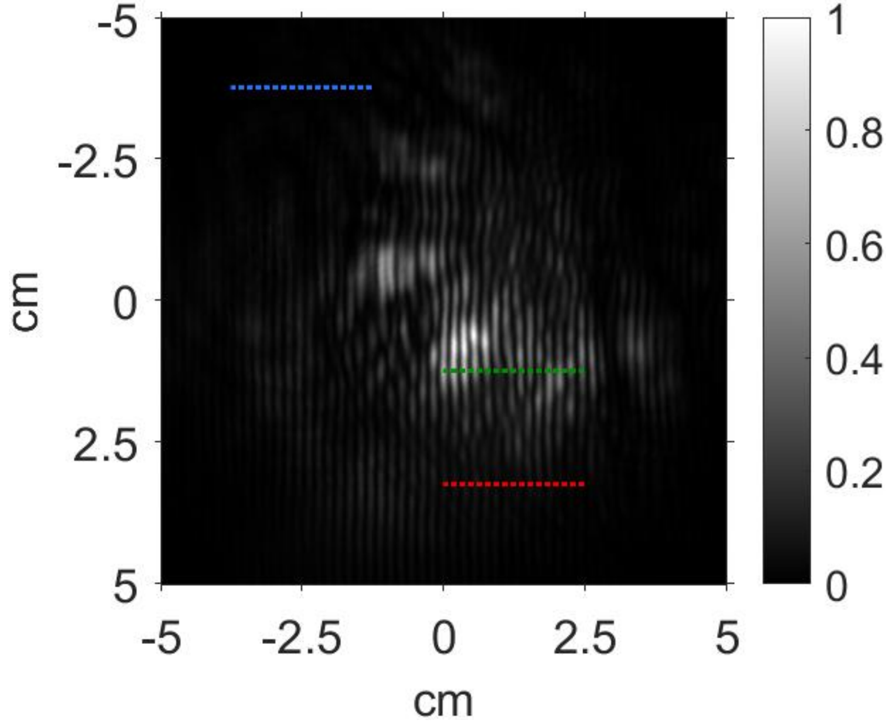


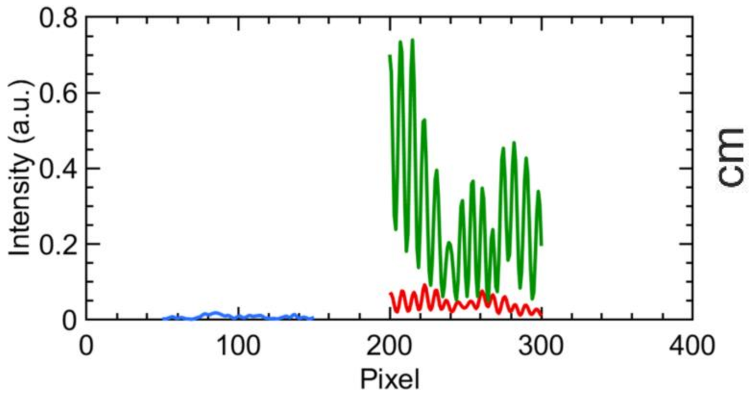
Wavelength: 1.07 mm (280 GHz)
Scanning step: 0.25 mm
Off-axis angle: 35°
Scanning area: 10×10 cm^2
One image =4 hrs

Zhao Y, But D, Georges M, et al. “Terahertz digital holography using field-effect transistor detectors,”44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). IEEE, 2019: 1-2.

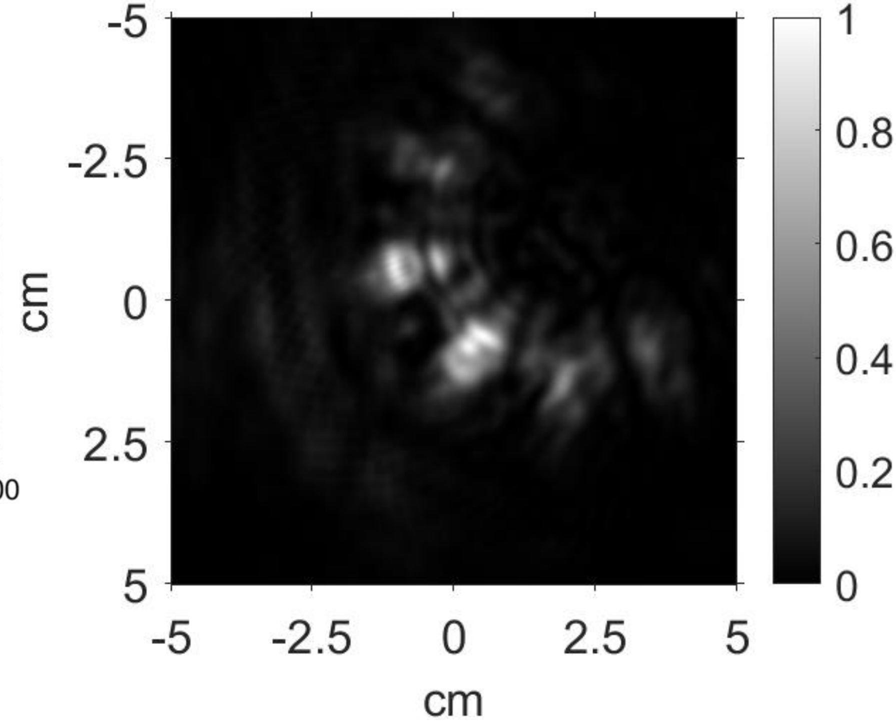
Phase retrieval assisted reconstruction: poor contrast hologram

Hologram

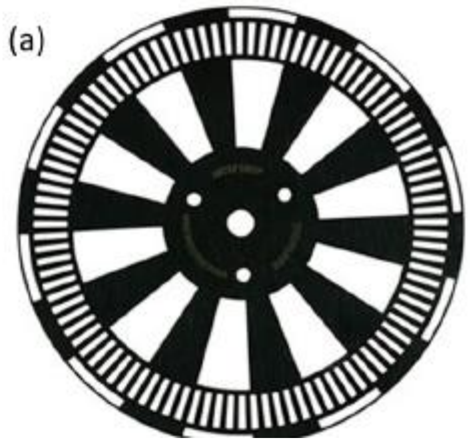


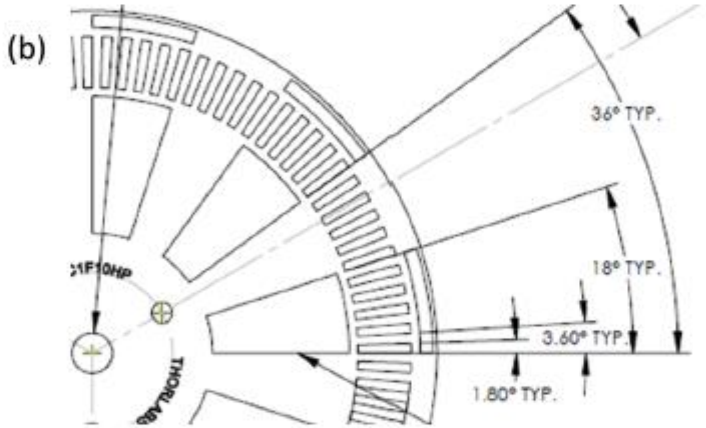


Object intensity

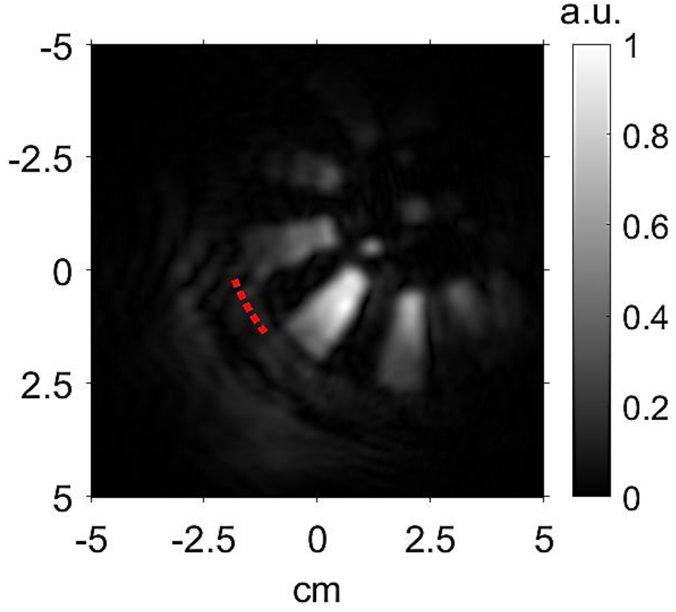


Phase retrieval assisted reconstruction: poor contrast hologram

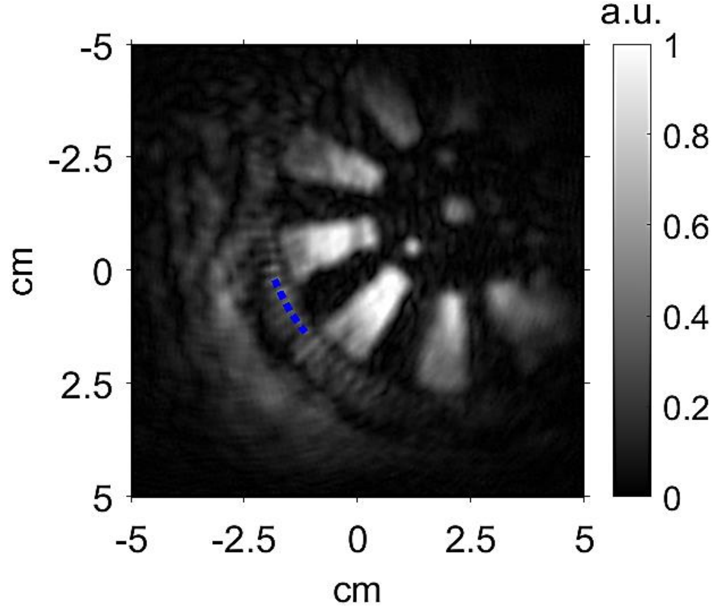


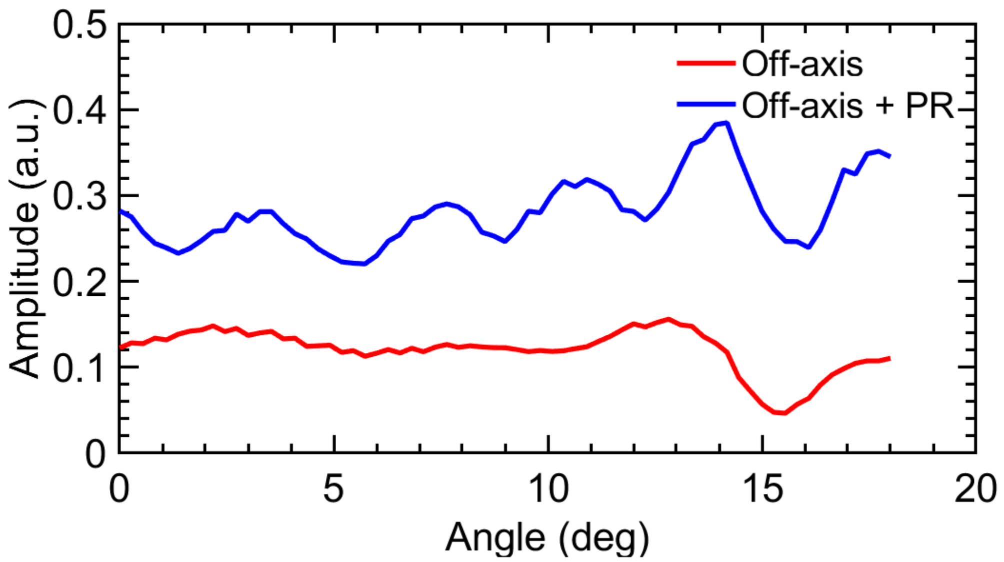


Off-axis reconstruction



Off-axis +PR





Conclusions on the development of THz digital holography

- THz off-axis DH @ 2.52 THz and 280 GHz
- Phase-retrieval method with object intensity improves the DH reconstruction quality

  - When suppressing the border artifact using apodization

  - When the off-axis hologram has poor contrast
- Limitations and difficulties:
  - Very short working distance for reference beam injection
  - Limited imaging area = $\min\{D_{cam}, D_{beam}\}$

Ptychography: reference wave-free, large imaging area, decouple illumination beam

Plan of presentation

Part 1: Overview of the THz technologies

Part 2: Overview of coherent lensless imaging techniques

Part 3: Developing THz digital holography

Part 4: Developing THz ptychography

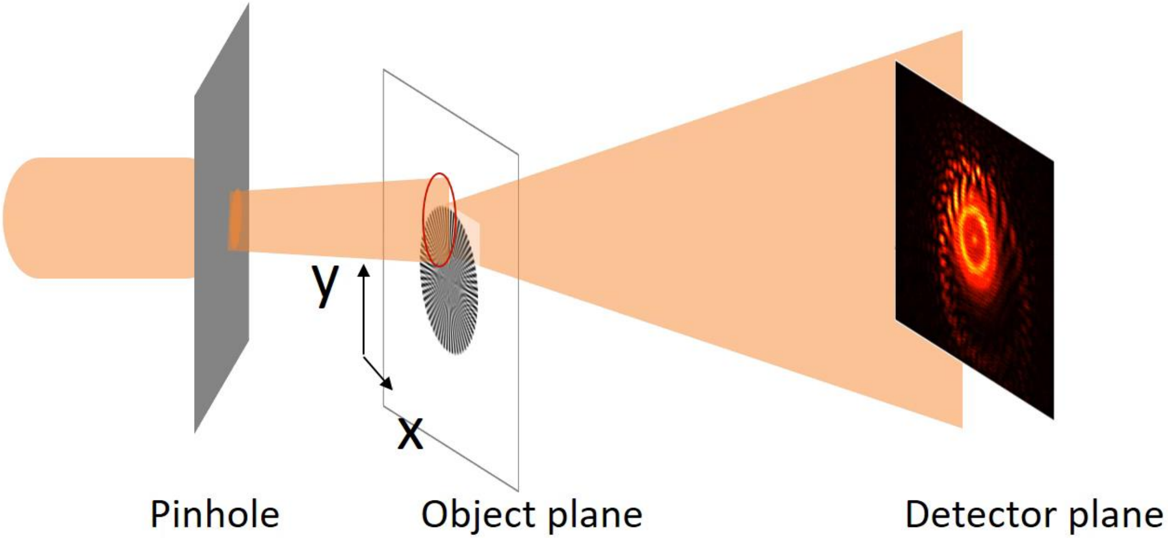
— Principle of ptychography

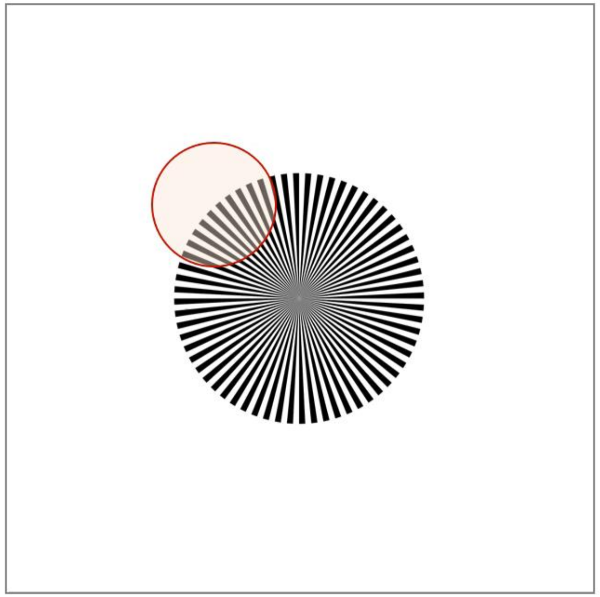
— THz reflective ptychography

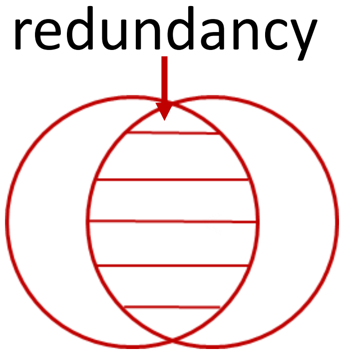
— Further improvement of THz ptychography

Part 5: Conclusions and perspectives

Ptychography: a special phase retrieval scheme

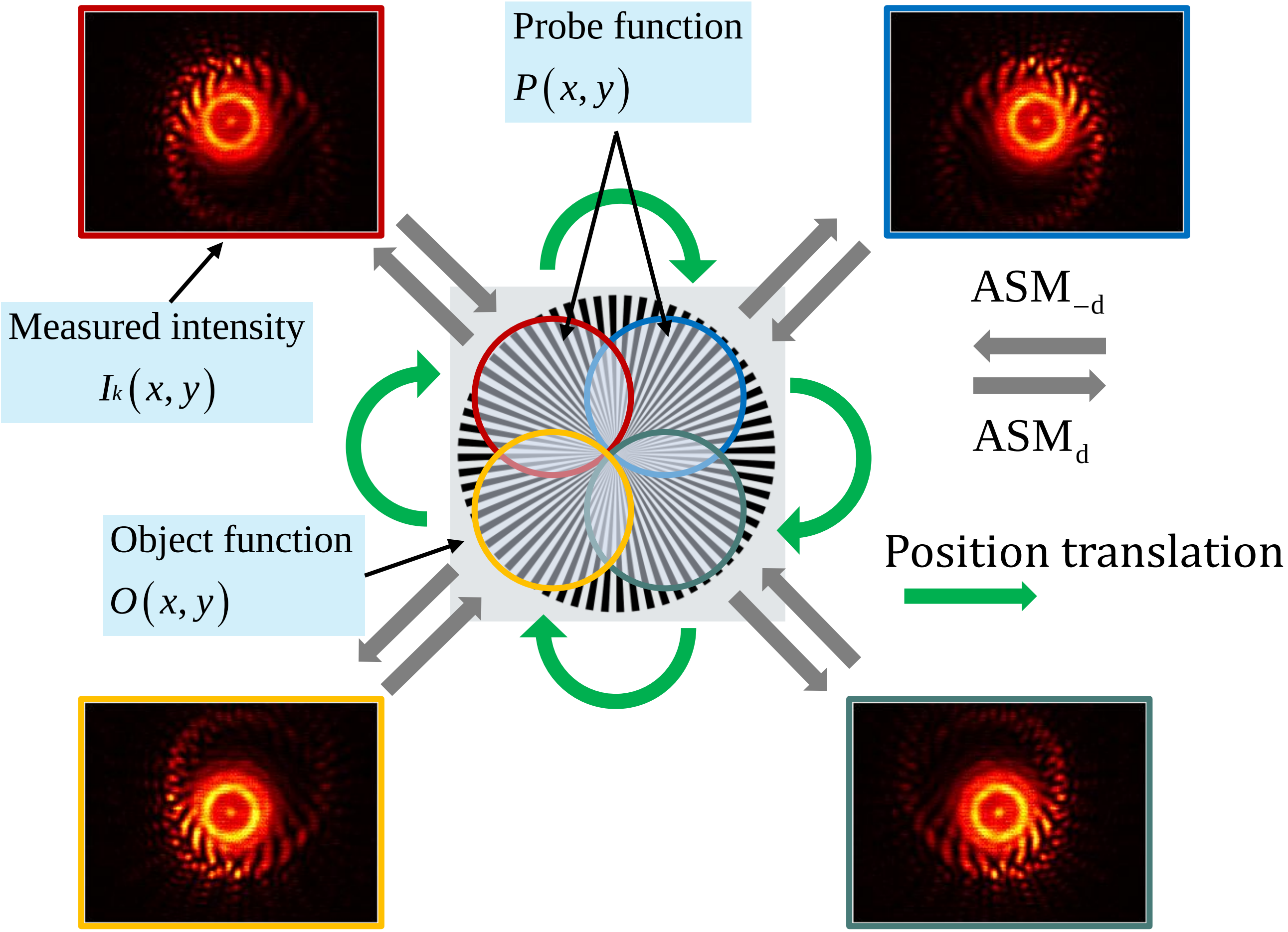






Ptycho: to fold

Extended ptychographic iterative engine (ePIE) for ptychography reconstruction



Object plane

exit wave at position k:

$$\Psi_k(x,y) = P_k(x,y)O_k(x-dx_k, y-dy_k)$$

Detector plane

updated complex wavefront at the detector:

$$\Psi'_k(x,y,\mathrm{d}) = \sqrt{I_k}\,\frac{\mathrm{ASM_d}\{\Psi_k(x,y,0)\}}{\left|\mathrm{ASM_d}\{\Psi_k(x,y,0)\}\right|}.$$

Object plane

updated exit wave:

$$\Psi'_k(x,y,0) = \mathrm{ASM_{-d}}\{\Psi'_k(x,y,\mathrm{d})\}.$$

updated object function and probe function:

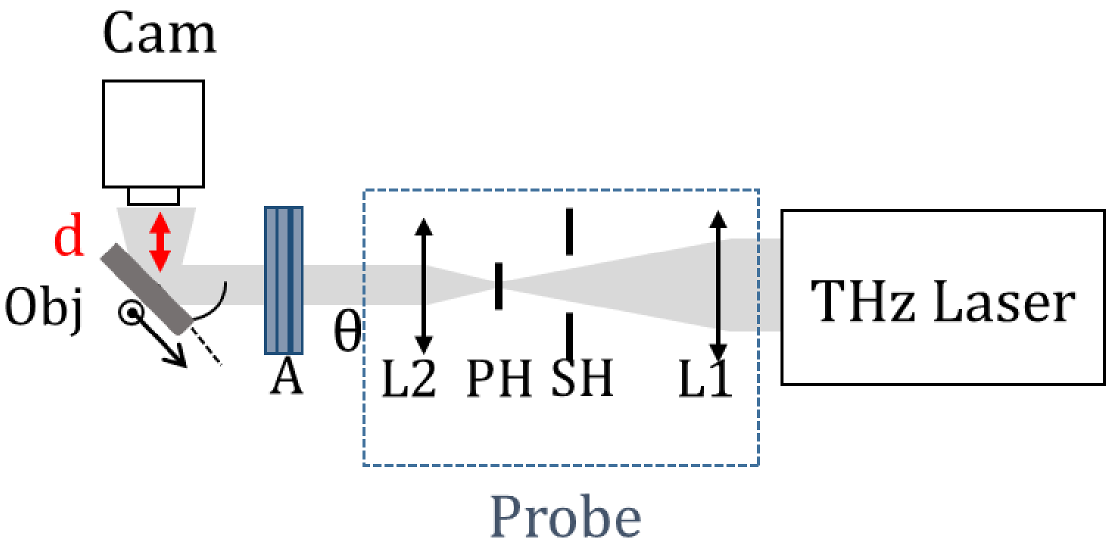
position k+1

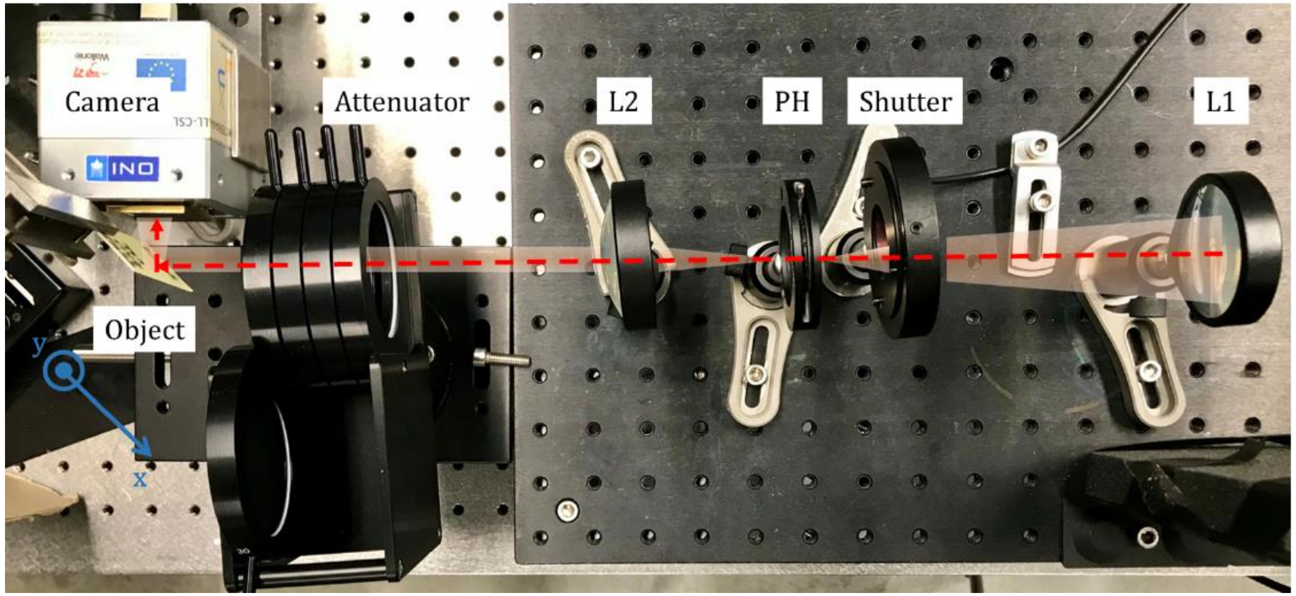
$$O'_{k+1}(x,y)$$

$$P'_{k+1}(x,y)$$

*(Maiden and Roddenburg, Ultramicroscopy **109**, 338-343, 2009)*

Terahertz Reflective Ptychography :Experimental setup





Wavelength: 96.5 µm

Object distance: 18 mm

Scanning position: 8×8

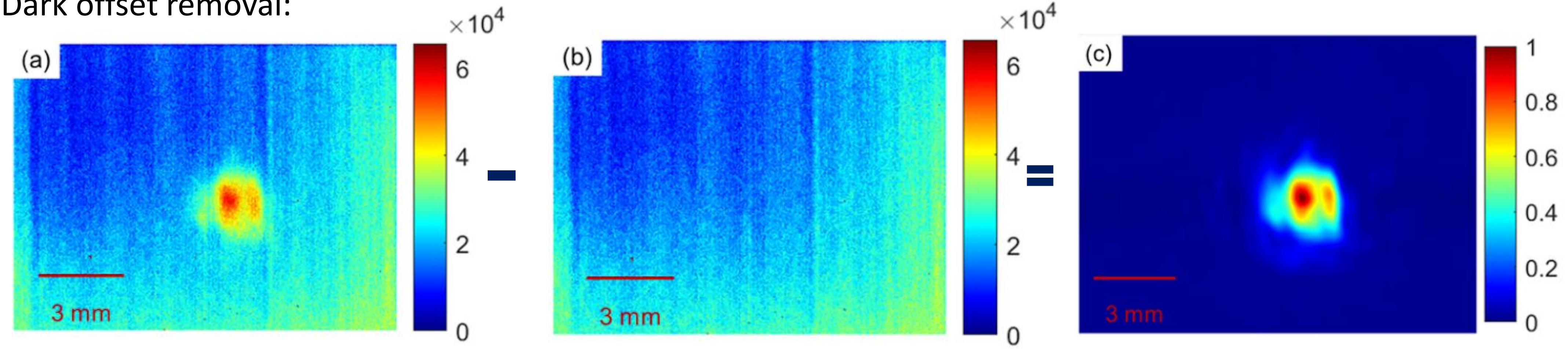
Probe size: 3 mm

Scanning step: 0.7 mm

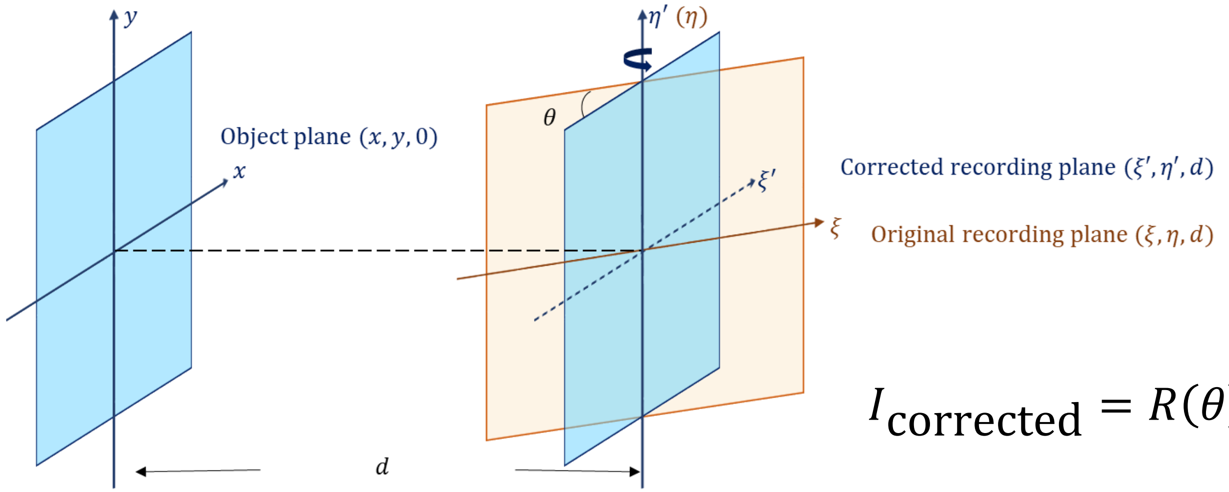
Rong, L., Tang, C., **Zhao, Y.**, Tan, F., Wang, Y., Zhao, J., Wang, D. and Georges, M., “Continuous-wave terahertz reflective ptychography by oblique illumination,” Opt. Lett. **45**(16), 4412 (2020).

Data pre-processing

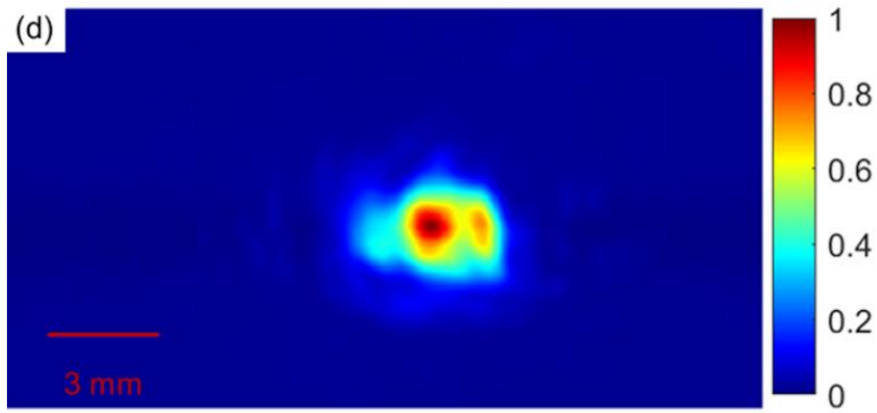
1. Dark offset removal:



2. Tilted plane correction

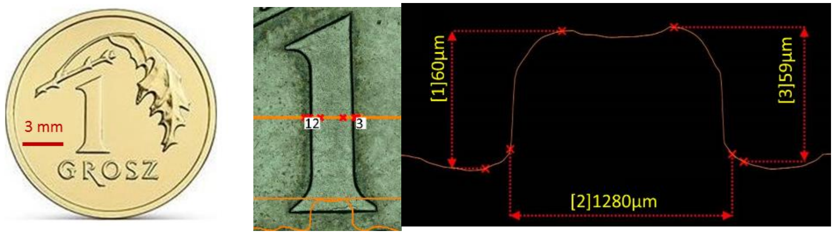


$$I_{\text{corrected}} = R(\theta) I_{\text{recorded}}$$

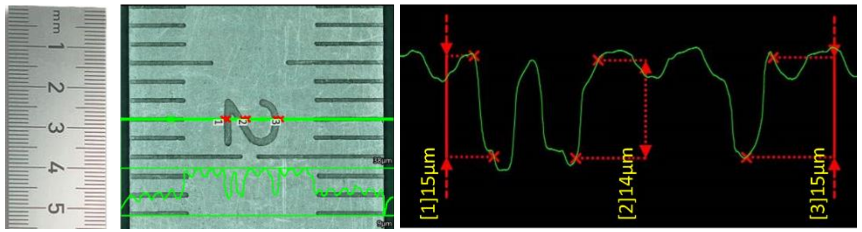


Results

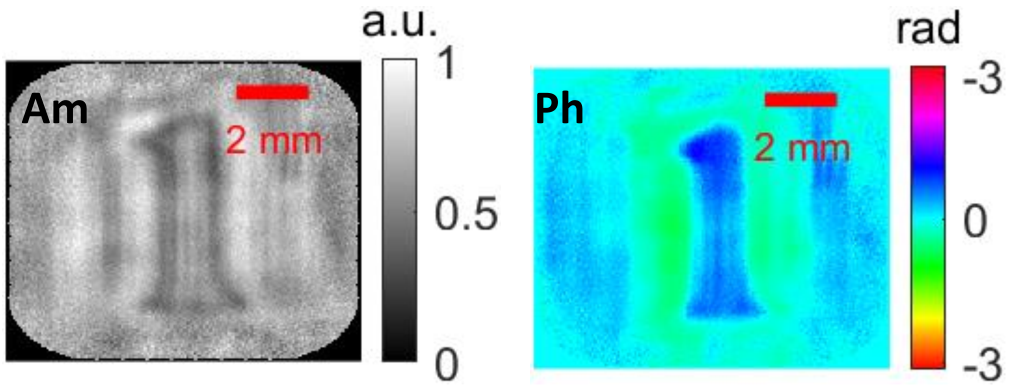
Sample 1



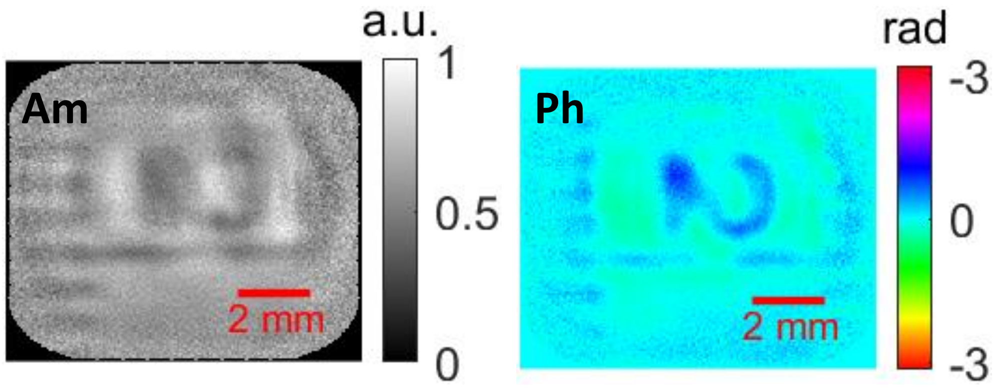
Sample 2



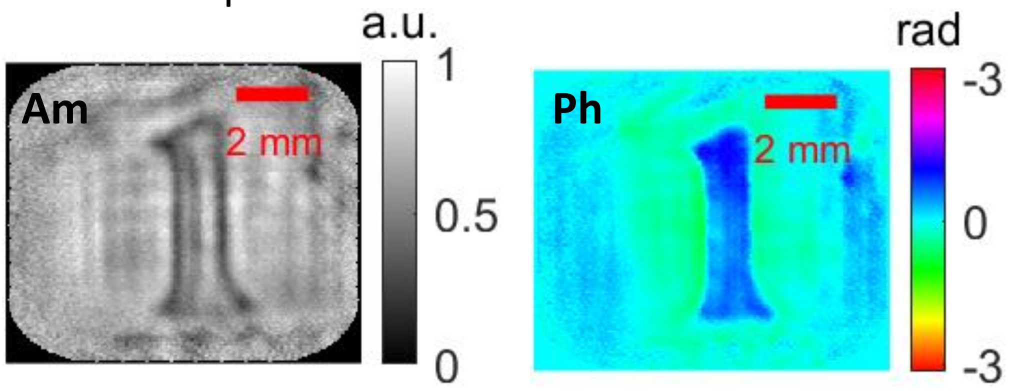
Without tilted plane correction



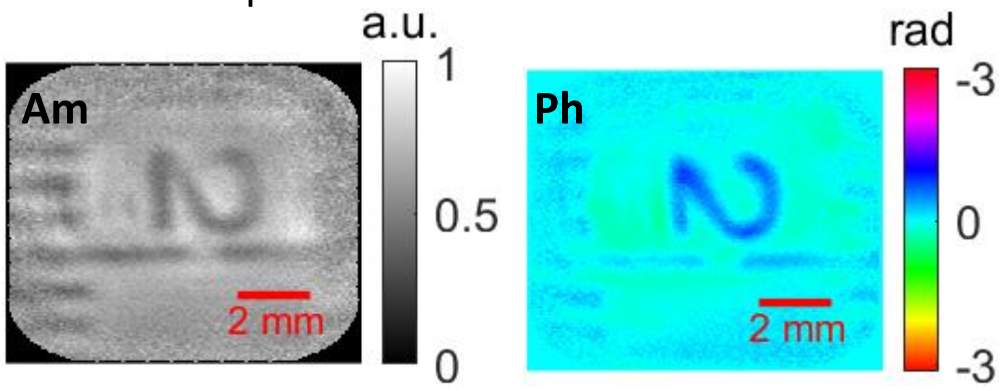
Without tilted plane correction



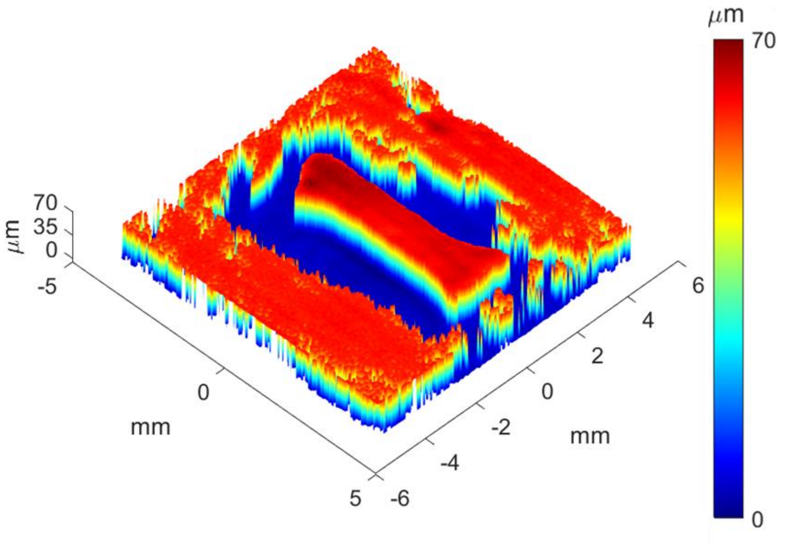
After tilted plane correction

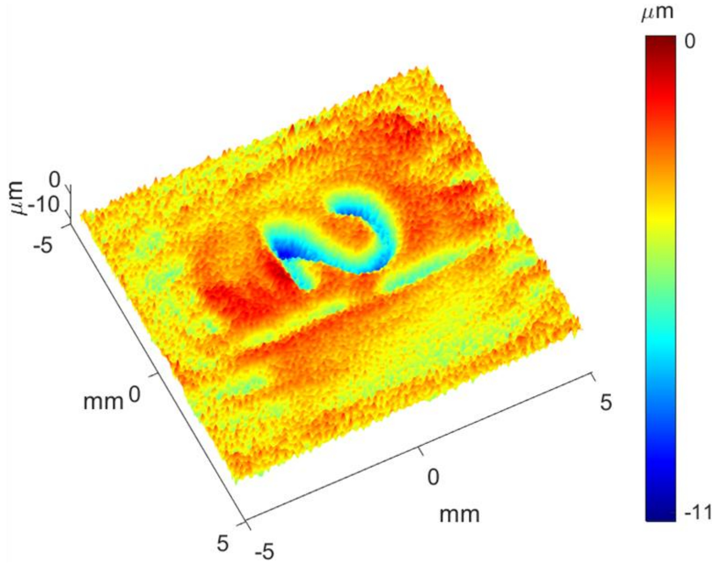


After tilted plane correction



Results





$$d(x,y) = \frac{\varphi(x,y)\lambda}{4\pi\cos\theta}$$

	Polish 1 Grosz coin	Stainless Steel ruler
Actual height [µm]	60 ($\pm$1.0)	-15 ($\pm$1.0)
Theoretical phase value [rad]	5.5 ($\pm$0.1)	-1.4 ($\pm$0.1)
Measured phase value [rad]	5.5 ($\pm$0.1)	-1.1 ($\pm$0.1)
Measured height [µm]	59 ($\pm$1.1)	-11 ($\pm$1.1)

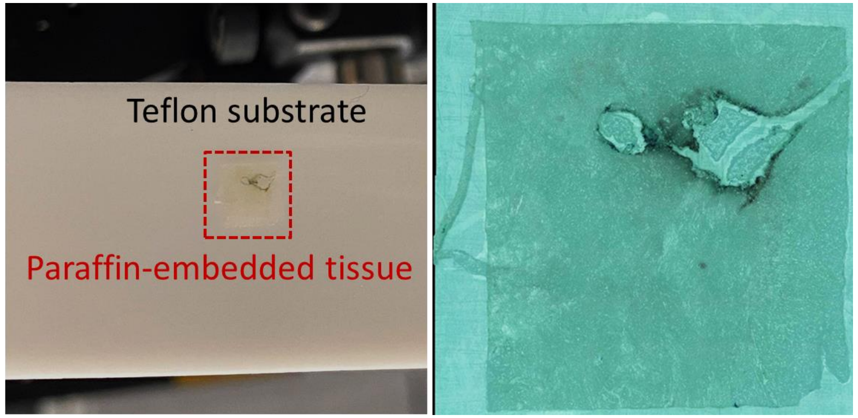
Limitations of current THz reflective ptychography

1. ePIE gets stagnated only after 15 iterations. Better image quality is expected.

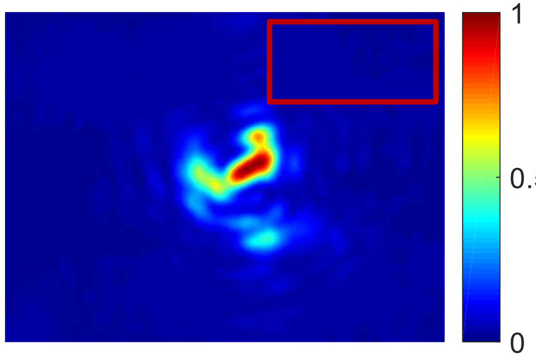
2. Limited FOV: larger samples require more scanning positions, time consuming.

Improvement towards biomedical sample imaging (1/3): background noise removal

First trial

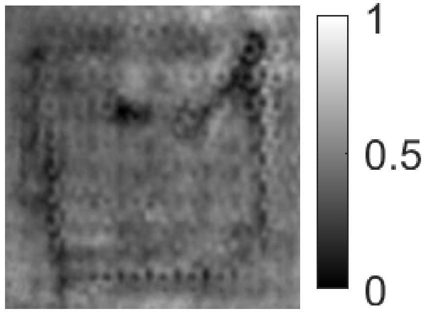


Diffraction pattern

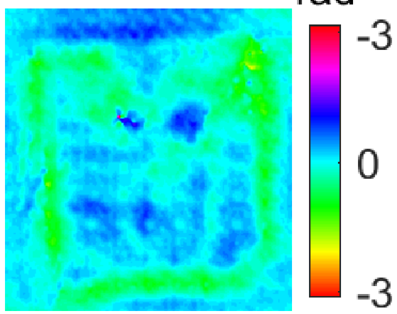


background noise residual

Am

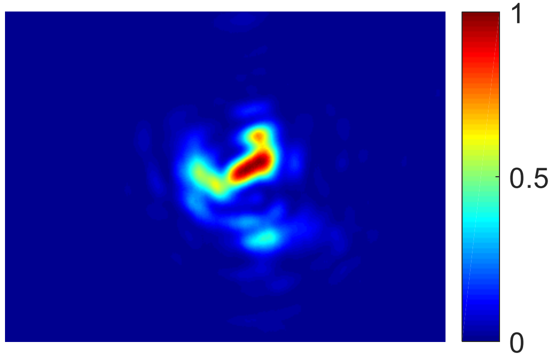


Ph

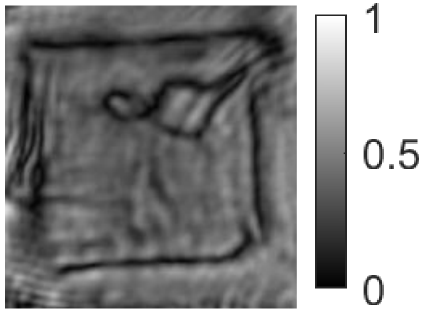


After removing the background noise residual

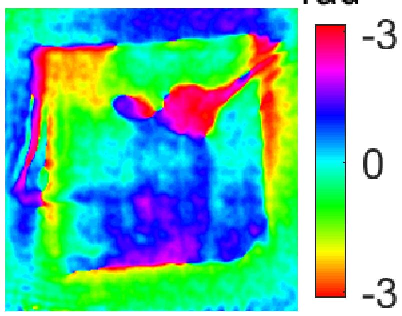
Diffraction pattern

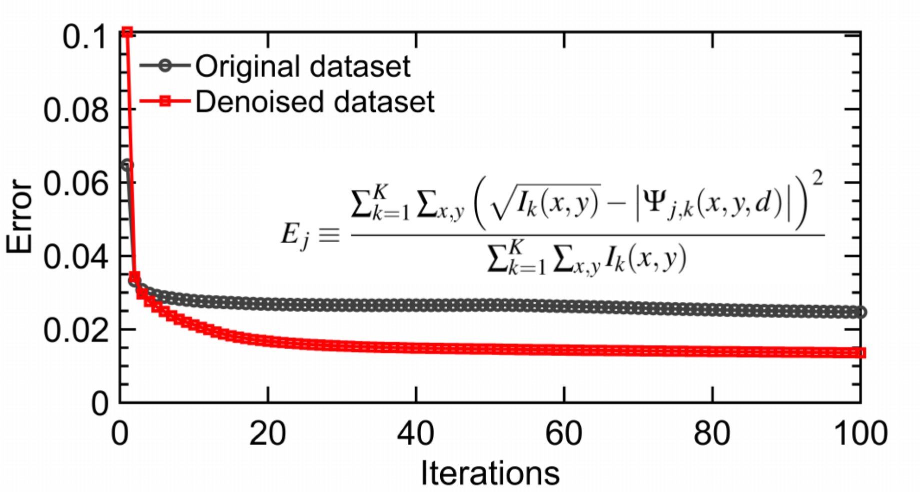


Am



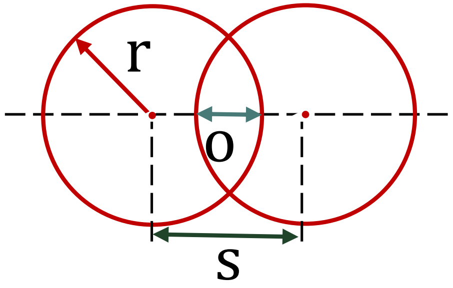
Ph





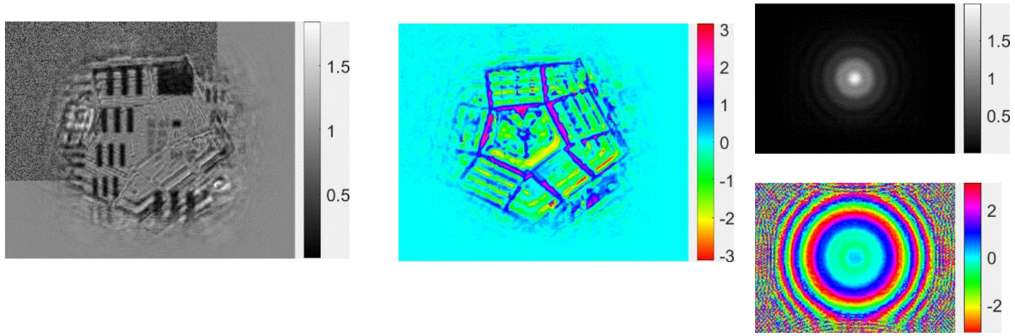
Improvement towards biomedical sample imaging (2/3): enlarging the FOV

Solution: Enlarge proportionally the radius of probe and the scanning step

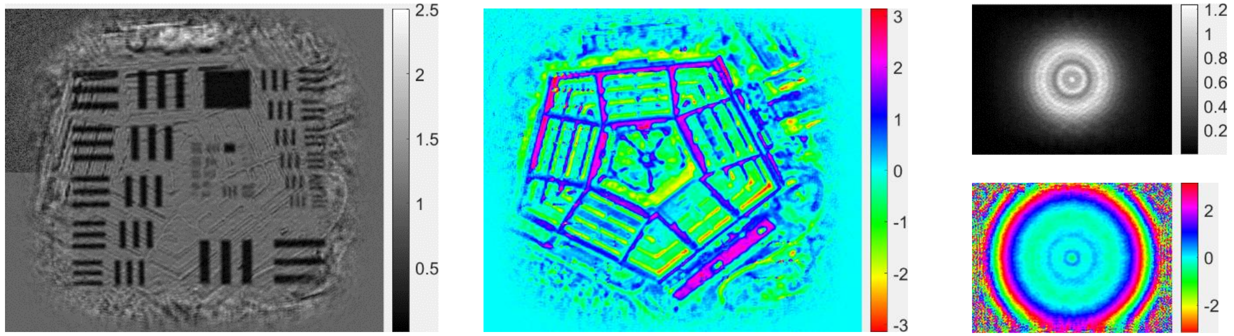


$$\text{overlap ratio} \equiv \frac{o}{2r} \times 100\% = (1 - \frac{s}{2r}) \times 100\%$$

Simulation:



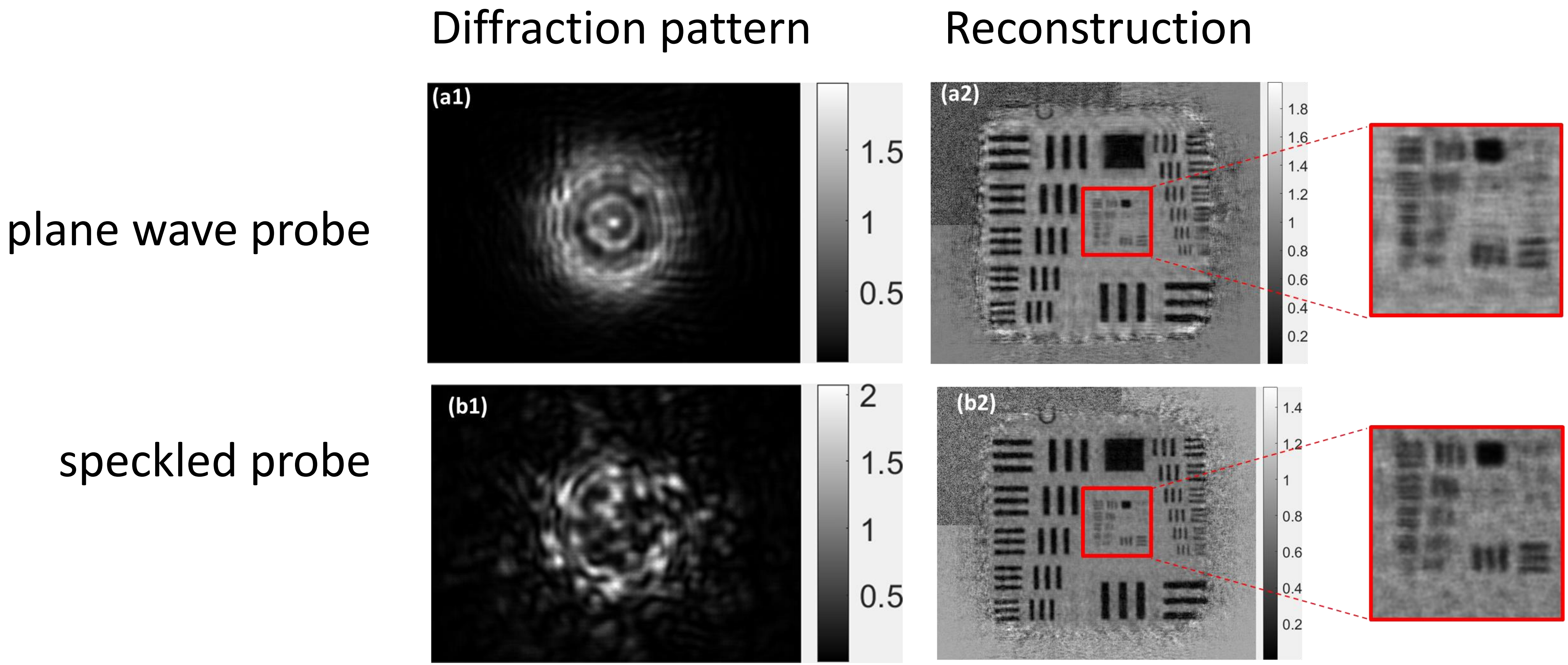
probe diameter: 3.3 mm;
step: 0.7 mm;
64 scanning positions;
theoretical FOV: 14.98 × 18.34 mm^2



probe diameter: 6.6 mm;
step: 1.4 mm;
64 scanning positions;
theoretical FOV: 19.88 × 23.24 mm^2

Improvement towards biomedical sample imaging (3/3): The benefit of diffuser

1. More flux on the border of detector



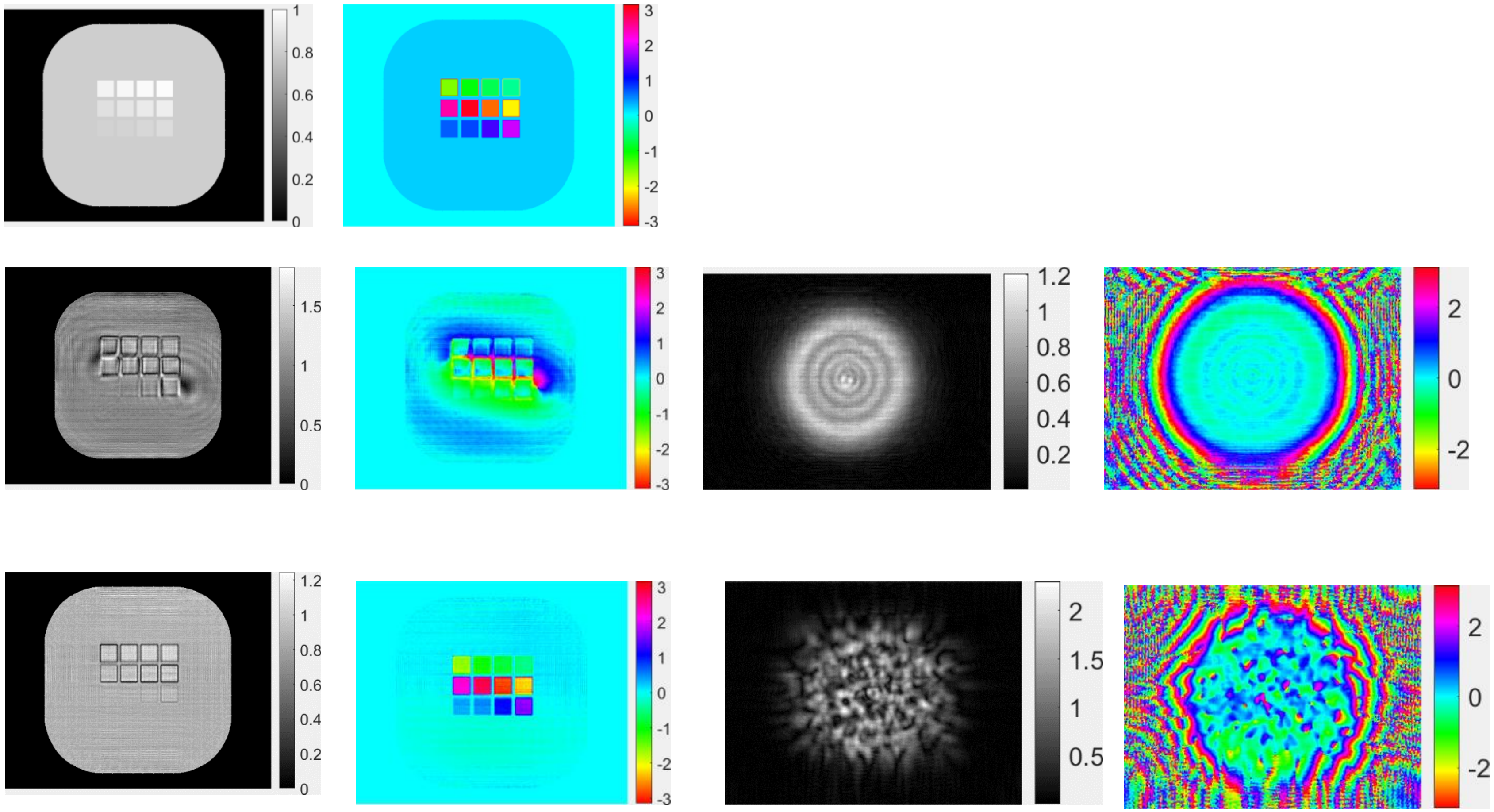
Improvement towards biomedical sample imaging (3/3): The benefit of diffuser

2. Higher effective overlap ratio on the object plane

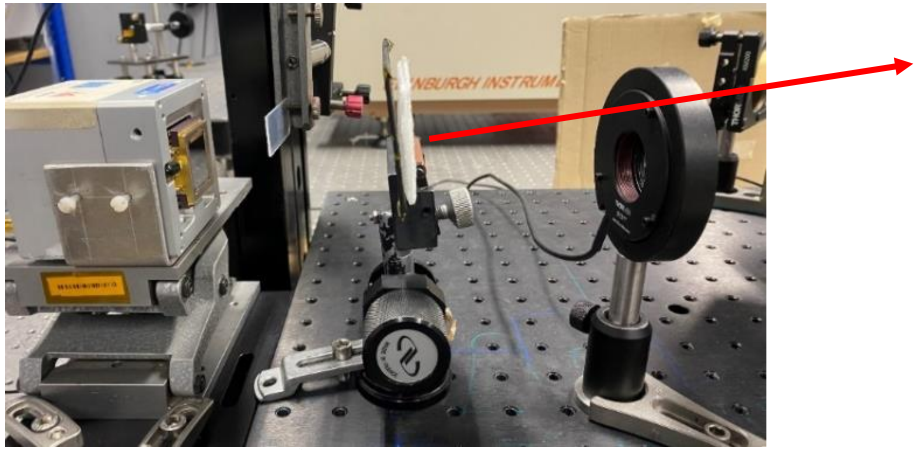
Simulated object

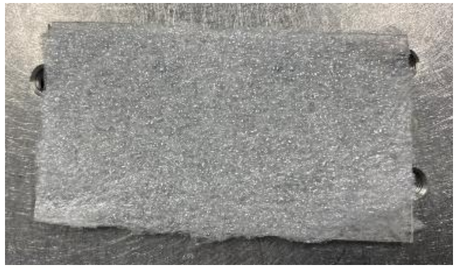
Plane wave probe

Speckled probe

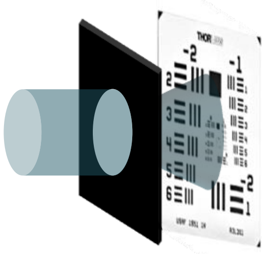


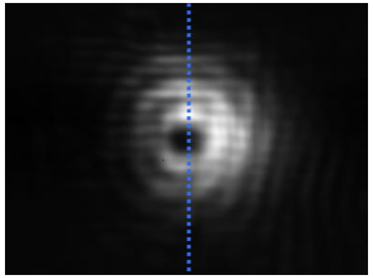
Improved THz ptychography setup

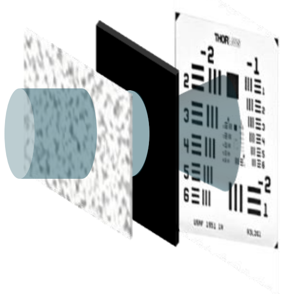


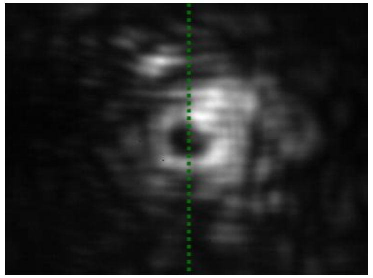


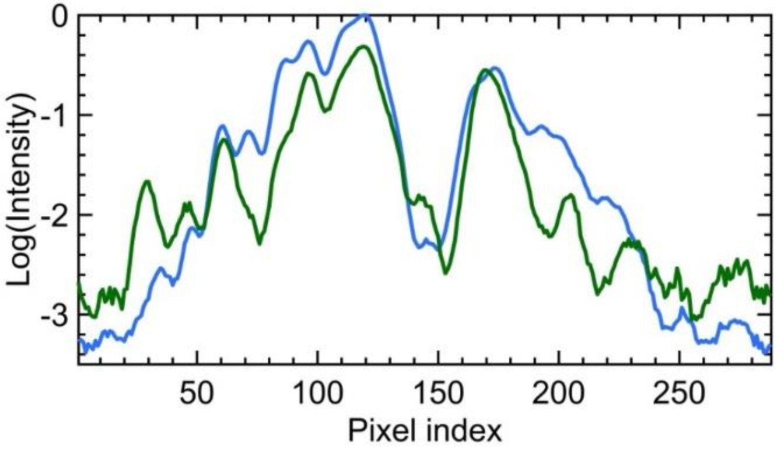
Homemade THz Diffuser



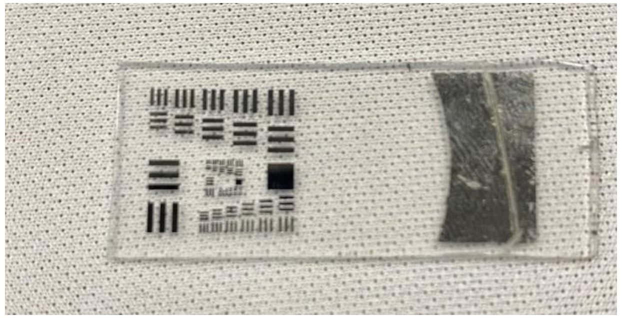


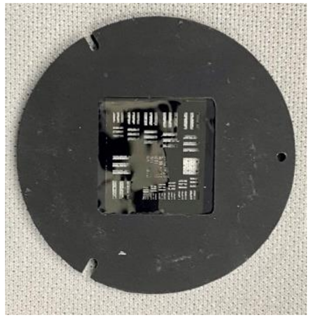






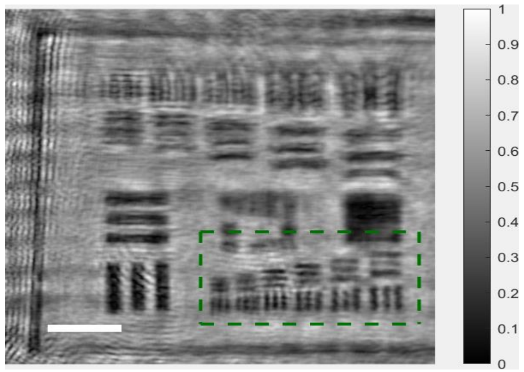
Experimental results: an amplitude contrast object

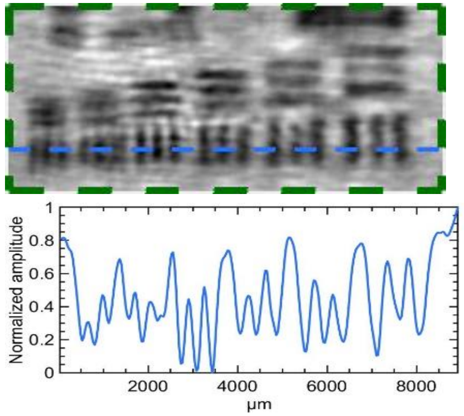




Wavelength: 118.83 μm
Scanned grid: 13 x 13 positions
distance:10.8 mm
50 iterations

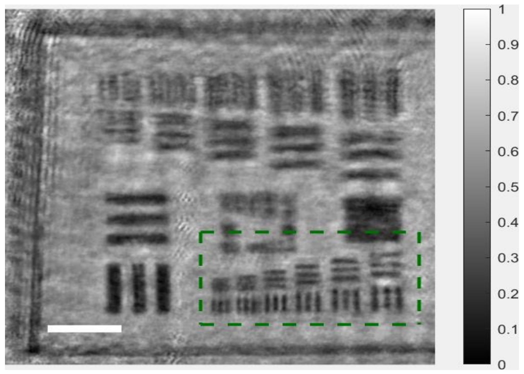
Plane-wave probe:

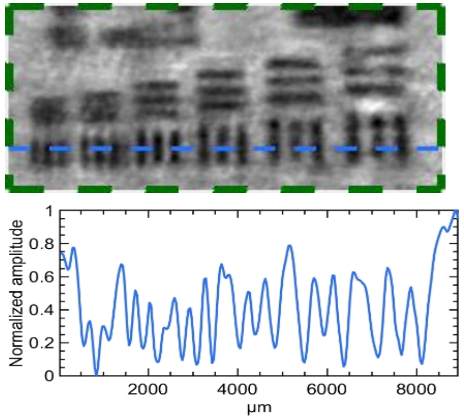




177.3 μm
(1.49 λ)

Speckled probe:

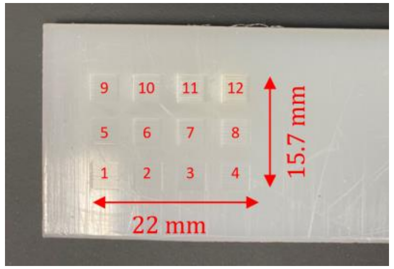


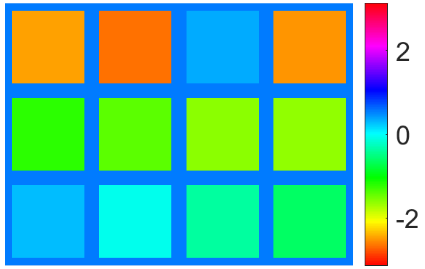


140.4 μm
(1.18λ)

Experimental results: phase contrast object

HDPE slab:

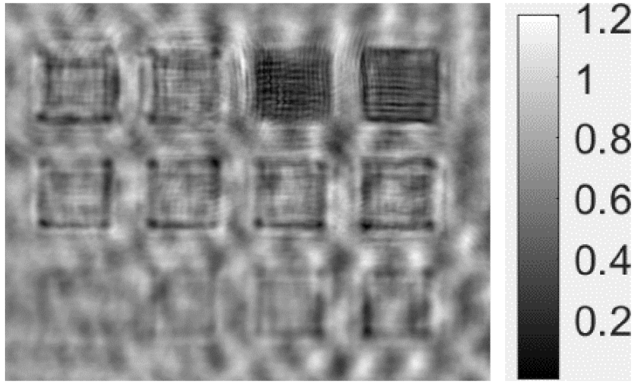


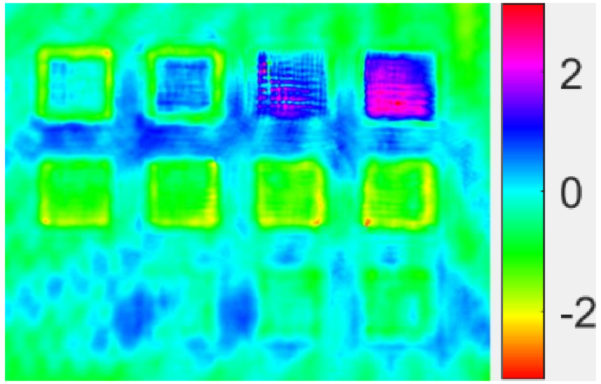


Wavelength: 118.83 µm
Scanned grid: 20 x 20 positions
distance:14 mm
100 iterations

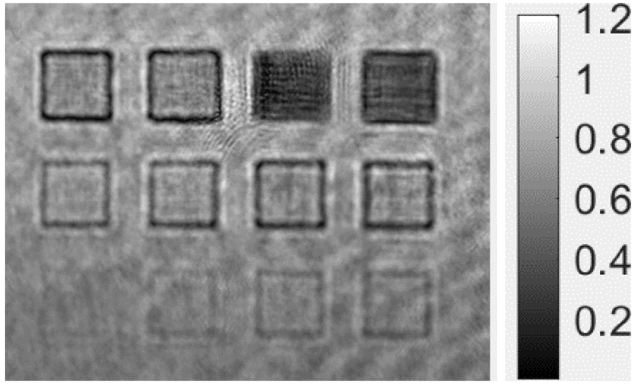
Amplitude | Phase

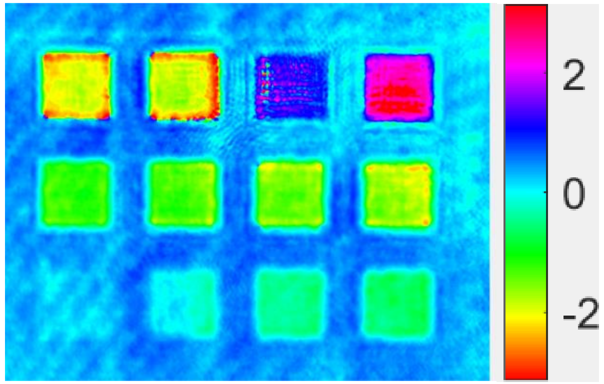
Plane-wave probe:



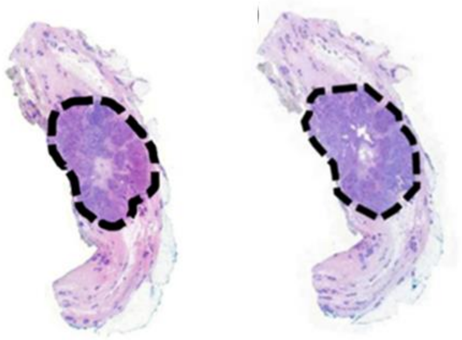


Speckled probe:



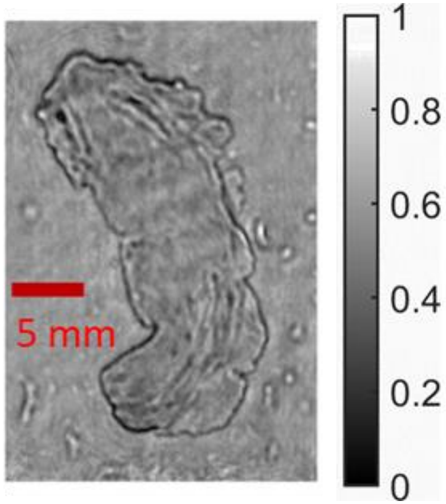


Experimental results: paraffin-embedded breast cancer tissue sample

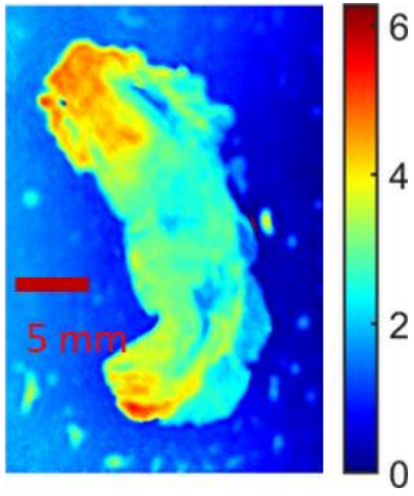


Wavelength: 118.83 µm
Scanned grid: 20 x 20 positions
Distance:14.8 mm
200 iterations

Ptychography

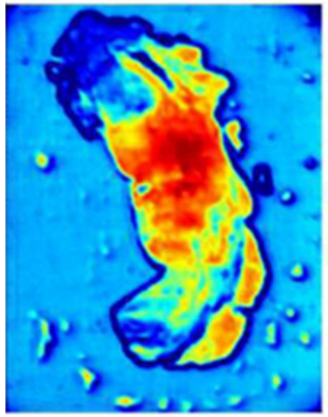


Amplitude



Phase

Phase map Vs. Reflective THz-TDS analysis



Amplitude at 1.12 THz using THz-TDS

Zhao, Y., Cerica, D., Boutaayamou, M., Verly, J. G., & Georges, M. P. (2022, May). Terahertz ptychography with efficient FOV for breast cancer tissue imaging. In *Unconventional Optical Imaging III* (Vol. 12136, pp. 48-56). SPIE.

Conclusions of the optimized THz ptychography setup

Three improvements

- Noise residual removal
- Larger probe, larger FOV
- Diffuser illumination

Performances

Lateral resolution
~ 140.4 μm (**1.18 λ**)

~2λ in Valzania et al., 2018

Phase resolution
0.1 rad

Plan of presentation

General Conclusions

1. A detailed study of THz technology and their readiness for THz imaging applications

FIR band

+	−
Higher TRL High resolution	Limited penetration

Sub-THz band

+	−
Good penetration	Lower TRL Lower resolution

2. Built a THz DH system and THz ptychography system, proposed further improvements

Digital holography

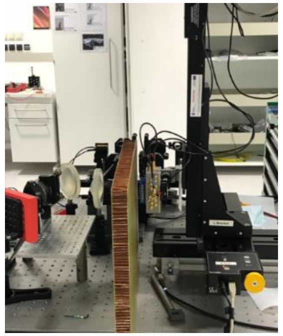
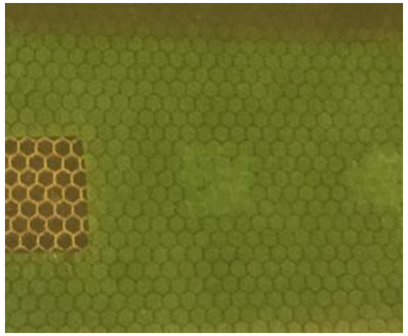
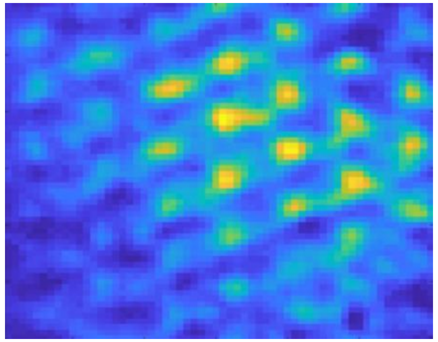
+	−
Single shot Fast reconstruction Reliable phase result	Limited FOV Reference wave

Ptychography

+	−
Reference wave free Unlimited FOV Decouple illumination beam	Lengthy acquisition Crosstalk Am Ph

Perspectives: THz lensless imaging towards industry

1. Developing THz ptychography at 280 GHz for NDT of composite with linear camera

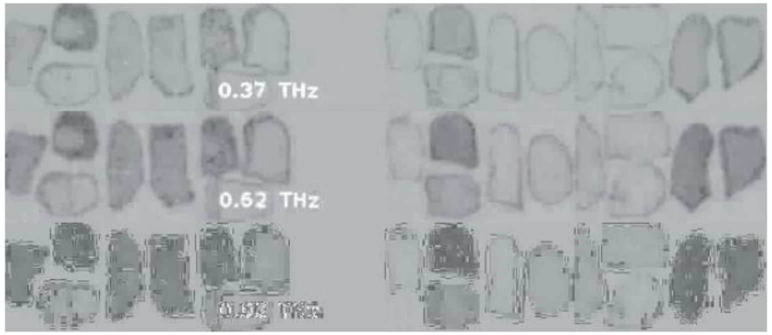




+

2. Application of FIR DH and ptychography towards plastic industry

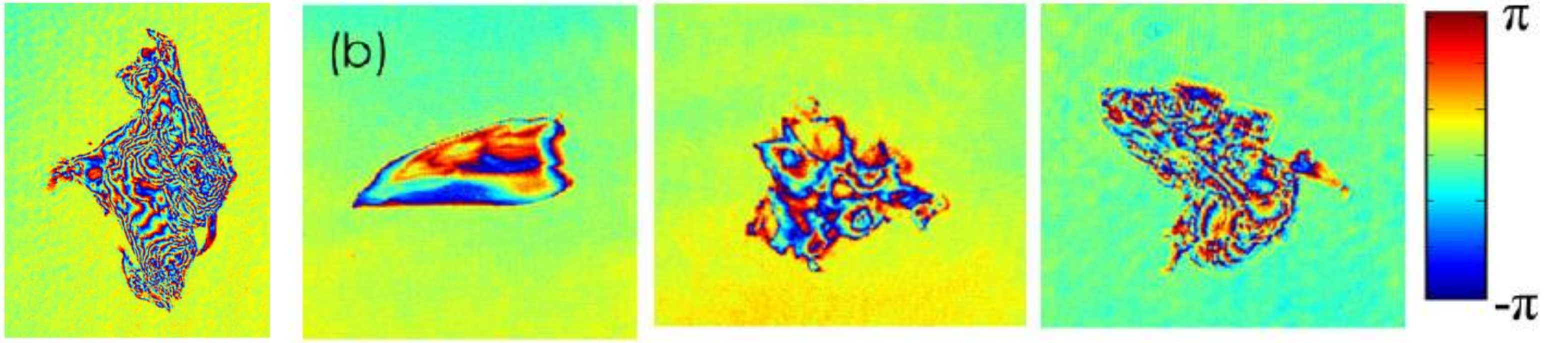
-Black plastic recycling

Black plastics under sub-THz imaging



Nüßler et al. (2014)

Transparent Microplastic under visible DH



Merola et al (2018)

Publication list

Chapter 2 and Chapter 3: THz coherent lensless imaging

Valzania, L[†]., **Zhao, Y.[†]**, Rong, L., Wang, D., Georges, M., Hack, E., & Zolliker, P. (2019). THz coherent lensless imaging. *Applied optics*, *58*(34), G256-G275.
Georges, M., **Zhao, Y**., & Vandenrijt, J. F. (2022). Holography in the invisible. From the thermal infrared to the terahertz waves: outstanding applications and fundamental limits. *Light: Advanced Manufacturing*, *2*, 1-14.

Chapter 4: Development of digital holography

Zhao Y, But D, Georges M, et al. “Terahertz digital holography using field-effect transistor detectors,”44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). IEEE, 2019: 1-2.
Zhao, Y., Vandenrijt, J. F., Kirkove, M., & Georges, M. (2019). Iterative phase-retrieval-assisted off-axis terahertz digital holography. *Applied Optics*, *58*(33), 9208-9216.
Zhao, Y., Zemmamouche, R., Vandenrijt, J. F., & Georges, M. P. (2018). Accuracy concerns in digital speckle photography combined with Fresnel digital holographic interferometry. *Optics and Lasers in Engineering*, *104*, 84-89.

Chapter 5 and Chapter 6: Development of ptychography

Rong, L., Tang, C., **Zhao, Y.**, Tan, F., Wang, Y., Zhao, J., Wang, D. and Georges, M., “Continuous-wave terahertz reflective ptychography by oblique illumination,” Opt. Lett. **45**(16), 4412 (2020).
Zhao, Y., Cerica, D., Boutaayamou, M., Verly, J. G., & Georges, M. P. (2022, May). Terahertz ptychography with efficient FOV for breast cancer tissue imaging. In *Unconventional Optical Imaging III* (Vol. 12136, pp. 48-56). SPIE.

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