Holography from thermal infrared to terahertz in view of applications in metrology and nondestructive testing

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Summary

- Some basics of holography
  - Recording-reconstruction
  - Applications
  - Where long wavelengths matter
- Long-wave IR digital holography
  - Applications in aerospace
- THz digital holography
  - FIR
  - Sub-THz
Holography at long wavelength (IR to THz waves)

- Holography: recording of whole wavefield information: amplitude and phase
- No analog hologram recording material
- Numerical recording of hologram with camera sensors: « Digital Holography »

Digital Holography principle

**Step 1: Recording hologram**

\[
I(u, v) = [U_o(u, v) + U_r(u, v)] \cdot cc
\]

\[
I(u, v) = I_{av}(u, v) \left[ 1 + m(u, v) \cos(\varphi_r(u, v) - \varphi_o(u, v)) \right]
\]

Hologram intensity at point \((u, v)\)
Holography

- Digital Holography principle - 2

**Step 2: Reconstruction by scalar diffraction theory**

\[ U(x, y, d) = \mathcal{F}^{-1}\{\mathcal{F}\{U(x, y, 0)\}. H(f_x, f_y)\} \]

**Rigorous: Angular Spectrum Method (ASM)**

\[ H_{ASM}(f_x, f_y) = \exp \left[ i \frac{2\pi}{\lambda} d \sqrt{1 - \lambda^2 (f_x^2 + f_y^2)} \right] \]

\[ f_x = x/\lambda d \quad ; \quad f_y = y/\lambda d \]

**Paraxial approximation:** distance \( d \gg \text{object size} \)

\[ H_{Fresnel}(f_x, f_y) \approx \exp \left[ i \frac{2\pi}{\lambda} d \left( 1 - \frac{\lambda^2}{2} \left( f_x^2 + f_y^2 \right) \right) \right] \]

**Fresnel lens-less DH reconstruction principle**

\[ U(x, y, d) = \frac{i}{\lambda d} e^{-i2\pi d/\lambda} \exp \left[ -i \frac{\pi}{\lambda d} (x^2 + y^2) \right] \iint I(u, v)U_r(u, v) \exp \left[ -i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \exp \left[ i \frac{2\pi}{\lambda d} (xu + yv) \right] dudv \]
Holography

- Digital Holography principle - 3

Reconstruction by Fresnel lensless DH principle

\[ U(x, y, d) = \iint I(u, v)U_r(u, v) \exp \left[ -i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \exp \left[ i \frac{2\pi}{\lambda d} (xu + yv) \right] dudv \]

\[ \mathcal{F}\left\{ I(u, v)U_r(u, v)\exp \left[ -i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \right\} \quad \text{“S-FFT”} \]

Off-Axis

In-line

Preliminary capture of separated beams

Suppress unwanted orders

Resolution: 1/4

Phase-shifting (4 acquisitions)

Extract object image

Resolution: full
Holography

- Digital Holography principle - 3

Reconstruction by Fresnel lensless DH principle

\[ U(x, y, d) \div \iint I(u, v)U_r(u, v) \exp \left[ -i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \exp \left[ i \frac{2\pi}{\lambda d} (xu + yv) \right] dudv \]

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Amplitude

\[ A_o(x, y, d) = \sqrt{Re^2(U_o(x, y, d)) + Im^2(U_o(x, y, d))} \]

Phase

\[ \varphi_o(x, y, d) = \tan^{-1} \left[ \frac{Im(U_o(x, y, d))}{Re(U_o(x, y, d))} \right] \]
Applications

- Imaging

  Reflecting objects
  © Picart

  Changing reconstruction distance $z$ to best focus at $z = d$

- Interferometry

  Record time series of holograms

  Reflecting objects
  displacements
deformations

  Transparent objects
  Refractive index changes

- Transparent objects
  © Dubois
Where long wavelength matters

- **Object size**
  \[ S \sim d \left[ \frac{\lambda}{\Delta} \right] \]
  \( d \): reconstruction distance
  \( \lambda \): wavelength
  \( \Delta \): pixel size

- **Stability of setup**
  Stability criterion during hologram recording:
  Hologram pattern \( \{ I(u, v) \} \) cannot move by a fraction of wavelength, generally \( \frac{\lambda}{10} \)

- **Measurement range in interferometric metrology**
  Measurement range:
  number of resolvable fringes depends on wavelength

- **Transmission of object/matter is function of wavelength**
  Obviously necessary for inspection/phase measurement of transparent objects
LWIR DH Interferometry

- Application in metrology for European Space Agency (ESA)
- ESA needs:
  - Full-field deformations of space reflectors in vacuum-thermal testing
  - Large reflectors: up to 4 m diameter
  - Industrial working conditions
  - Range of deformations: 1 µm – 250 µm

LWIR DH well suited
**LWIR DH Interferometry**

- Application in metrology for European Space Agency


Diffuser

- Uncooled \(\mu\)-bolometer
- 640x480 pixels
- Pixel Pitch: 25 \(\mu\)m
- Frame rate 60 Hz
- 16 bits

**CO\(_2\) LASER**

- \(\lambda: 10.6\ \mu\text{m}\)
- Power: 8 Watts
LWIR DH Interferometry

- Application in metrology for European Space Agency (ESA)
LWIR DH Interferometry

- Application in metrology for European Space Agency (ESA)

Measure during vacuum-cryogenic test:
- Deformation of each detector
- Deformation of ensemble
- Rigid body motions of each detector
- Large rigid body motion of ensemble

In the range of LWIR DHI

Terahertz Digital Holography

- **Motivation:**
  - Application in defect detection (NDI) in materials transparent
  - Digital holography allows reconstruction at different depths numerically based on single shot

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**Materials transparent in THz**

- Silicon
- Plasmas, teflon,...
- Foams
- Paints & varnishes

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**Radome (glass fiber composite)**

- Material transparent in sub-THz

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**State of art: scanning**

© Fraunhofer ITWM
Terahertz Digital Holography

**Motivation:**

- Application in defect detection (NDI) in plastics/composites
- Digital holography allows reconstruction at different depths numerically based on single shot

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**Transfer our knowledge from LWIR to THz**

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**Optimized FIR camera**

- 384×288
- 35 µm pitch

**LWIR camera**

- 640x480
- 17 µm pitch

LWIR camera has good response in FIR!!

(Without lens...)

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**Gas laser**

P=500 mW @ λ=118.8 µm (2.5 THz)
Terahertz Digital Holography

- **Validity of paraxial approximation at FIR**
  - Object must be very close to the sensor (a few cm)
  - Reconstruction by S-FFT feasible but lateral resolution very poor

- **Solution: Use rigorous Angular Spectrum Method (ASM)**
  - Size of reconstructed object = size of detector
  - Lateral resolution proportional to distance object-sensor $d$

- **Set-up:**
Terahertz Digital Holography

- Improve resolution
  - Decrease distance $d$
  - Problem: occlusion of reference beam by object
  - Large angles: difficult and occlusion by camera frame

*Occlusion of reference beam by object*

*Image degradation!*

*Recorded holograms with occlusion*
Terahertz Digital Holography

- Use of phase retrieval to recover image and improve resolution

**Initial guess** of $U_0$:
Reconstruction from off-axis hologram

- Off-axis digital hologram
- In-line recording

**Object plane**
- $U_o(d)$
- $|U_o(d)|$  $\arg\{U_o(d)\}$

**Detector plane**
- $|U_o(0)|$  $\arg\{U_o(0)\}$  $\sqrt{I_o(0)}$  $\arg\{U_o(0)\}$
Terahertz Digital Holography

- Use of phase retrieval to recover image and improve resolution

**Simulated**

<table>
<thead>
<tr>
<th>Off-axis Hologram</th>
<th>Initial</th>
<th>Improved</th>
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<tbody>
<tr>
<td><img src="image1" alt="Hologram" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
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Intensity in-line

**Experimental**

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Intensity in-line

Resolution: \( \rho = \frac{\lambda d}{N\Delta} \)

- \( \rho_H = 114.7 \ \mu m \)
- \( \rho_V = 152.9 \ \mu m \)

- Simulated

- Experimental

- Off-axis Hologram

- Initial

- Improved
Terahertz Digital Holography

- Many composite materials are not transparent enough at FIR
- Move to sub-THz (1 mm wavelength)  
  - Other detectors/sources
  - No cameras - Single point detectors or line sensors (FET)
- Transparency test with true aerospace materials

Collaboration with CENTERA Poland
Terahertz Digital Holography

- Scanning hologram with single point detectors
- Digital holography validation

**Amplitude object:** metallic cross  
**Phase object:** plastic stick

- 100 mm*100 mm hologram
- pitch: 0,5mm
- 2 hours scan
Conclusion – Discussion

- **LWIR digital holography**
  - Large deformation of space structures in industrial environment
  - Large objects

- **THz digital holography**
  - FIR: development of techniques (improvement of resolution)
  - Sub-THz: first steps for composites NDI
  - In future: line-scanning

- **Improvement of DH**
  - Use of DH principle and all associated post-processing
  - From FIR to sub-THz
  - State-of-art in lensless imaging techniques
    - EMPA, Switzerland
    - Beijing Univ. Technology, China
    - CSL, Belgium

Phase retrieval
Numerical auto-focusing
Synthetic aperture
Compressed sensing
...

"THz coherent lensless imaging techniques – A Review"
L. Valzania, Y. Zhao, L. Rong, D. Wang, M. Georges,
E. Hack, P. Zolliker (submitted)
Further readings


Announcement

“SPIE Photonics Europe 2020 Call for Papers”

Strasbourg (FR), March 29-April 2, 2020

Thank you for your attention!

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