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Infrared digital holography with a quantum cascade laser

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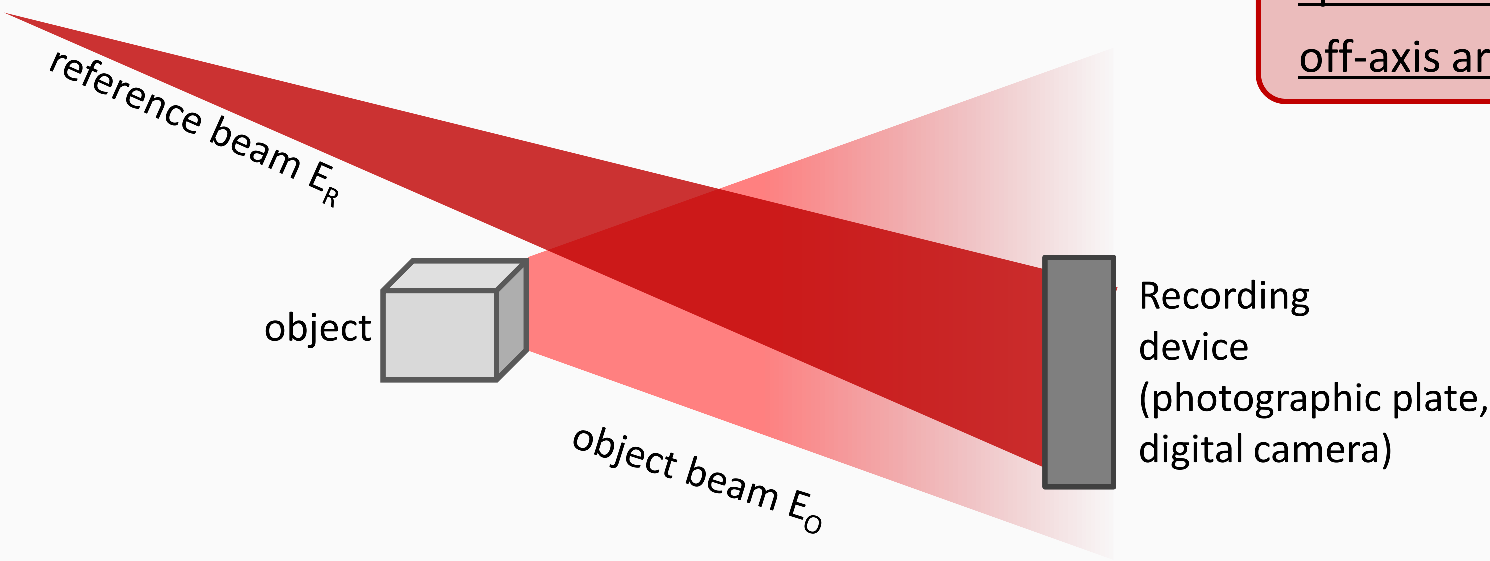
Outline

- **Infrared digital holography**
  - Analog/Digital hologram reconstruction
  - Long wavelength holography
- **Mid-IR QCL based holography**
  - Experimental setup and results
  - Holographic interferometry
- **THz QCL based holography**
  - Experimental setup and preliminary results
- **Conclusion**

Hologram recording



speckle holography

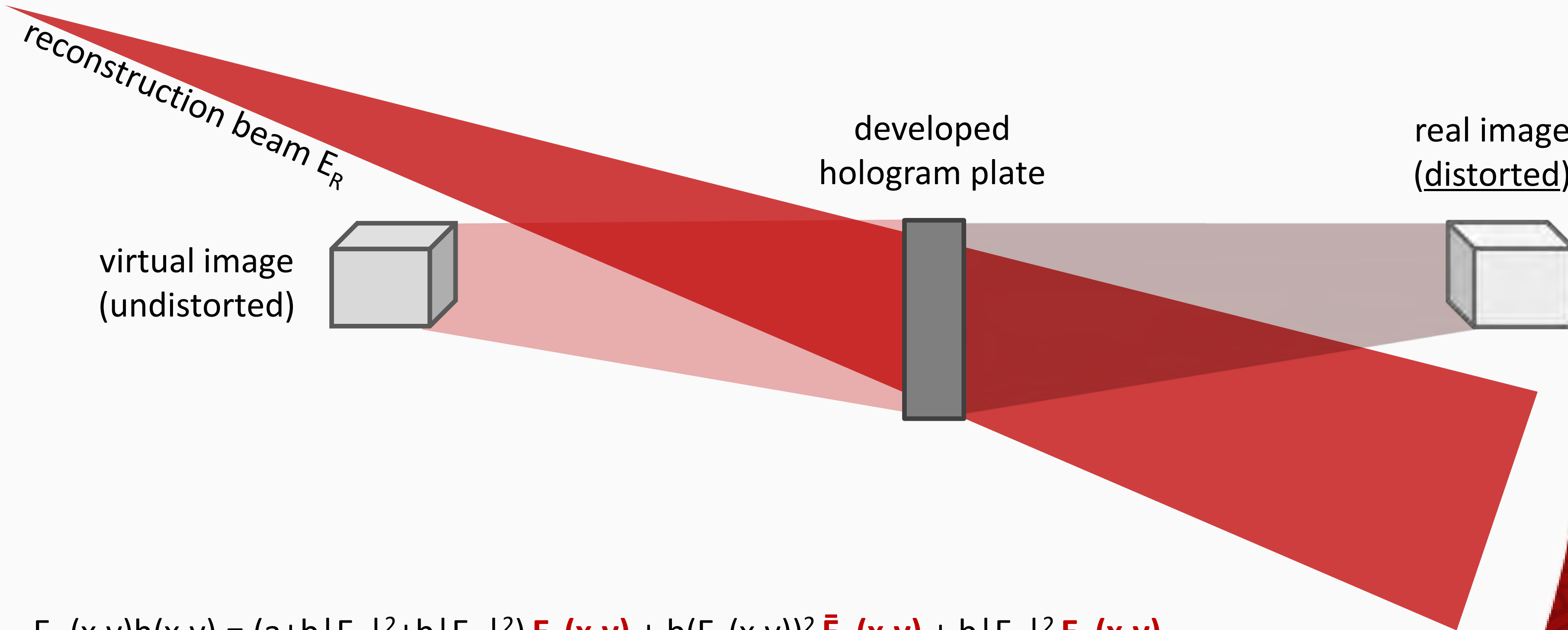
off-axis arrangement

Recorded intensity $I(x,y)=|E_O(x,y)+E_R(x,y)|^2$

Plate transmission $h(x,y)=a+b|E_O(x,y)+E_R(x,y)|^2$

Hologram reconstruction

Analog holography



$$E_R(x,y)h(x,y) = \underbrace{(a+b|E_R|^2+b|E_O|^2)\,E_R(x,y)}_{\textbf{undiffracted wave}} + \underbrace{b(E_R(x,y))^2\,\bar{E}_O(x,y)}_{\textbf{real image}} + \underbrace{b|E_R|^2\,E_O(x,y)}_{\textbf{virtual image}}$$

Hologram reconstruction

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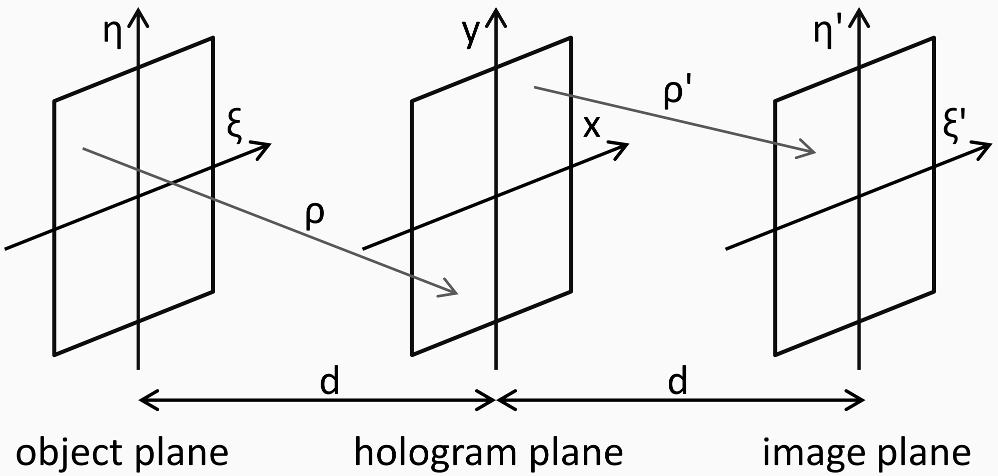


Digital holography

$$\Gamma(\xi',\eta') = -\frac{i}{\lambda}\iint h(x,y)E_R(x,y)\frac{e^{ik\rho'}}{\rho'}dxdy$$

Kirchhoff diffraction integral

$$\Gamma(\xi',\eta') = -\frac{ie^{ikd}}{\lambda d}\iint h(x,y)E_R(x,y)\exp\left\{\frac{ik}{2d}\left[(\xi'-x)^2+(\eta'-y)^2\right]\right\}dxdy$$

Fresnel approximation

$$\nu = \frac{\xi'}{\lambda d} \qquad \mu = \frac{\eta'}{\lambda d}$$

$$\Gamma(\nu,\mu) = -\frac{ie^{ikd}e^{i\pi\lambda d(\nu^2+\mu^2)}}{\lambda d}\times\mathcal{F}\left\{h(x,y)E_R(x,y)\exp\left[\frac{ik}{2d}(x^2+y^2)\right]\right\}$$

Fourier Transform

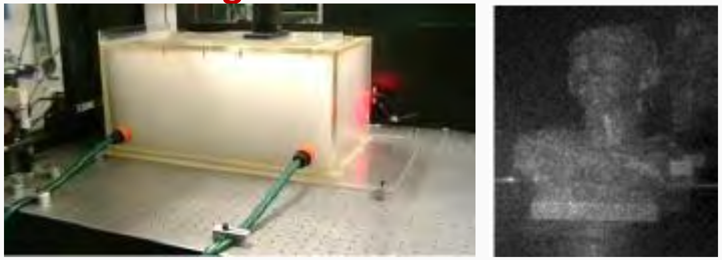
The acquired hologram is a 2D matrix h(m,n) → calculation of a DFT

Infrared digital holography

Long wavelength acquisition

- reduced sensitivity to vibrations
- large field of view (scales with λ)
- high resolution
- reduced sensitivity to scattering
- use of CO_2 lasers

Vision through smoke

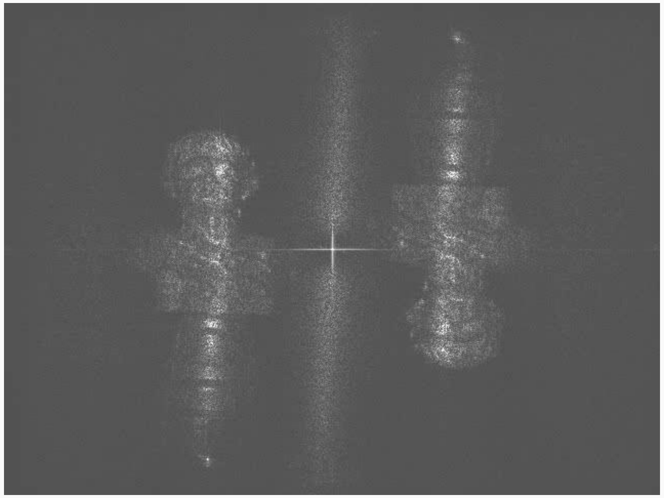


M. Locatelli et al., Opt. Express (2013).

Human size holograms

A. Pelagotti et al., J. Disp. Technol. (2010).

Dynamic scene recording



Use of a mid-IR QCL instead of a CO_2 laser? And a Terahertz QCL?

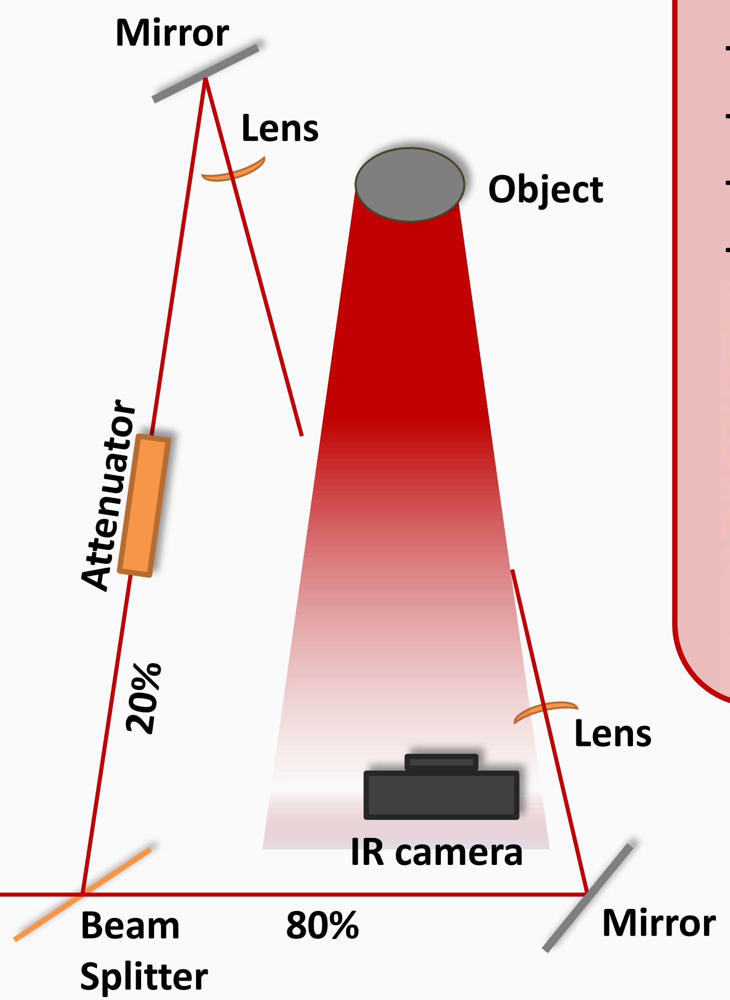
QCL based mid-IR digital holography

Quantum cascade laser

- Dayligth solution ECqcL
- Wavelength = 8μm ± 350nm
- Linewidth ≤ 100 MHz
- Output power (CW) ≈ 80mW
- TEM_{00} beam, div ≤ 5mrad

Bolometric camera

- Miricle 307K
- 640 × 480 pixel
- Pixel pitch 25 μm
- Sensitivity ≤ 50mK

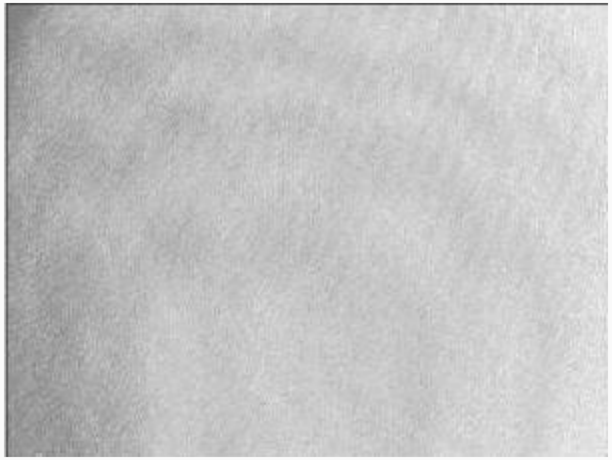


QCL based mid-IR digital holography

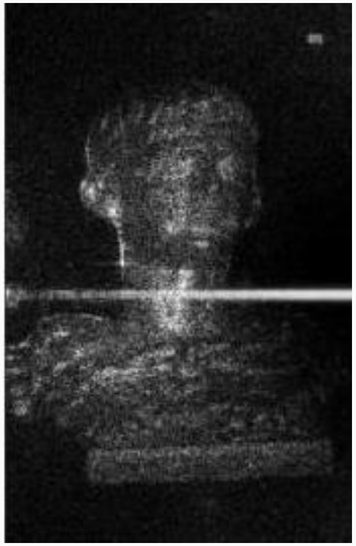
Experimental results

10 cm

bronze statue



640 x 480 hologram
frame rate 25 Hz



reconstructed amplitude image

$|\Gamma(\xi',\eta')|$

- no table vibration damping during acquisition
- real time hologram processing by Fresnel method (frame rate 5 Hz)
- maximum object dimensions limited by the QCL power

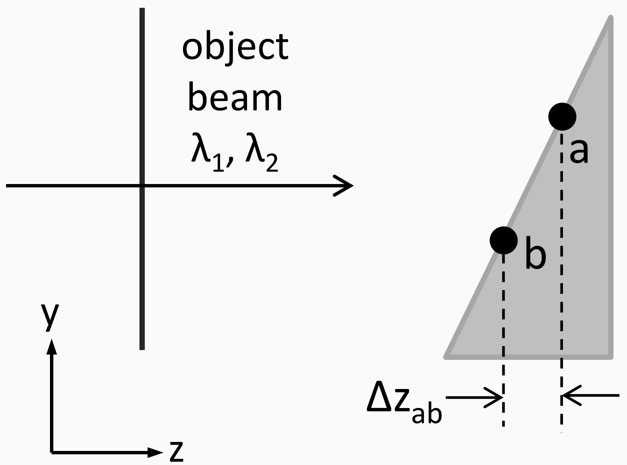
<u>*M. Ravaro et al., Opt. Letters **39**, 4843 (2014)*</u>

Mid-IR holographic Interferometry

Reconstructed phase

$$\varphi(\xi',\eta') = \operatorname{atan}\left\{\frac{\mathrm{Im}[\Gamma(\xi',\eta')]}{\mathrm{Re}[\Gamma(\xi',\eta')]}\right\}$$

Two wavelength interferometry



$$\Delta\varphi_{1,2} = 2\pi\frac{|\lambda_1 - \lambda_2|}{\lambda_1\lambda_2}\Delta z_{ab} = 2\pi\frac{\Delta z_{ab}}{\Lambda_{12}}$$

$$\Lambda_{12} = \frac{\lambda_1\lambda_2}{|\lambda_1 - \lambda_2|}$$ <u>Synthetic wavelength</u>

$\Delta z_{noise} = \Lambda \times \Delta\varphi_{noise}/2\pi$ noise amplification

Analog holographic interferometry

Multiple exposures of the same photographic plate at different λ

Digital holographic interferometry

Subtraction of the reconstructed phase of distinct holograms

HI with a tunable laser diode

- Adjustement of the synthetic wavelength to the optical path length to be measured
  <u>no need for phase-unwrapping</u>
- Possible hierarchical phase unwrapping based on progressive synthetic wavelengths:
  <u>high dynamic range and low noise</u>

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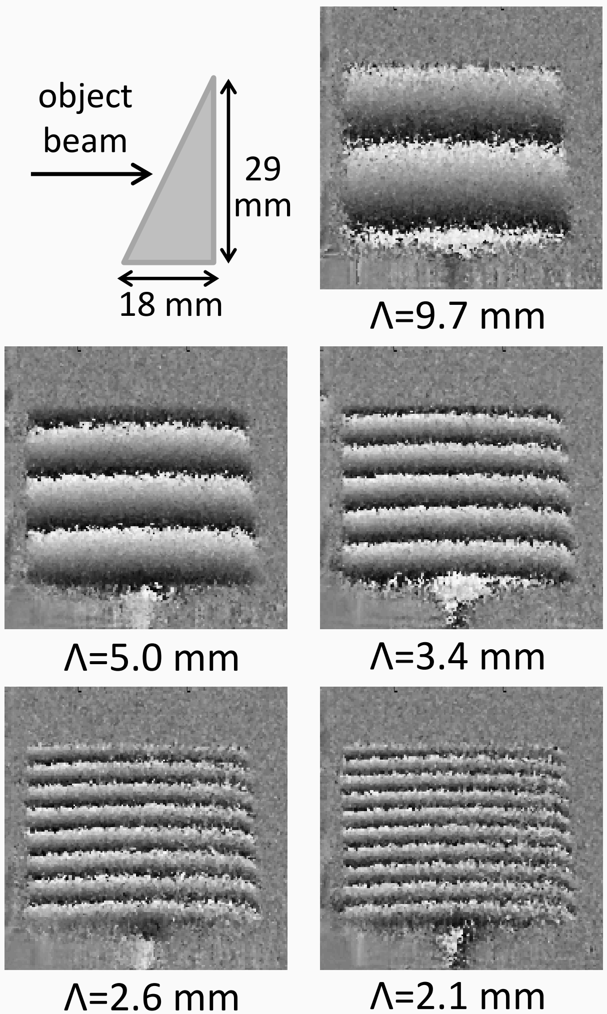
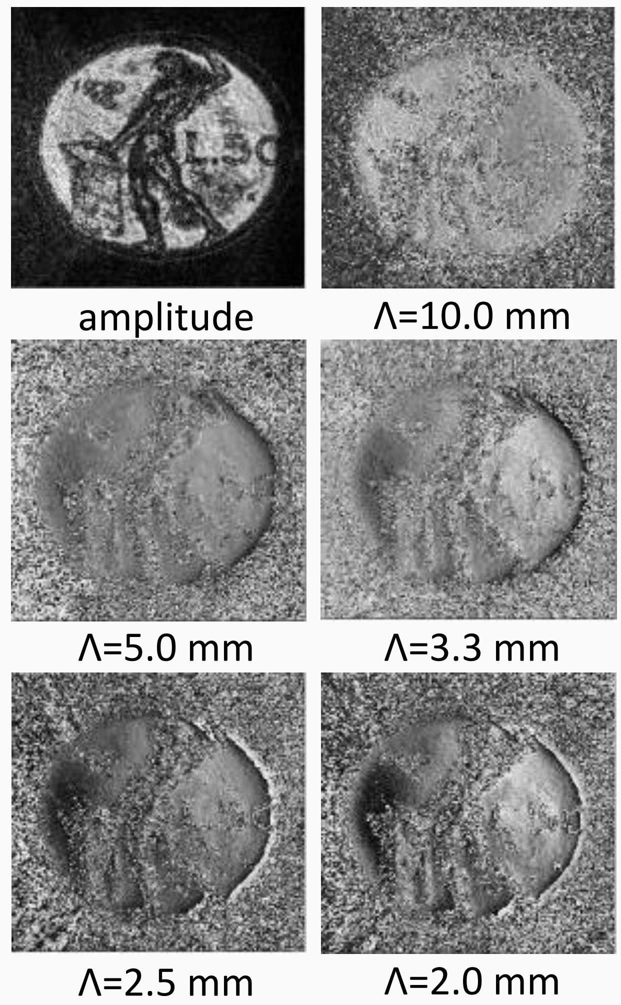
Mid-IR holographic Interferometry

Wedge contouring



50L coin amplitude and phase

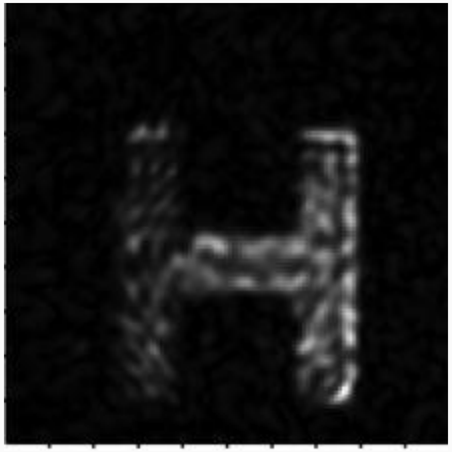


ECqcL → synthetic wavelength range from 100s µm to ≈ 20 mm

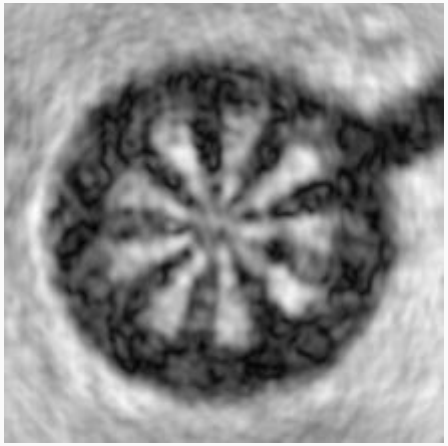
THz Digital Holography

Key features

- reduced sensitivity to vibrations
- large field of view
- reduced sensitivity to scattering
- high resolution
- proprties of THz radation



S. Ding et al. Opt. Lett. (2011)



E. Hack et al., Opt. Express (2013)

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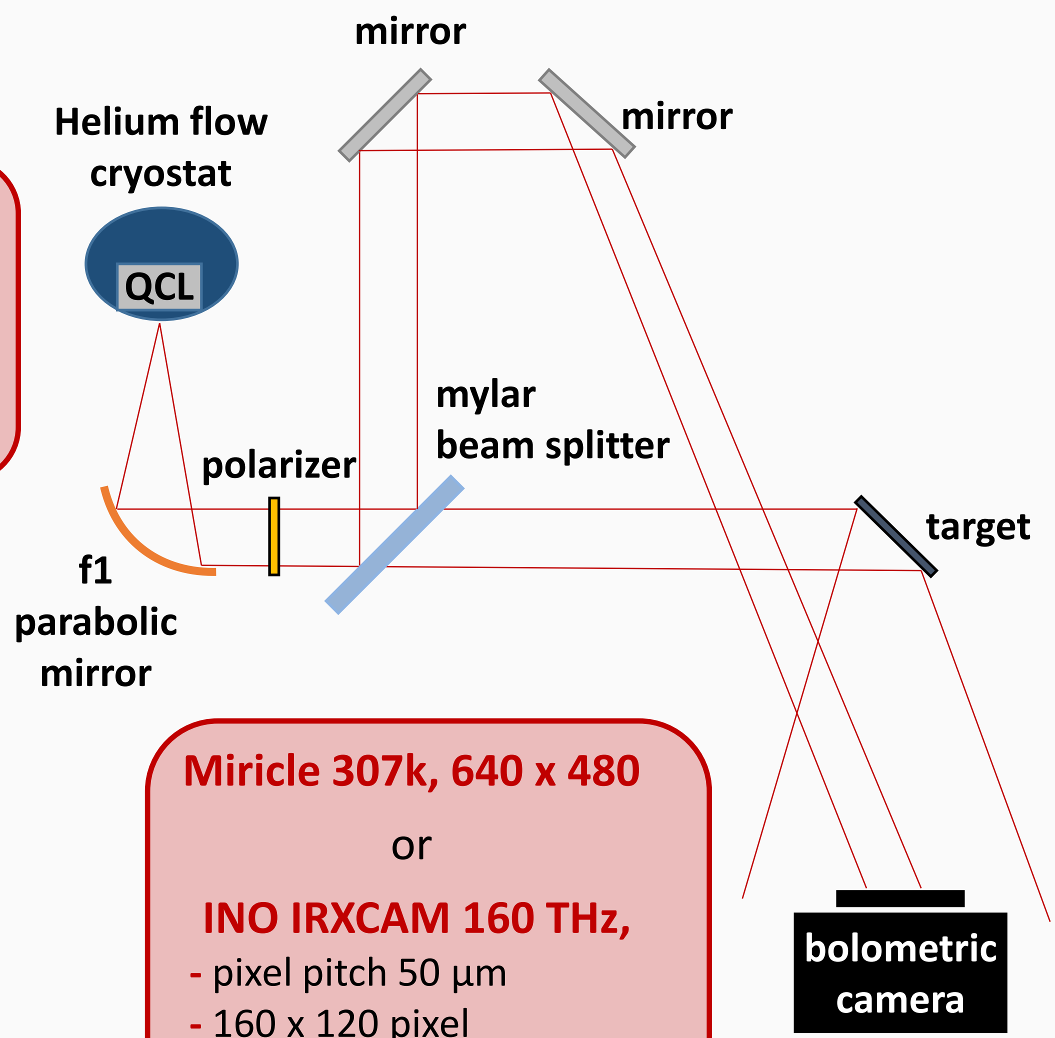
Digital Holography with a THz QCL

Experimental setup

Terahertz QCL

- bound to continuum
- single plasmon waveguide
- T = 20 K
- output power 4 mW



Miricle 307k, 640 x 480

or

INO IRXCAM 160 THz,

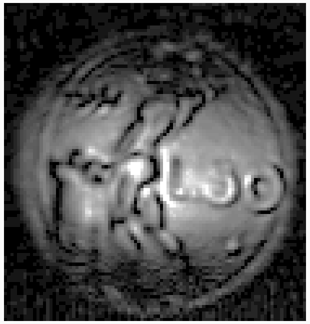
- pixel pitch 50 µm
- 160 x 120 pixel
- NEP 100 pW

Digital Holography with a THz QCL

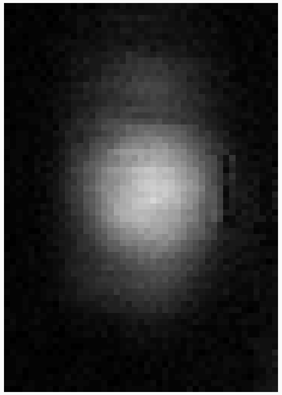
Preliminary results

Small button

50 Lire coin

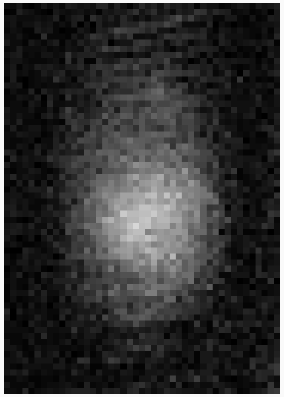


Moving target



Speed = 10mm/s

… behind 1mm black Polypropylene plate



Conclusions

- **Digital holography based on Mid-IR QCLs**

  - Compact setup for IR DH
  - Coverage of a broad Mid-IR spectrum (3-16 μm)
  - Use of external cavity QCLs for versatile path length measurements

- **Digital holography based on terahertz QCLs**

  - First demonstration of speckle digital holography
  - Work in progress: holography of biological samples, non destructive analysis, THz path length measurements