CLEO

Dual-Comb Hyperspectral Digital Holography

Edoardo Vicentini, Zhenhai Wang, Kasper van Gasse, Theodor W. Hänsch, Nathalie Picqué

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Outline

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- **Introduction**
  - Frequency comb and dual-comb spectroscopy
  - Digital holography

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- **Dual-comb hyperspectral digital holography**
  - Experimental setup
  - Experimental result

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- **Dual-comb hyperspectral digital holography**
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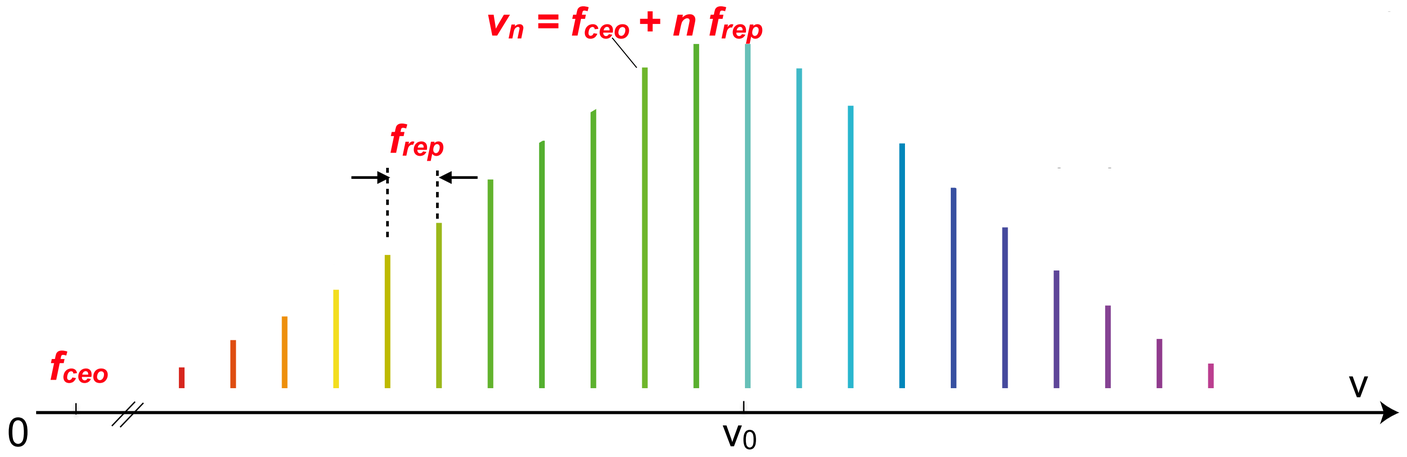
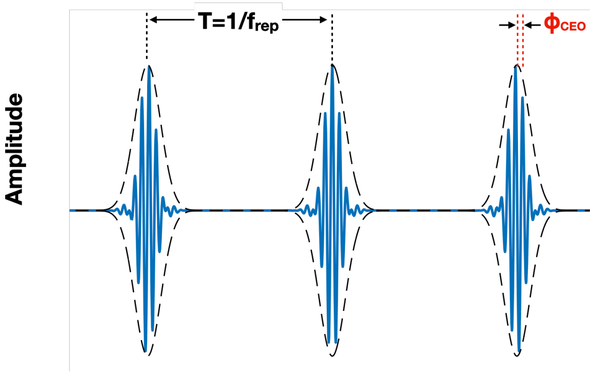
  - Experimental result

- **Conclusion and future perspective**

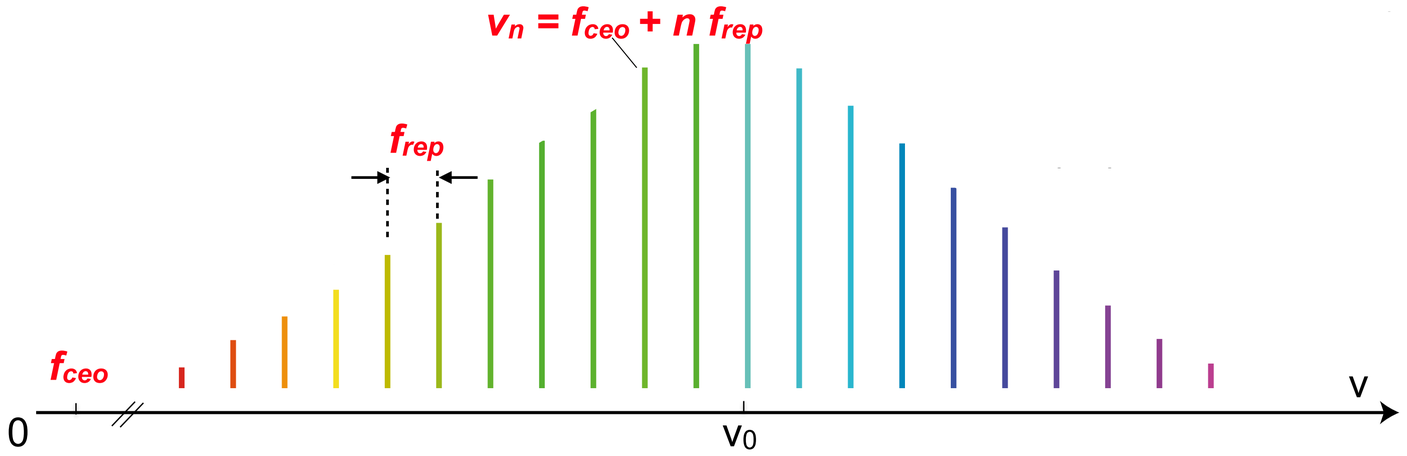
Frequency comb and dual-comb spectroscopy

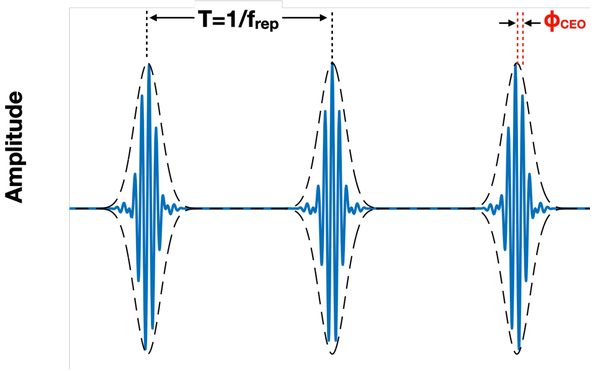
Frequency comb and dual-comb spectroscopy

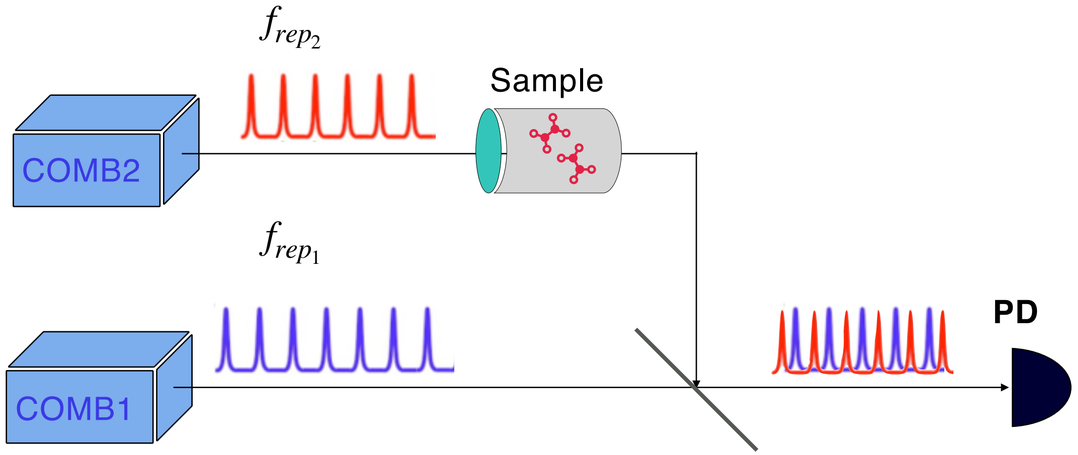




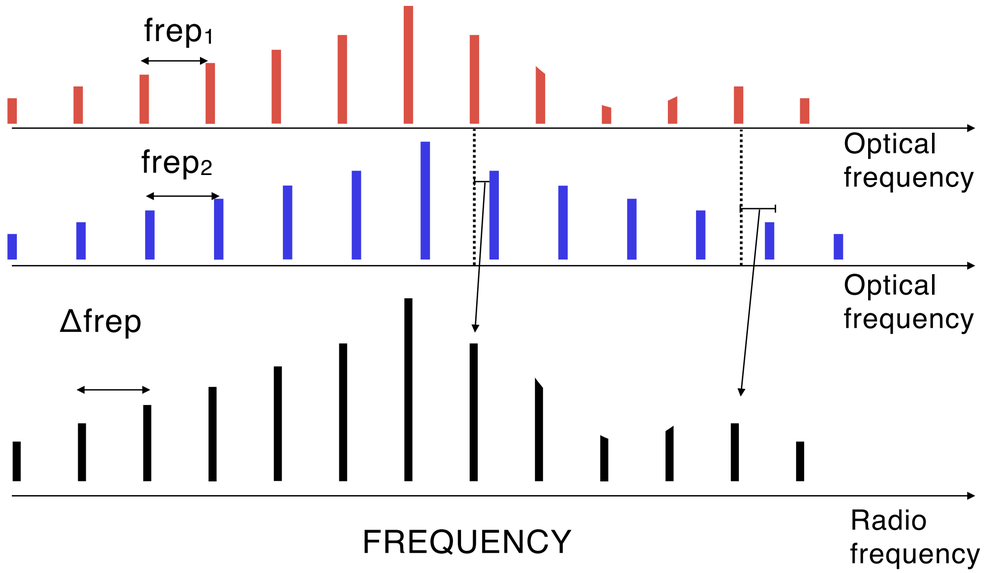
Frequency comb and dual-comb spectroscopy







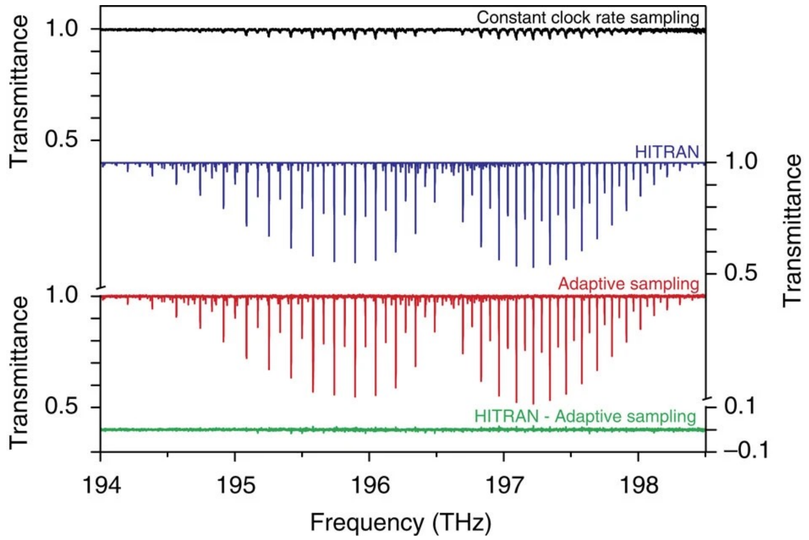
$$\Delta f_{rep} = f_{rep1} - f_{rep2}$$



Frequency comb and dual-comb spectroscopy

Frequency comb and dual-comb spectroscopy

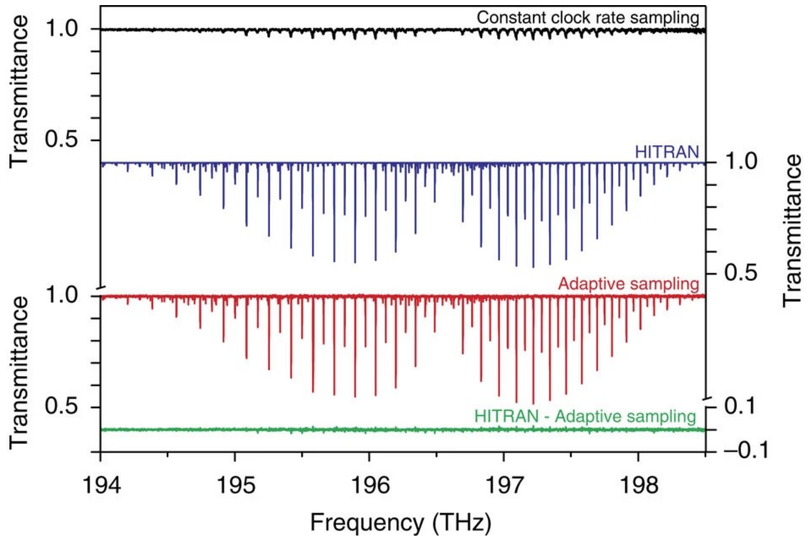
High resolution
and broadband spectroscopy



Ideguchi, T., Poisson, A., Guelachvili, G. *et al.* Adaptive real-time dual-comb spectroscopy. *Nat Commun* **5,** 3375 (2014). https://doi.org/10.1038/ncomms4375

Frequency comb and dual-comb spectroscopy

High resolution and broadband spectroscopy



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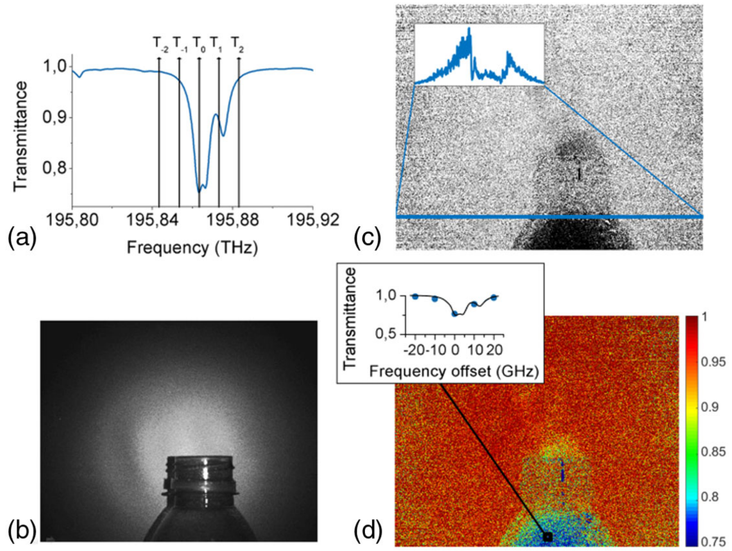
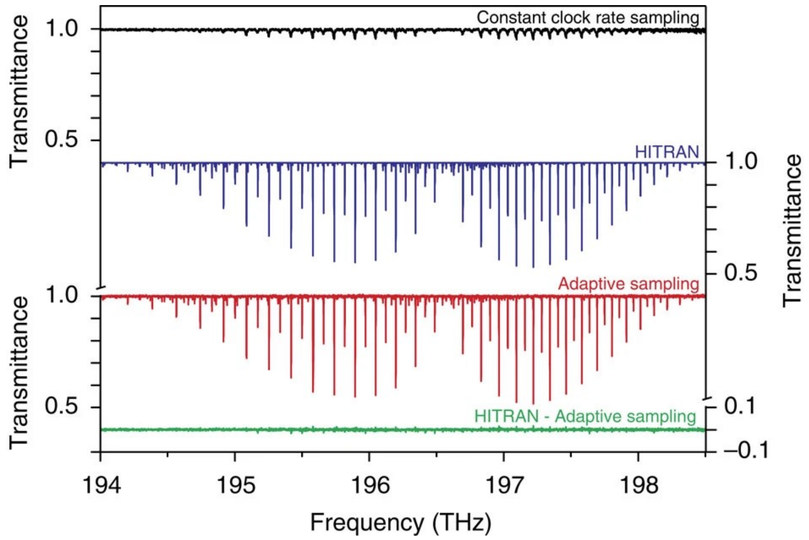
Hyperspectral imaging



Martín-Mateos, Pedro, Farid Ullah Khan, and Oscar Elías Bonilla-Manrique. "Direct hyperspectral dual-comb imaging." *Optica* 7.3 (2020): 199-202

Frequency comb and dual-comb spectroscopy

High resolution and broadband spectroscopy



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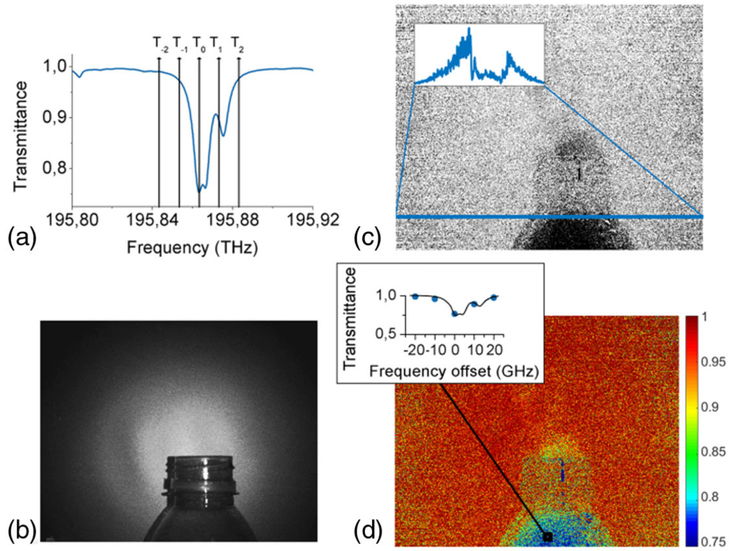
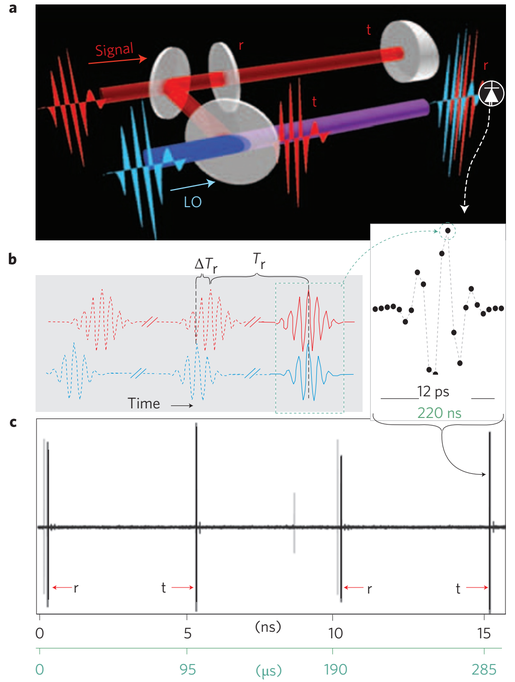
Hyperspectral imaging



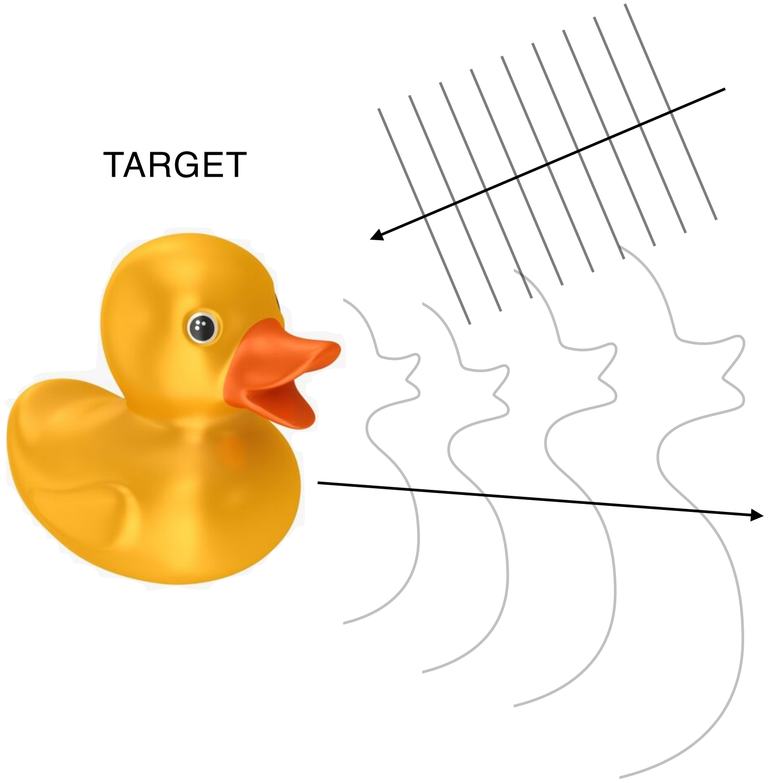
Martín-Mateos, Pedro, Farid Ullah Khan, and Oscar Elías Bonilla-Manrique. "Direct hyperspectral dual-comb imaging." *Optica* 7.3 (2020): 199-202

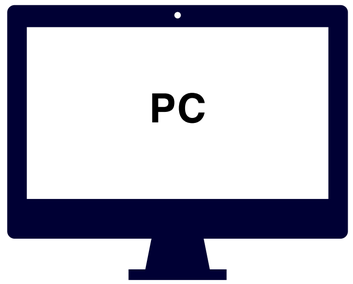
Ranging measurement

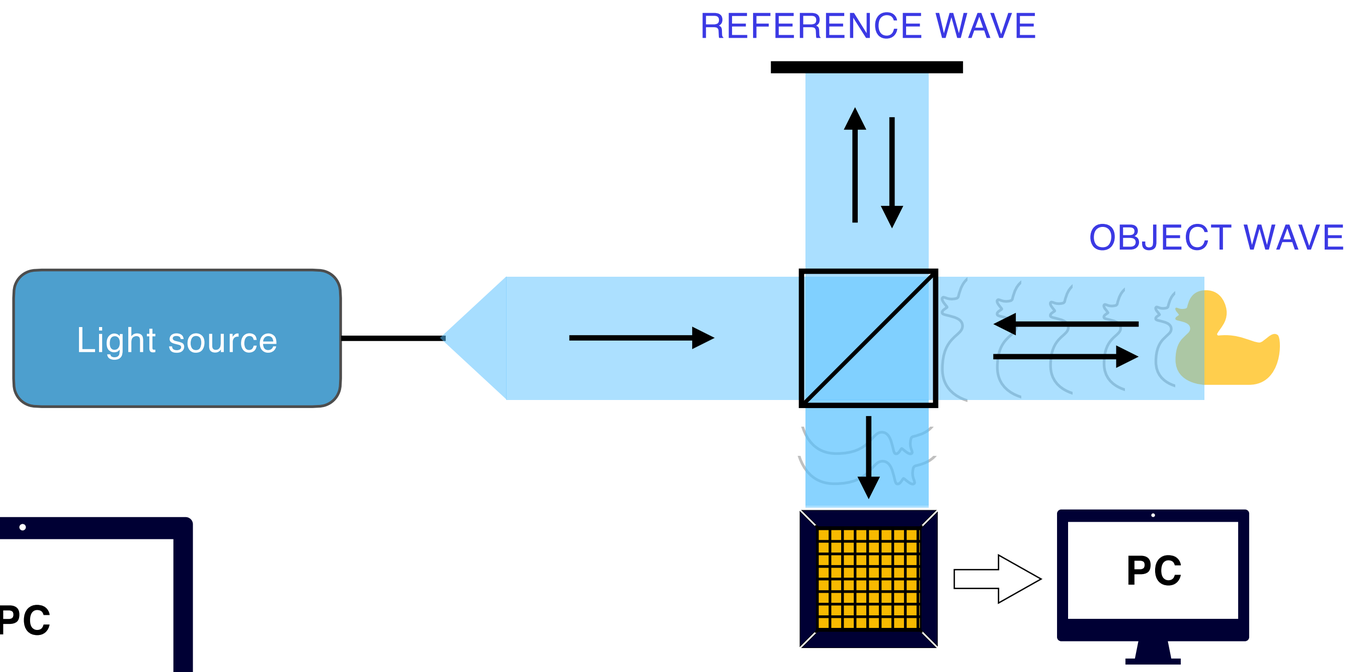


Coddington, I., Swann, W., Nenadovic, L. *et al.* Rapid and precise absolute distance measurements at long range. *Nature Photon* **3,** 351–356 (2009). https://doi.org/10.1038/nphoton.2009.94

Digital Holography





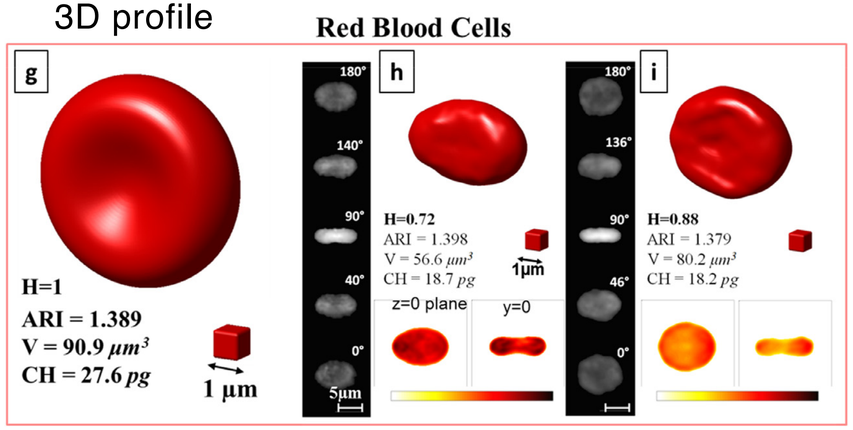


Measuring AMPLITUDE and PHASE
of reflected/transmitted radiation

Digital Holography

Biology

3D profile



Merola F, Memmolo P, Miccio L, Savoia R, Mugnano M, Fontana A, et al. Tomographic flow cytometry by digital holography. Light 2017;6:e16241.

Digital Holography

Biology

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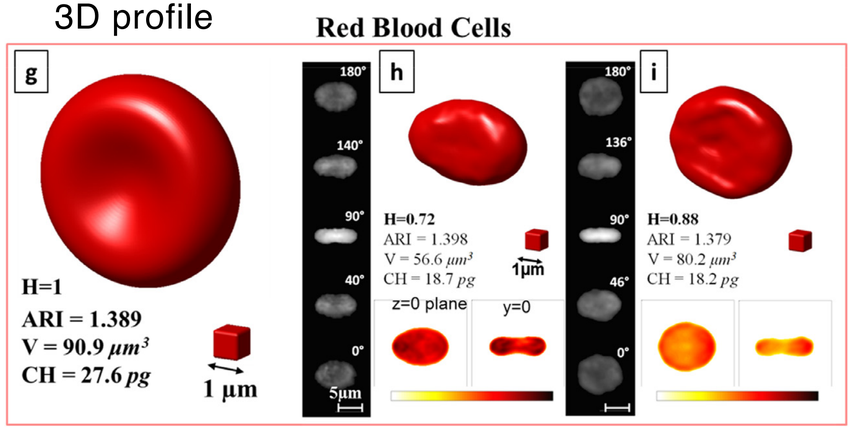

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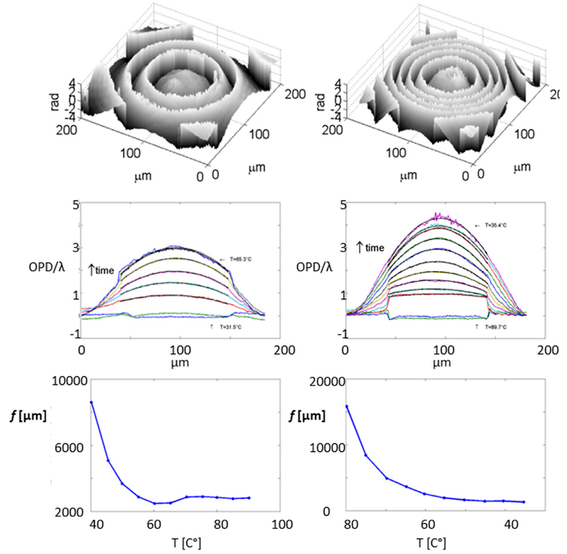
Industries

Lens characterisation



Miccio L, Finizio A,Grilli S, Vespini V, Paturzo M,DeNicola S, et al. Tunable liquid microlens arrays in electrode-less configuration and their accurate characterization by interference microscopy. Opt Express 2009;17:2488.

Digital Holography

Biology

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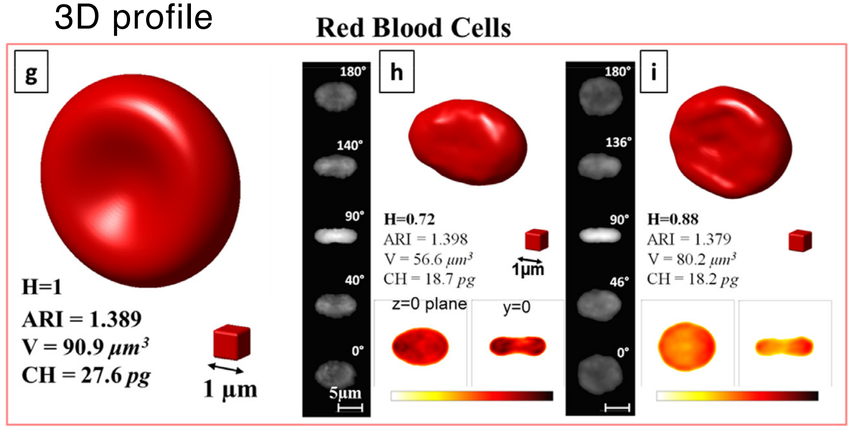

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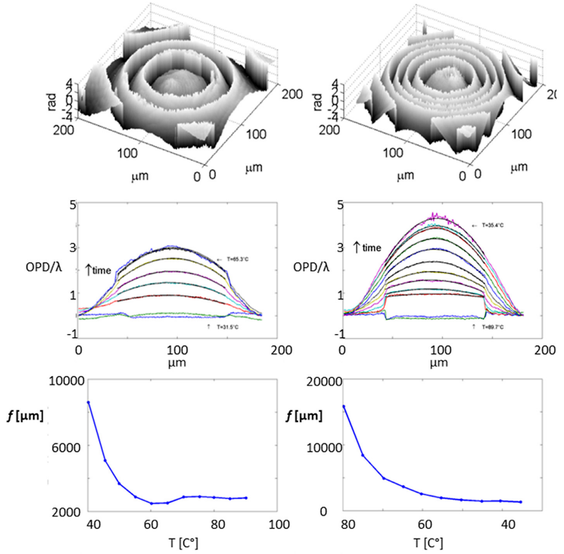
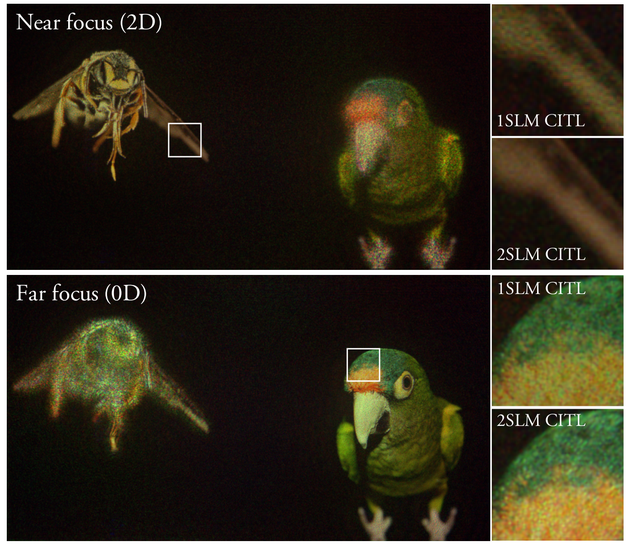


Miccio L, Finizio A,Grilli S, Vespini V, Paturzo M,DeNicola S, et al. Tunable liquid microlens arrays in electrode-less configuration and their accurate characterization by interference microscopy. Opt Express 2009;17:2488.

Image quality

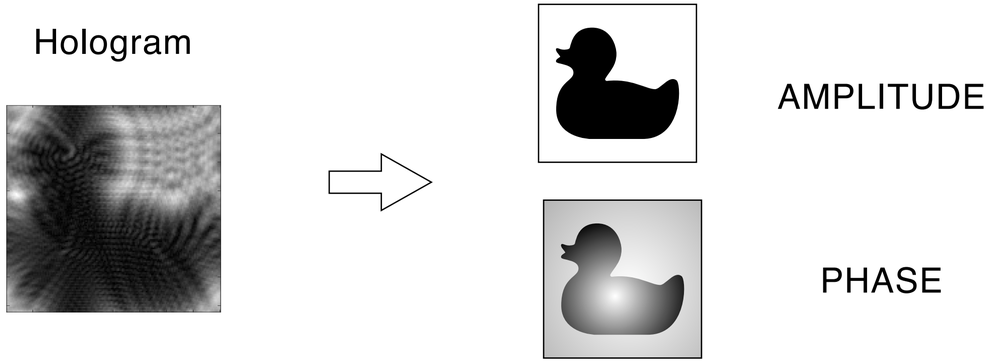
Multi focusing



Choi, Suyeon, et al. "Optimizing image quality for holographic near-eye displays with Michelson Holography." *Optica* 8.2 (2021): 143-146

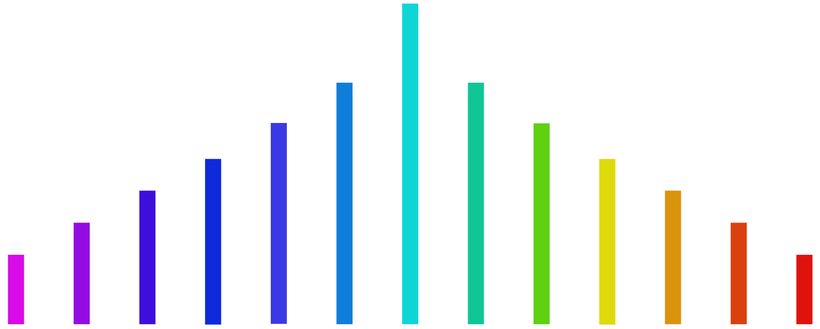
Dual-Comb Hyperspectral Digital Holography

Digital Holography



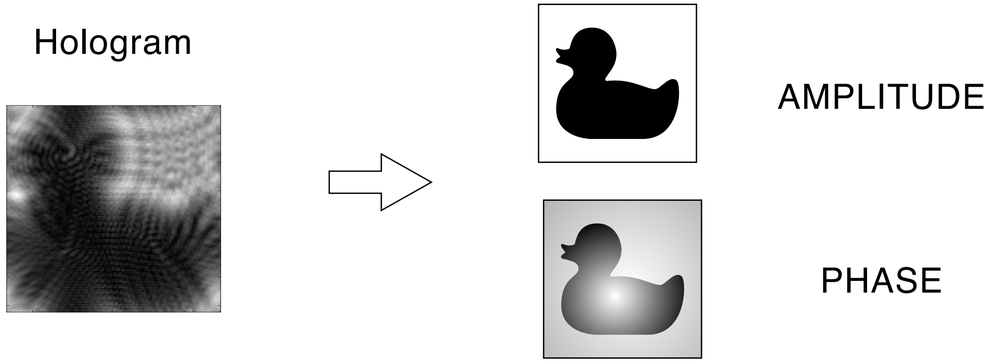
- 3D reconstruction
- Digital focusing
- Spatial filtering
- Wavefront characterisation

Frequency comb



- Broad bandwidth source
- Thousand of CW laser
- High resolution
- High precision

Digital Holography



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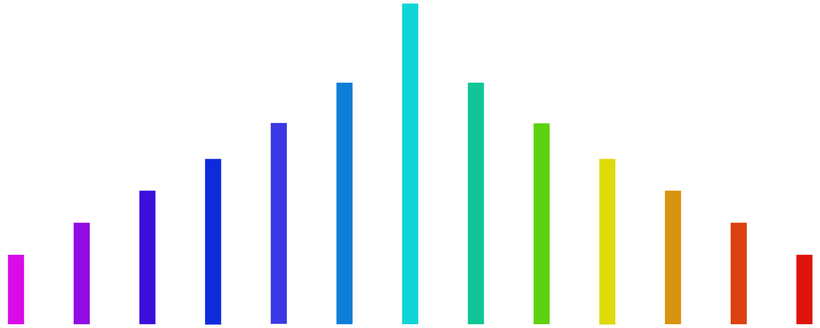
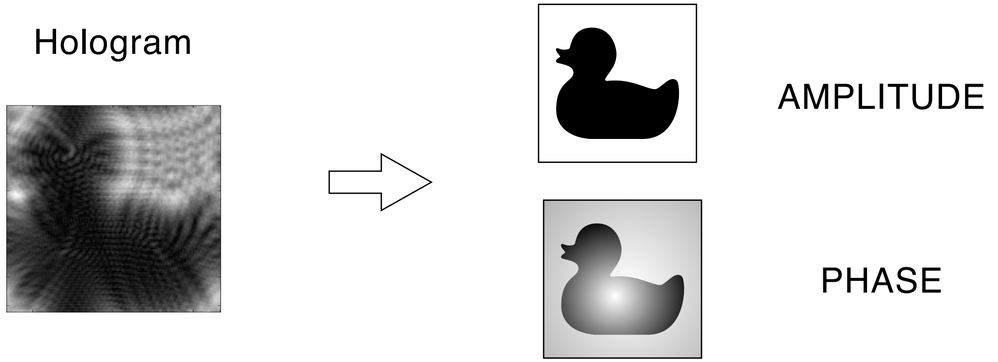
Dual-Comb Hyperspectral Digital Holography

Frequency comb



Digital Holography

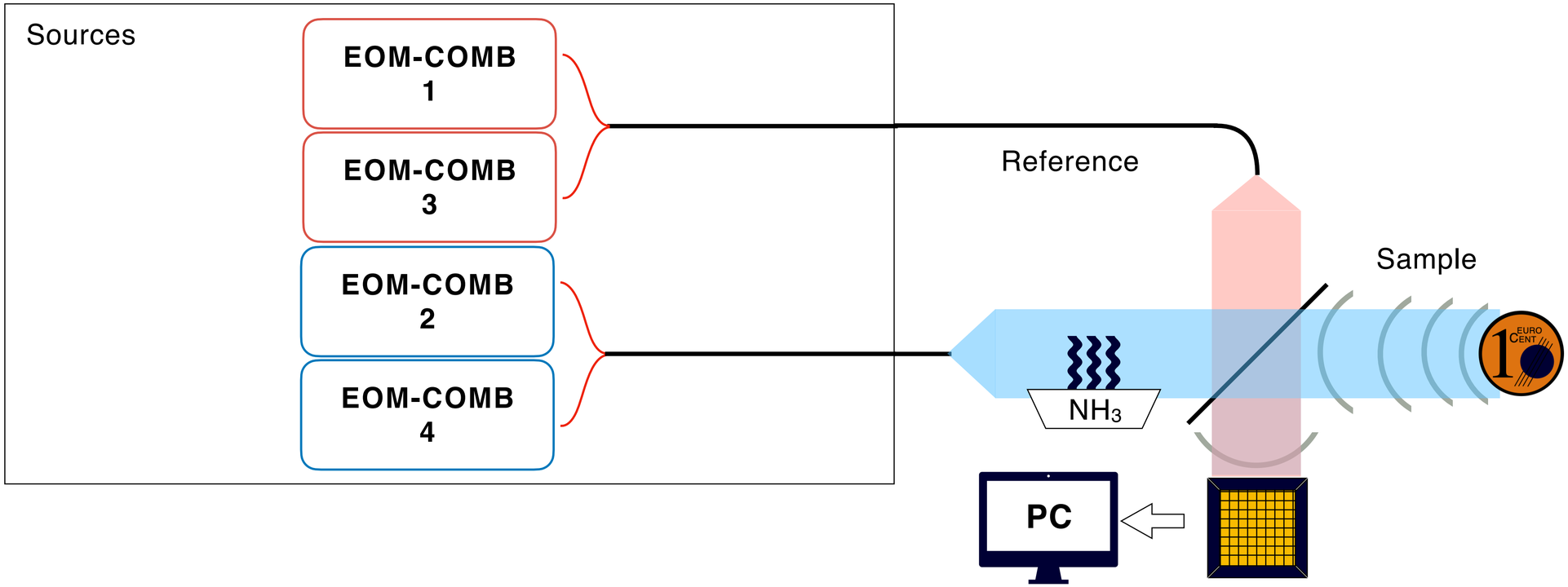


- 4D information (3 spatial and frequency)
- Phase unwrapping to large scale and with high precision
- Inline configuration without filtering

Experimental Setup

Sources

Experimental Setup



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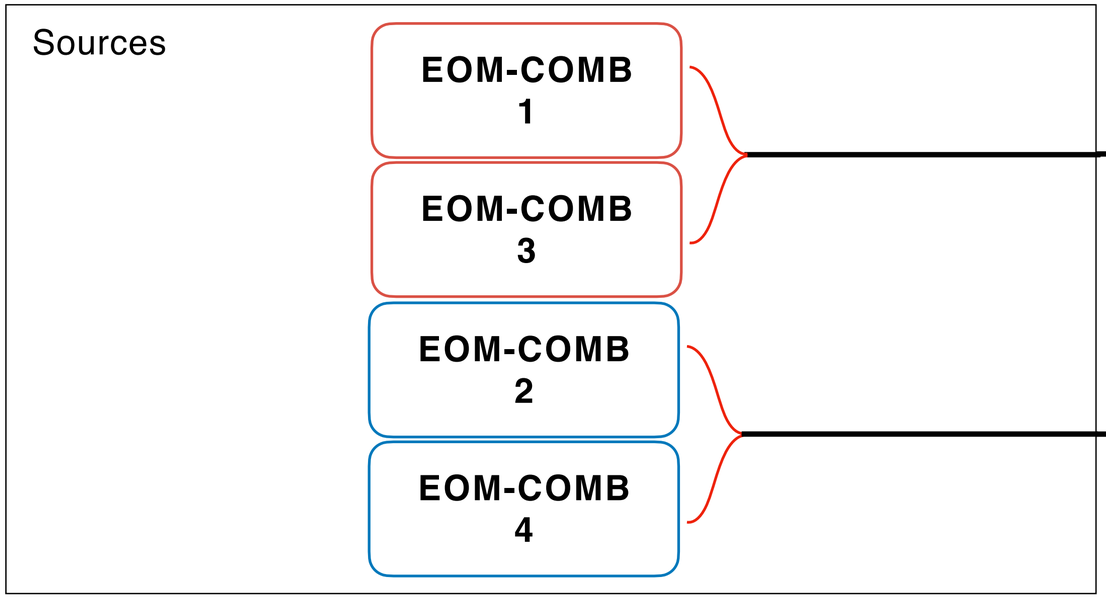

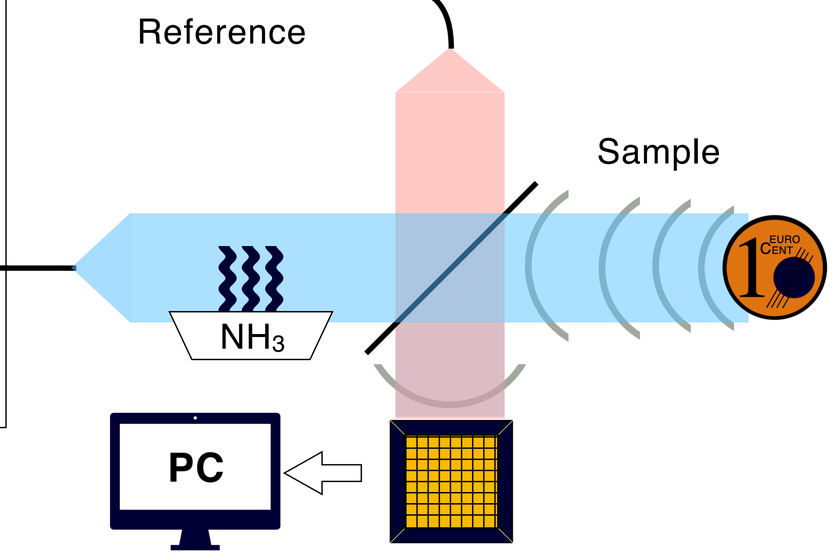

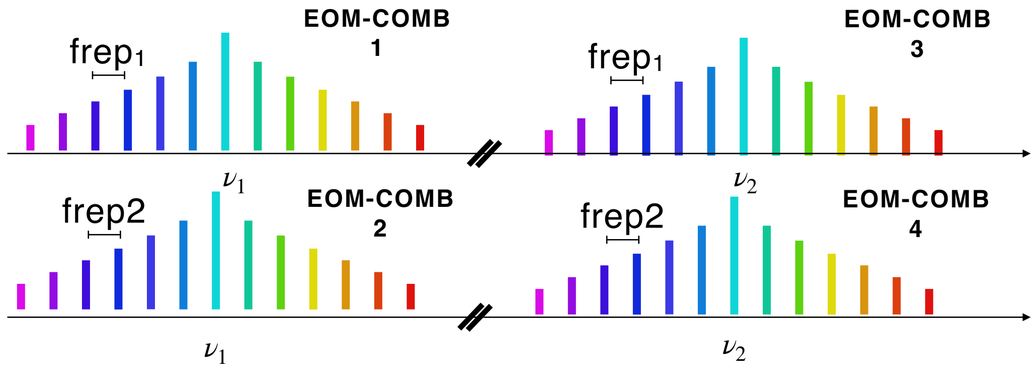

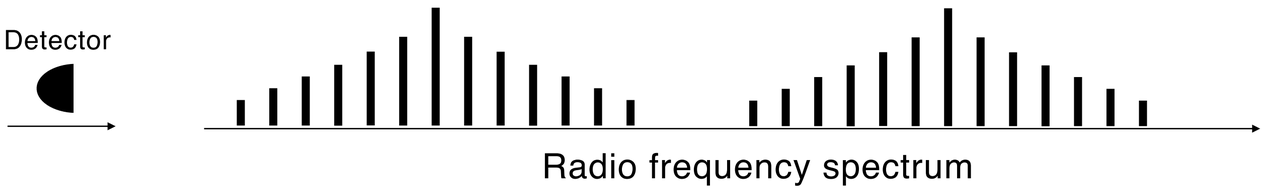

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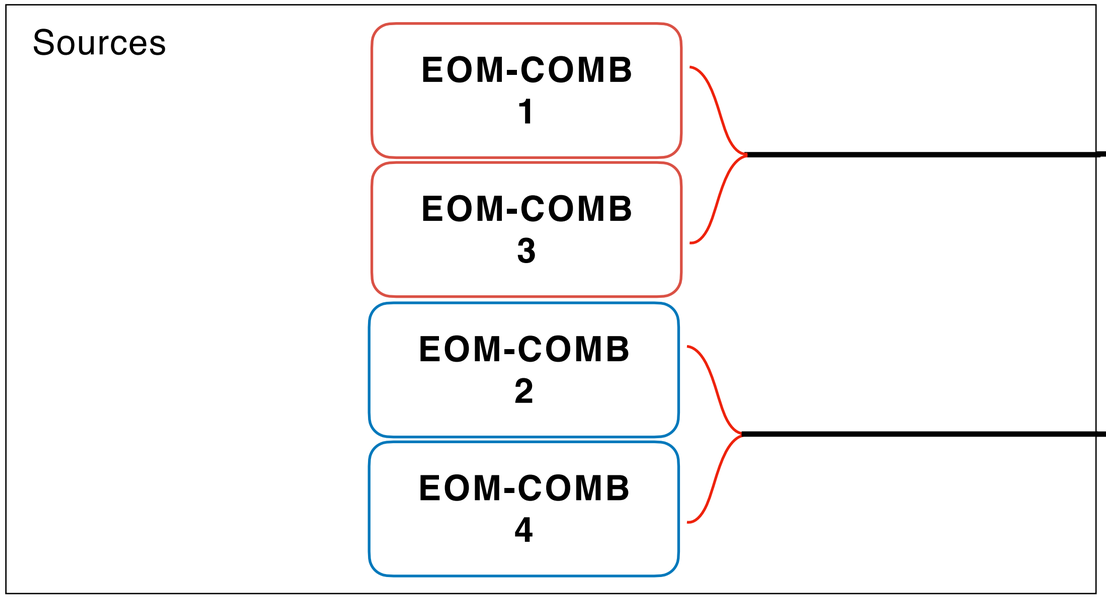

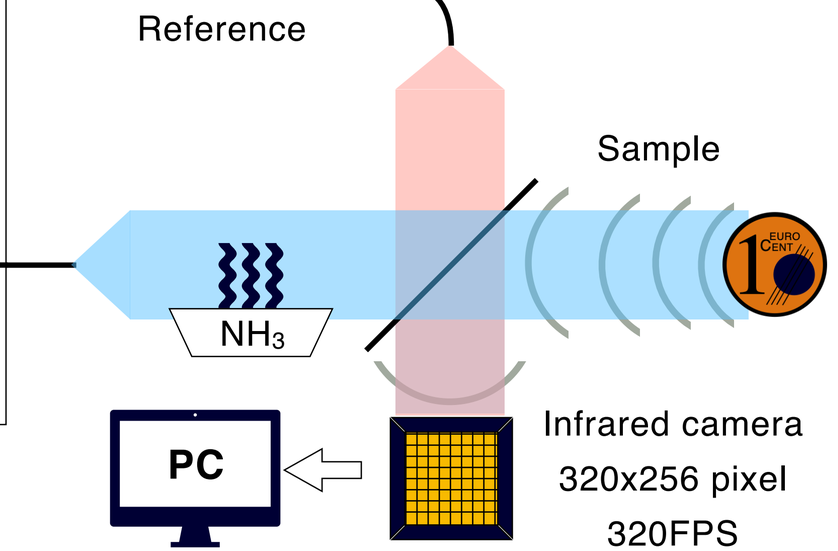

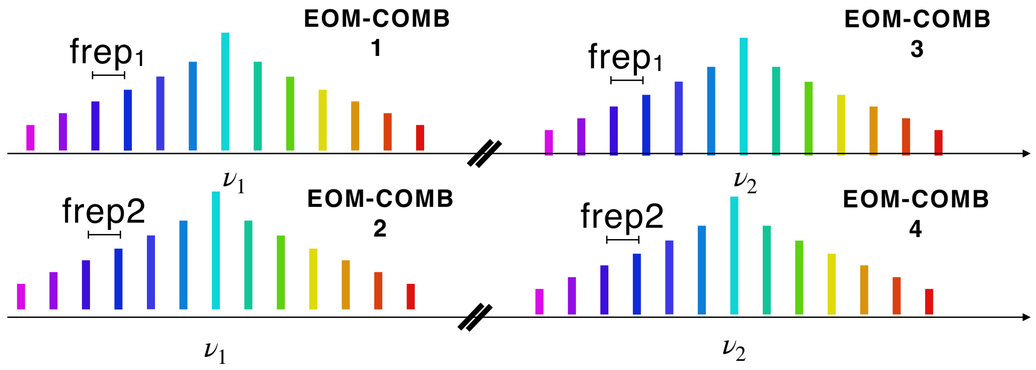

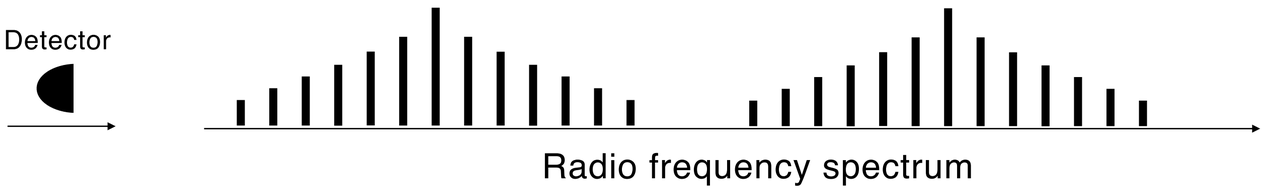

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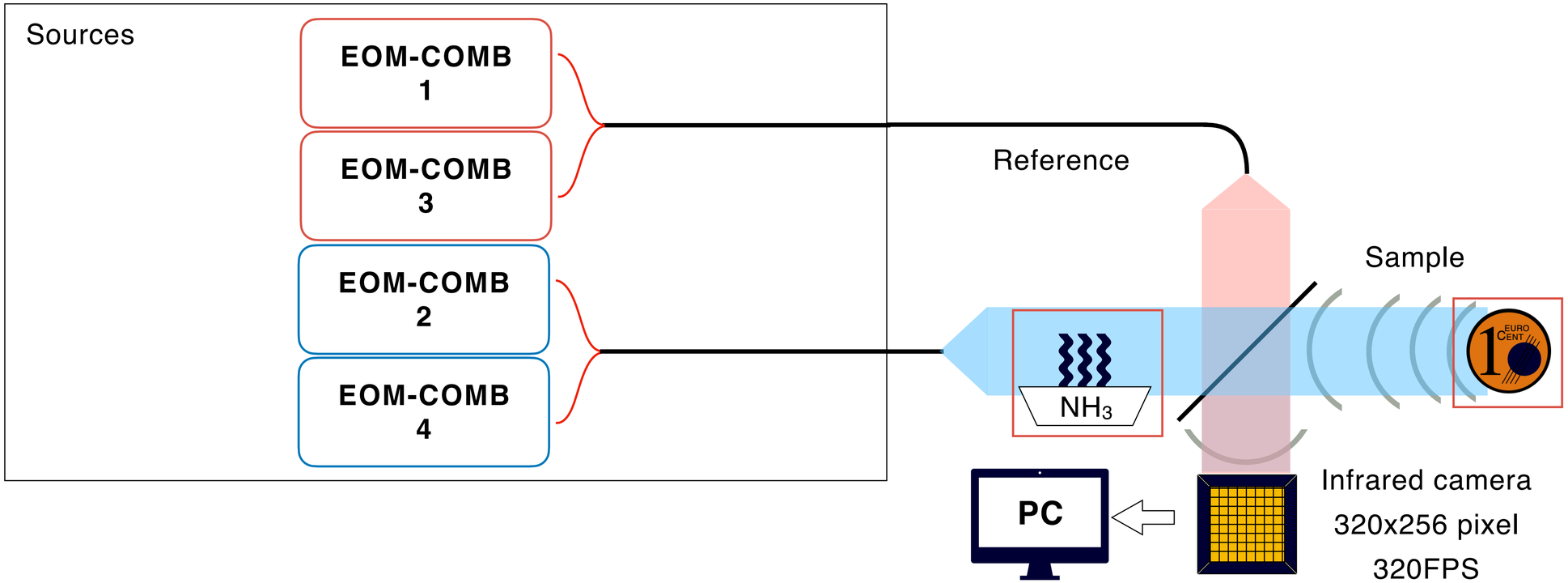

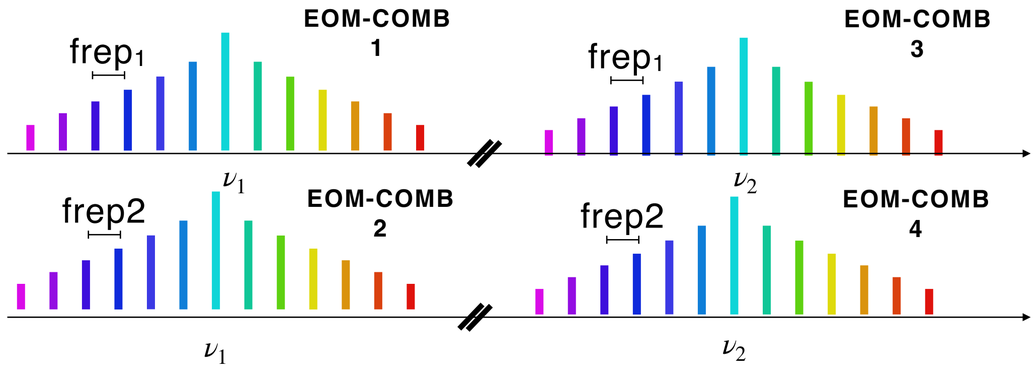

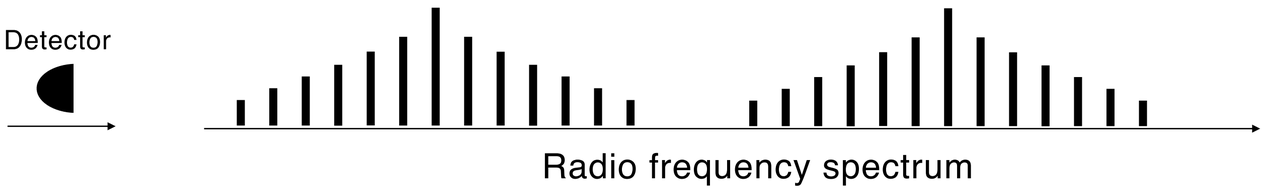

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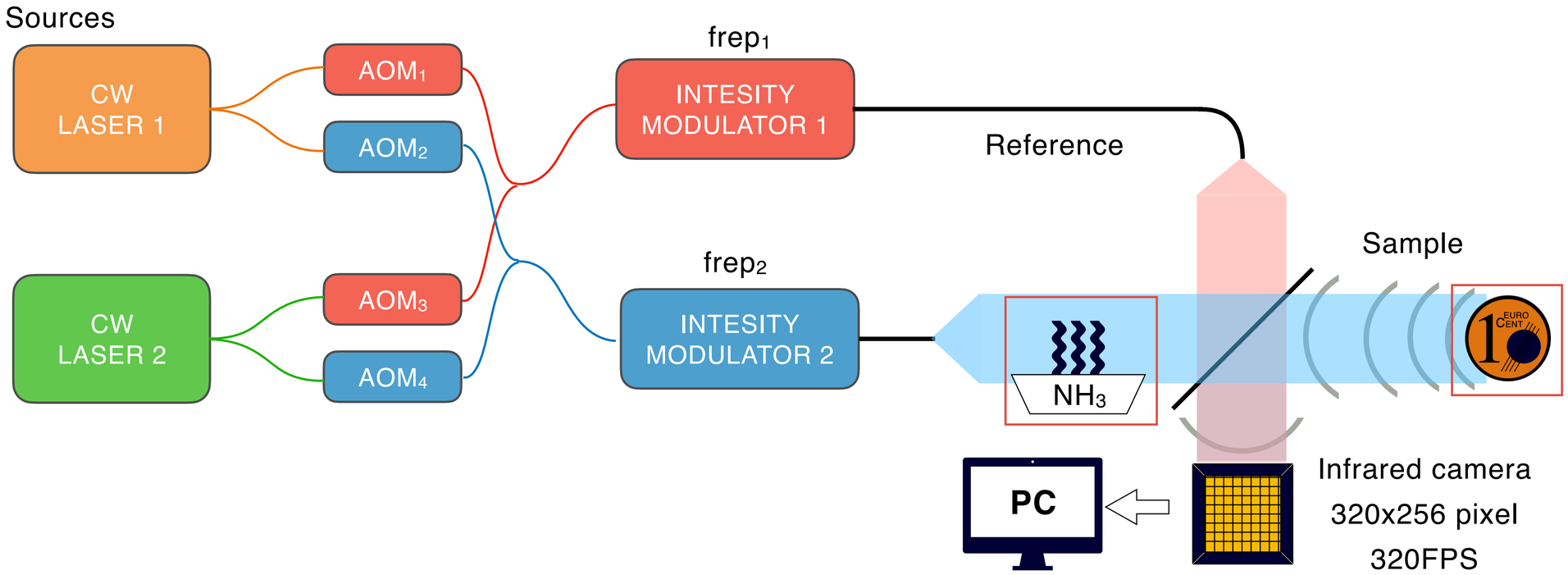


ν_1 = 195.353 THz

AOM_1 = 25 MHz

AOM_2 = 25 MHz + 40 Hz

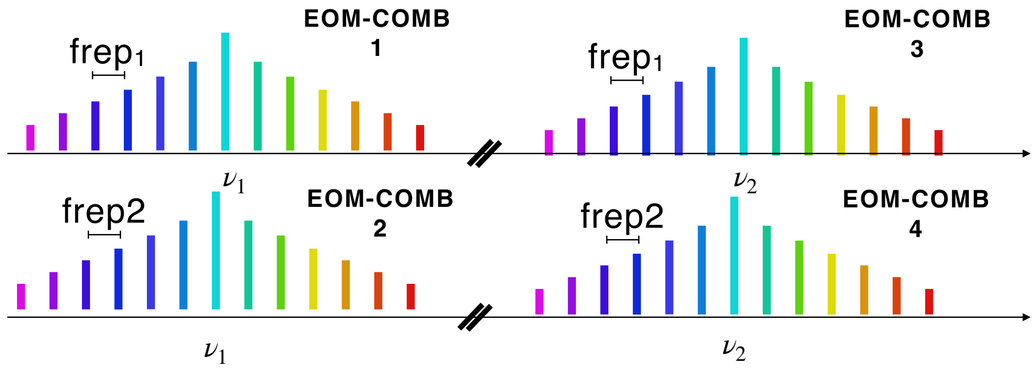
f_{rep1} = 500 MHz

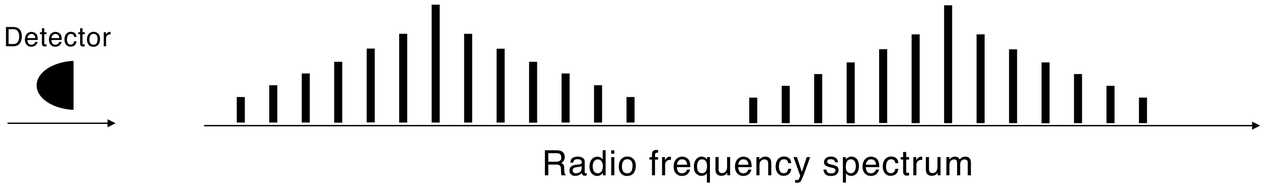
ν_2 = 195.736 THz

AOM_3 = 40 MHz

AOM_4 = 40 MHz + 120 Hz

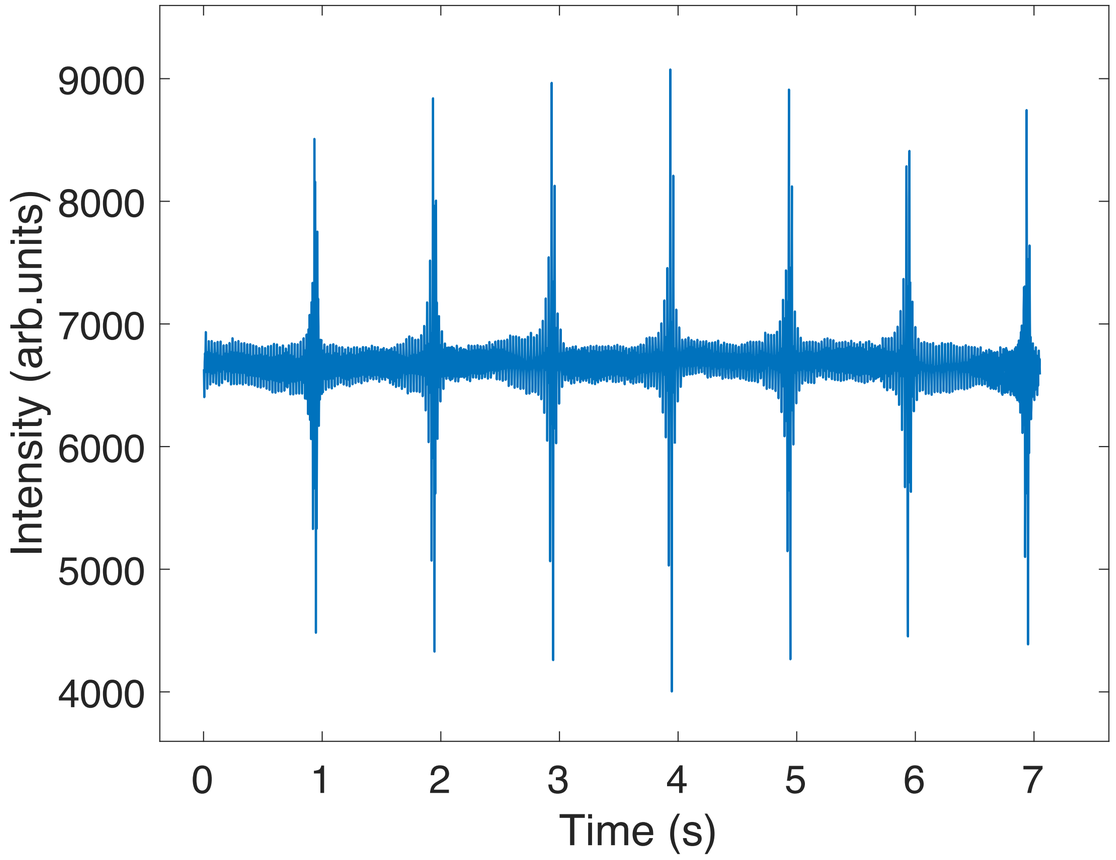
f_{rep2} = 500 MHz + 1 Hz

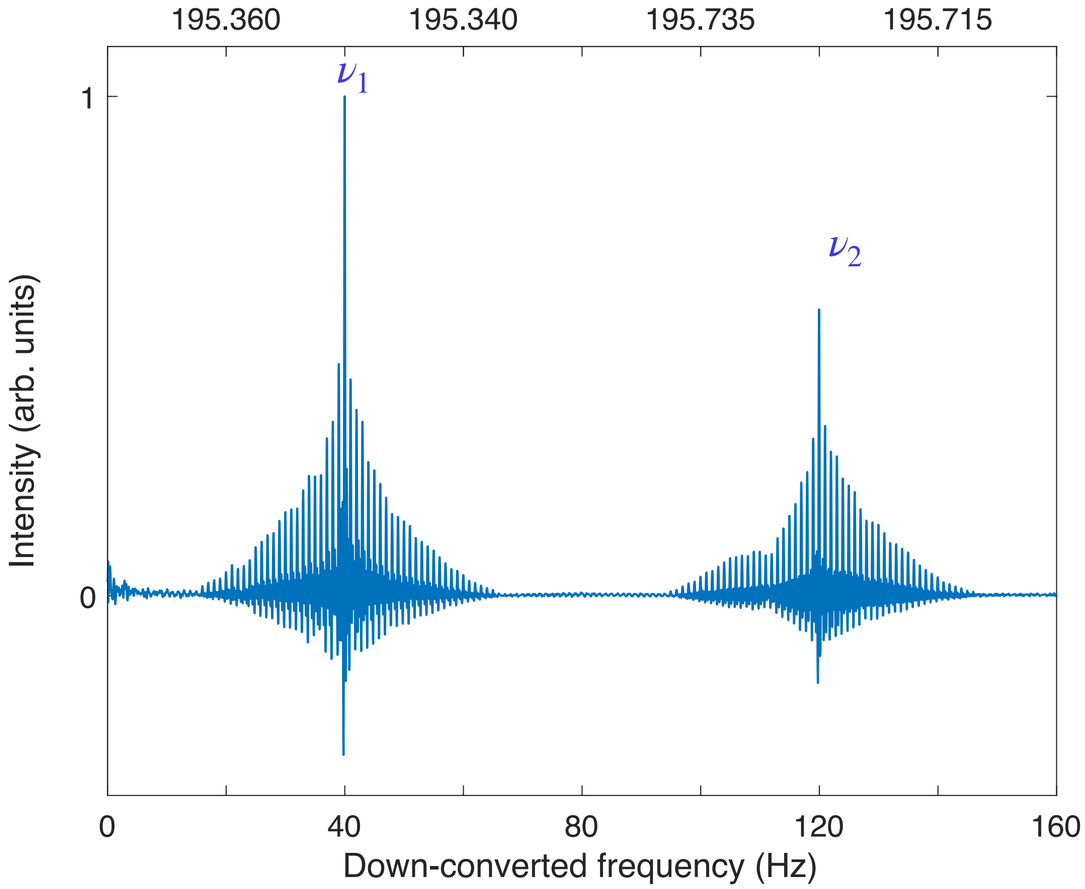




Experimental results

Single pixel

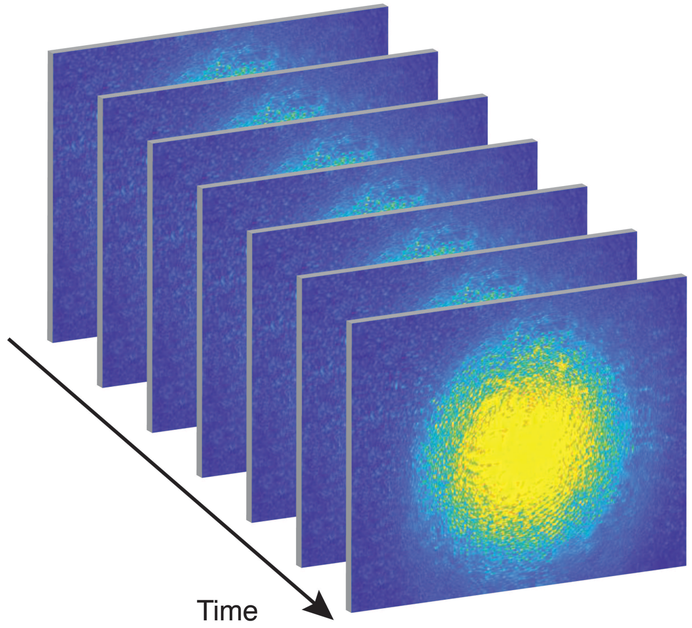


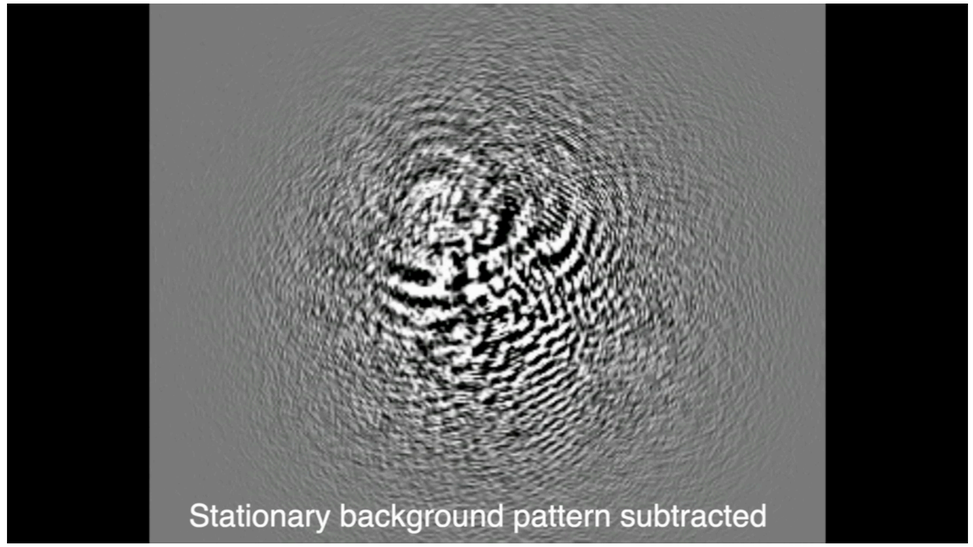


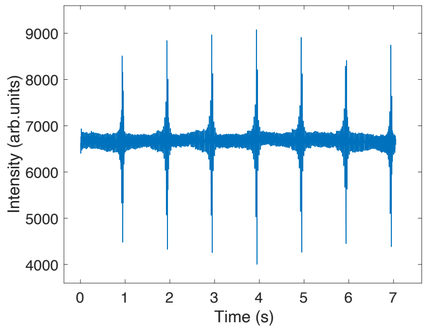
Experimental results

Experimental results

a) Time-domain interference frame measurement







Experimental results

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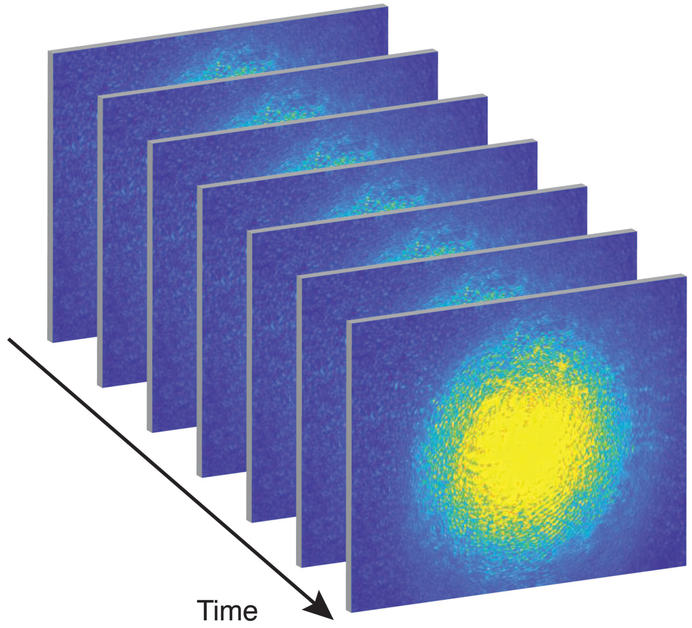
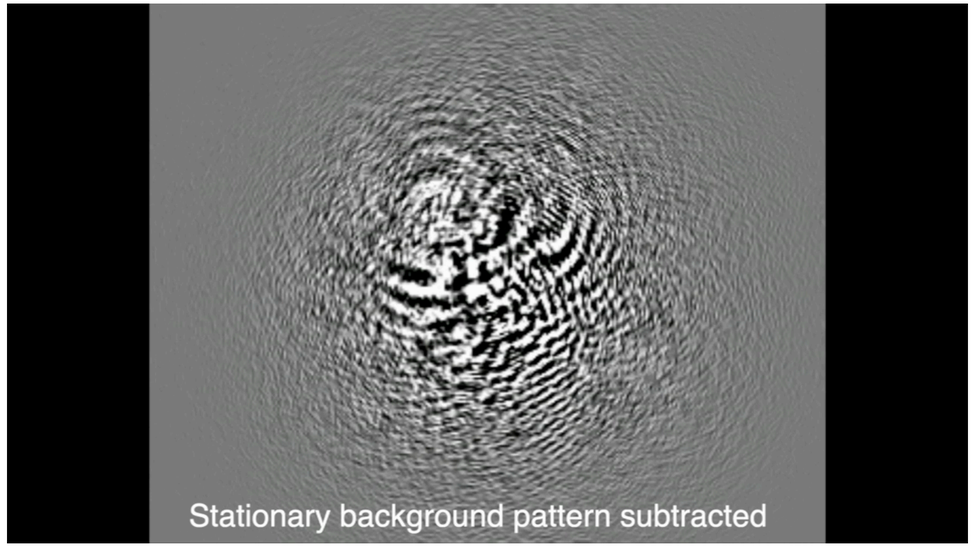
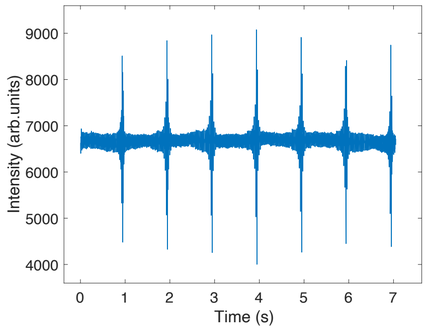






TIME-DOMAIN

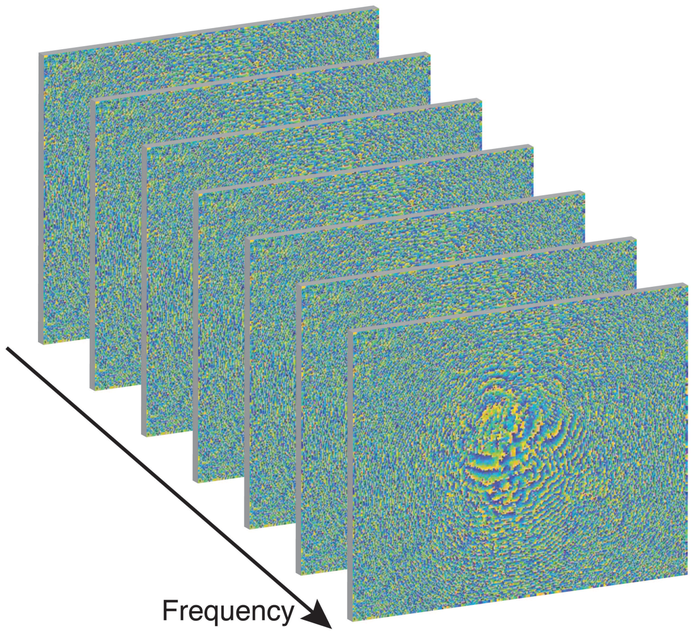
FOURIER

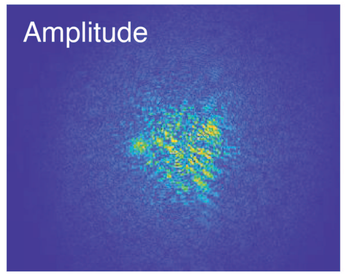
TRANSFORM

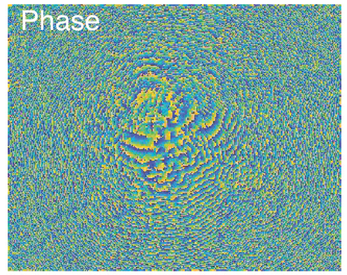
Experimental results

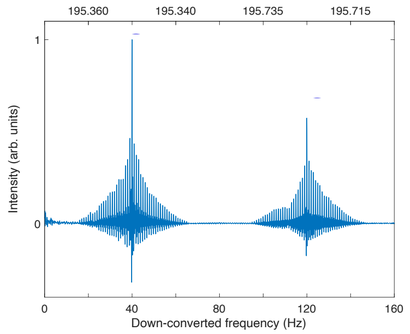
Experimental results

c) Hologram hypercube



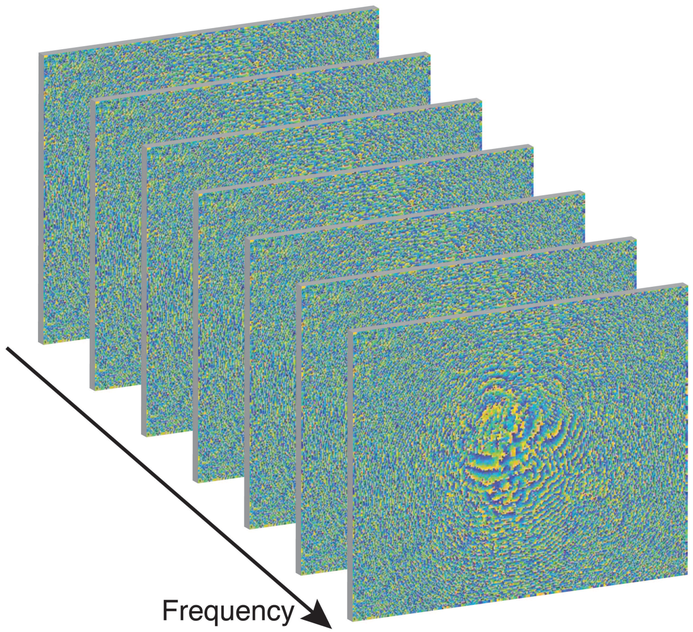


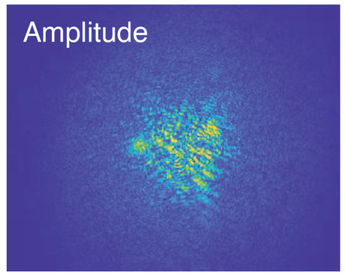


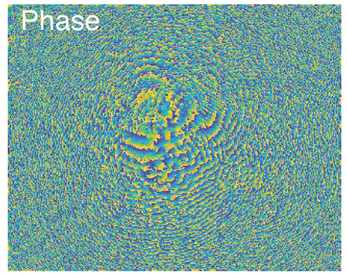


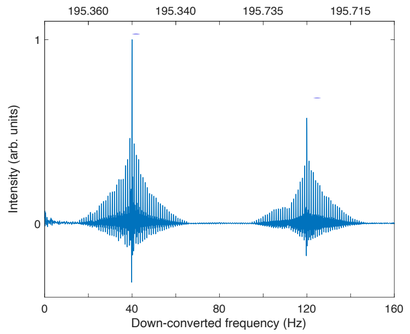
Experimental results

c) Hologram hypercube





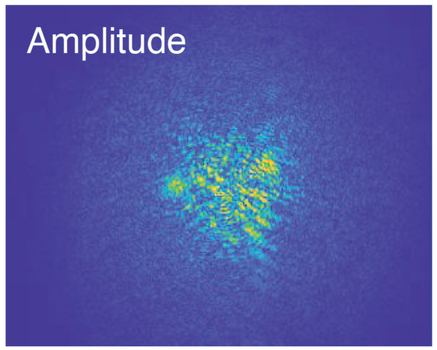




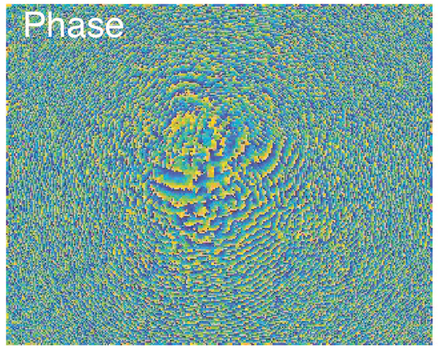
Experimental results

Experimental results

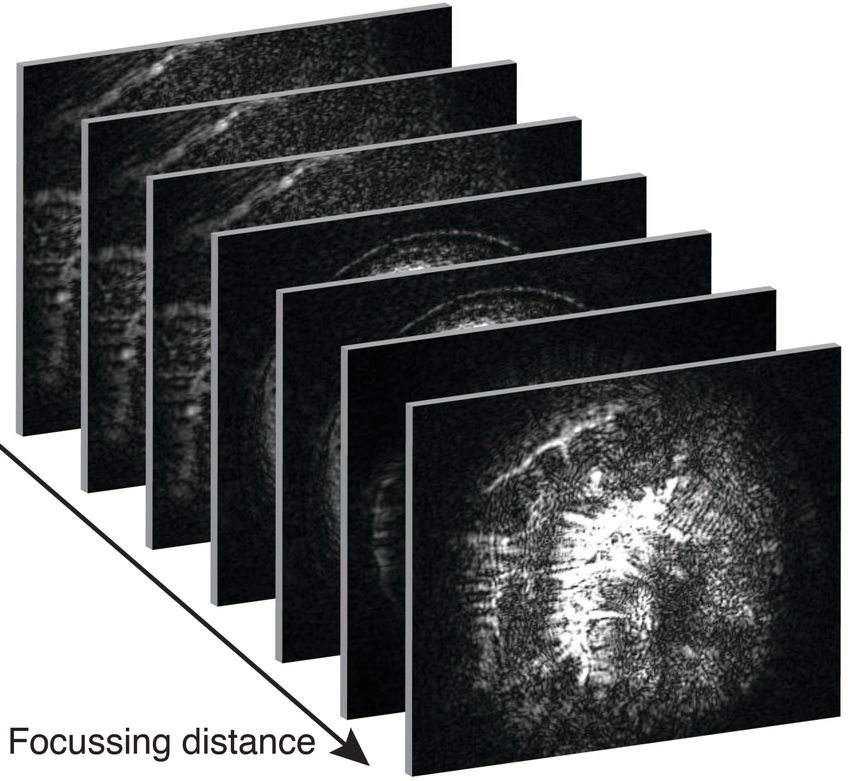
d) For each frequency



hologram

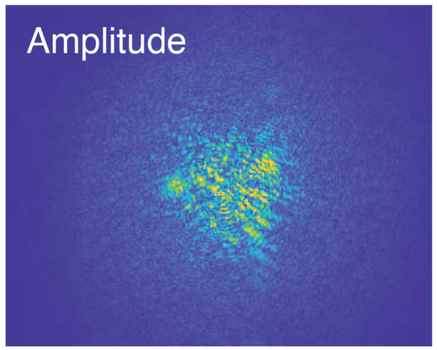


Inverse
Fresnel
transform

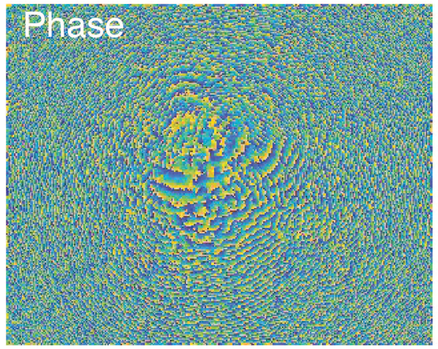


Experimental results

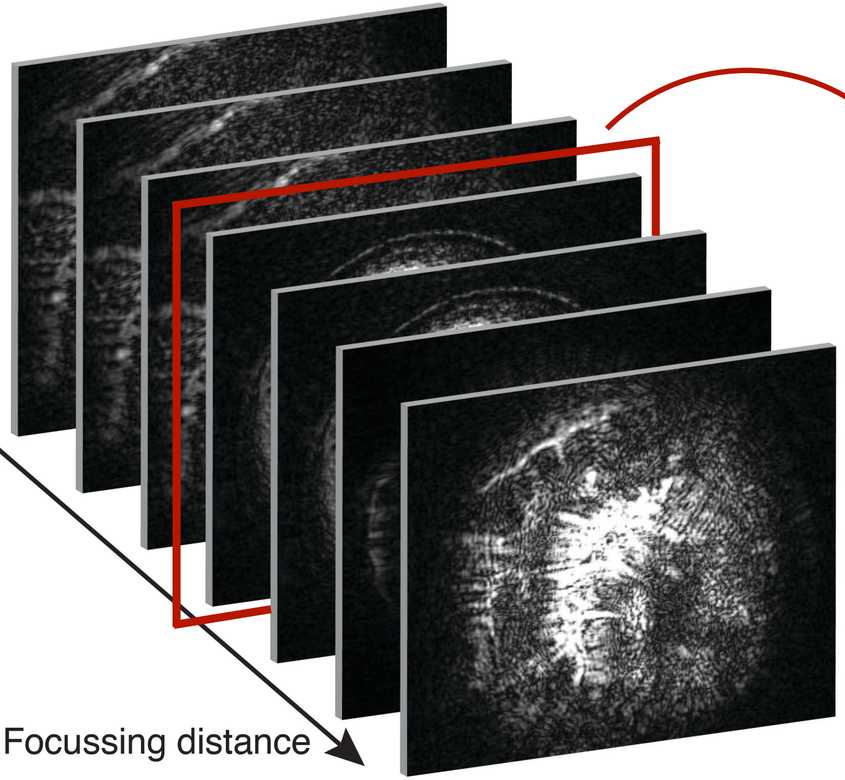
d) For each frequency

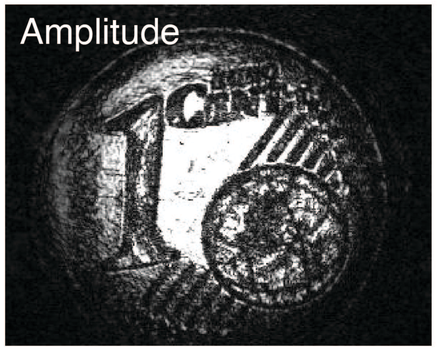


hologram

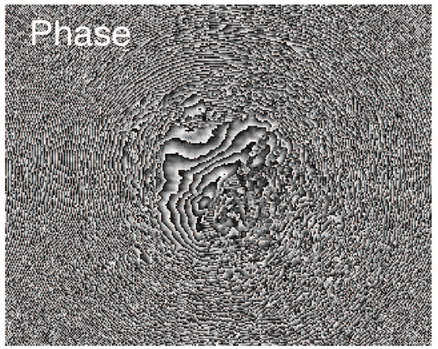


Inverse
Fresnel
transform



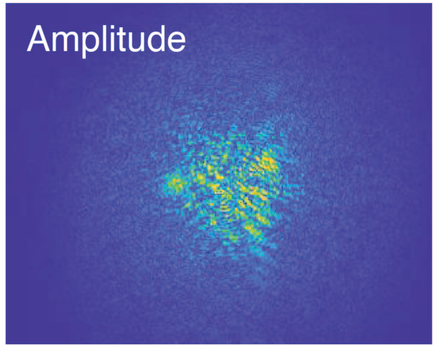


Reconstruction at focus

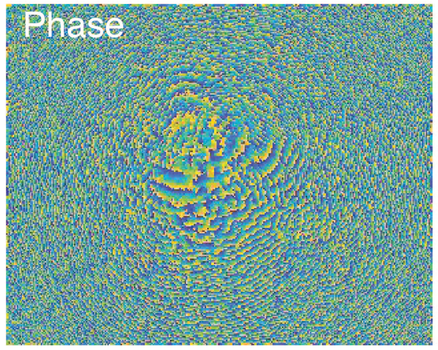


Experimental results

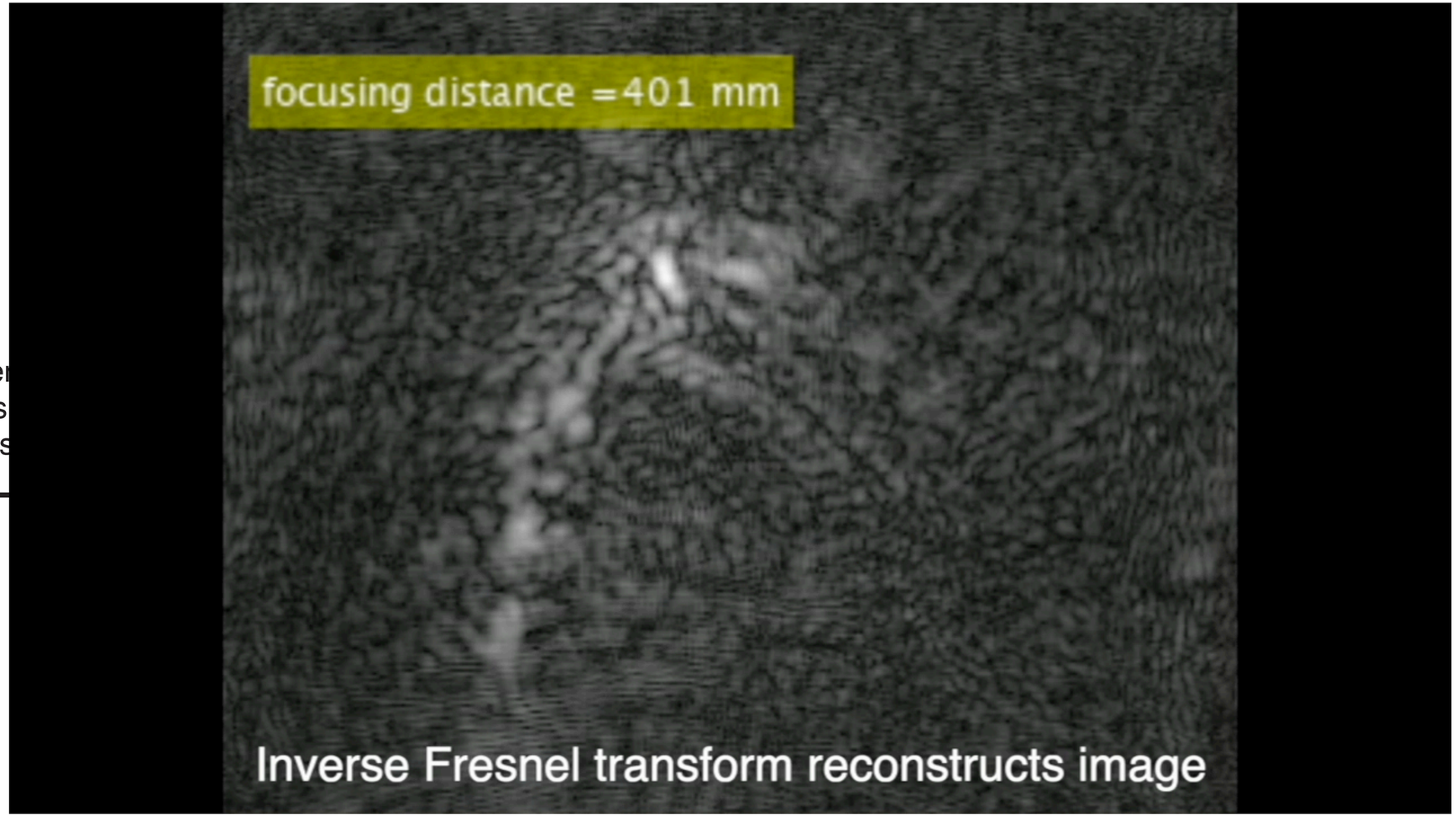
d) For each frequency



hologram

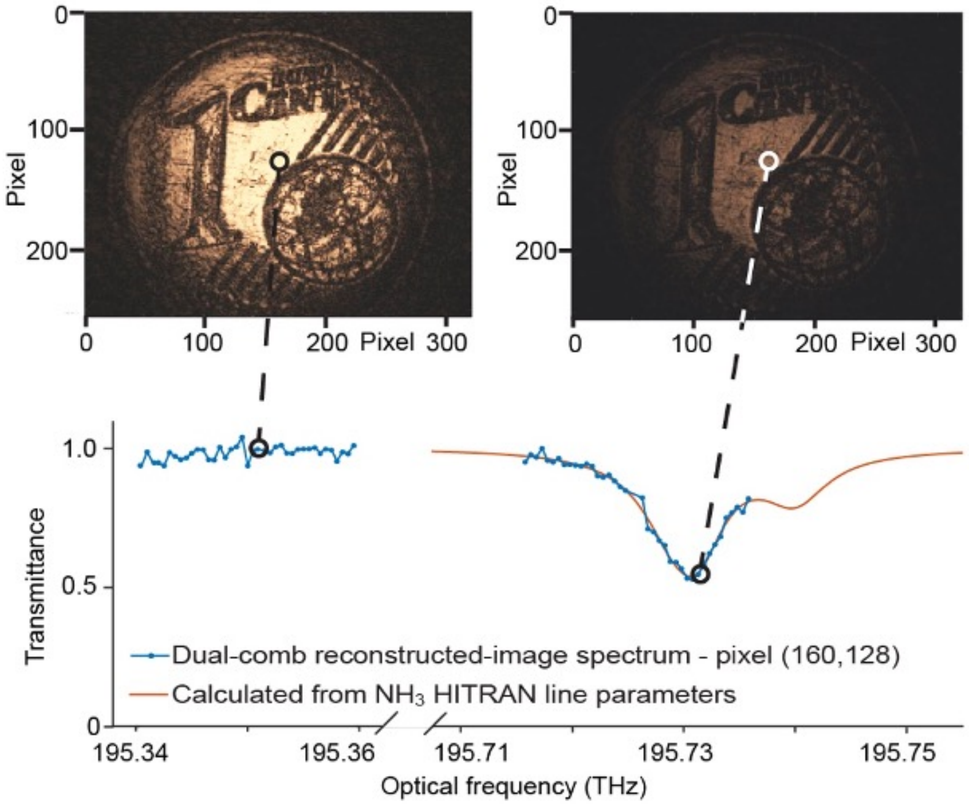


Inver
Fres
trans



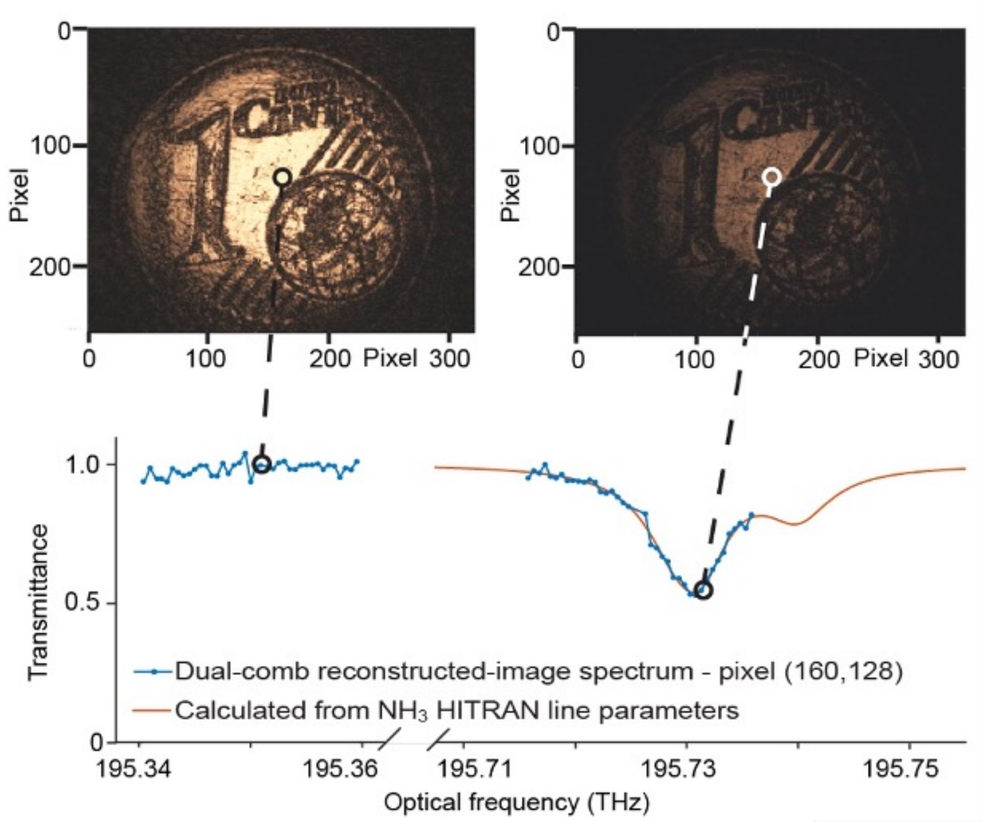
Experimental results

Hyperspectral imaging

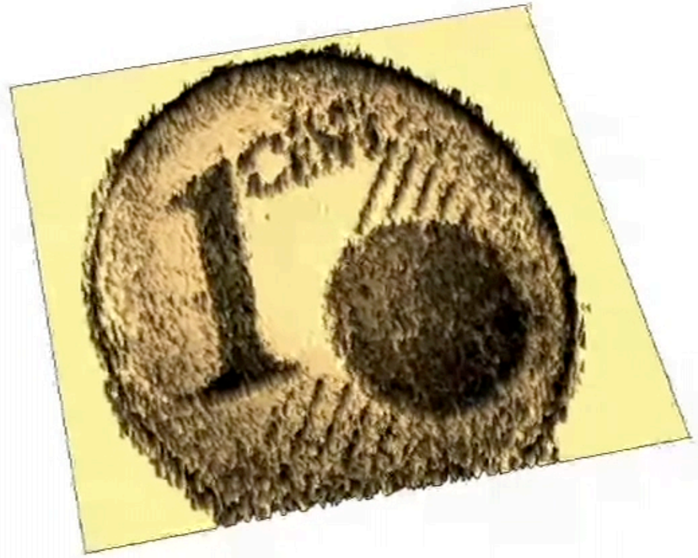


Experimental results

Hyperspectral imaging



3D profile



Conclusion

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- Possibility to apply dual-comb spectroscopy to digital holography
- High-resolution spectroscopy 500 MHz
- 3D imaging

Conclusion

- Possibility to apply dual-comb spectroscopy to digital holography
- High-resolution spectroscopy 500 MHz
- 3D imaging

and future perspective

- Spectra SNR characterisation
- 3D precision

- Improving camera frame rate, number of pixel
- Implementation with large bandwidth frequency comb

CLEO

CLEO

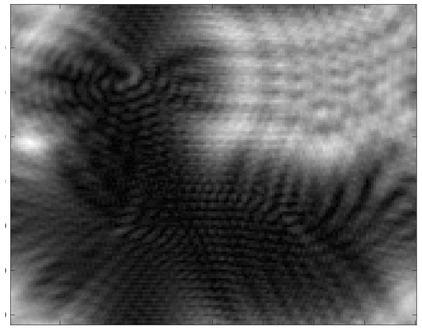
Thank you for your attention

Digital Holography - data processing

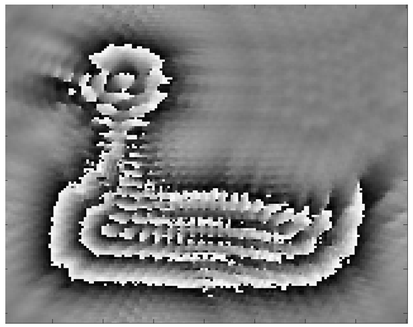
Digital Holography - data processing

Digital hologram

AMPLITUDE



PHASE

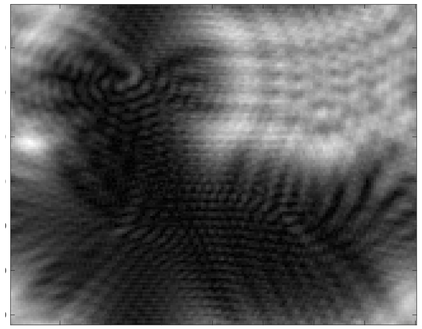


Digital Holography - data processing

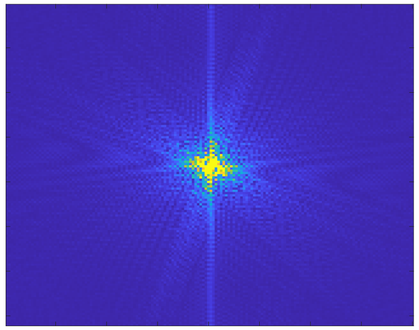
Digital hologram

Fourier hologram

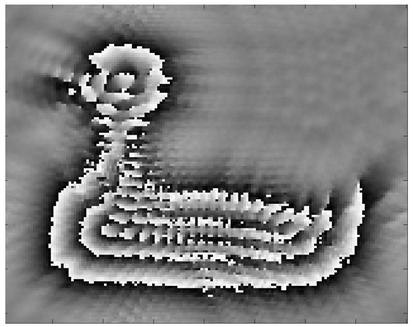
AMPLITUDE

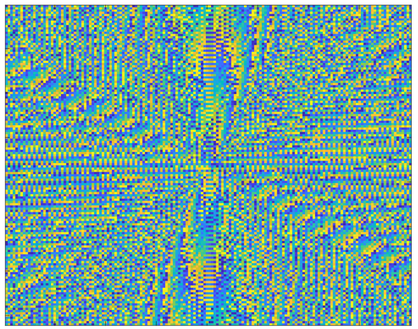


2D
Fourier
transform



PHASE



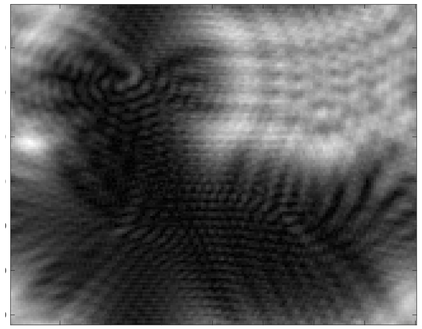


Digital Holography - data processing

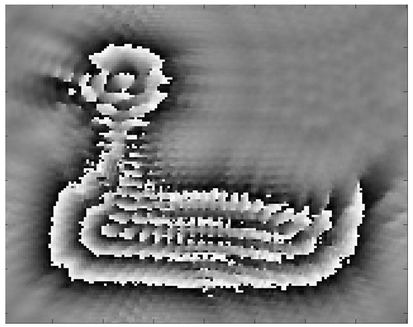
Digital hologram

Fourier hologram

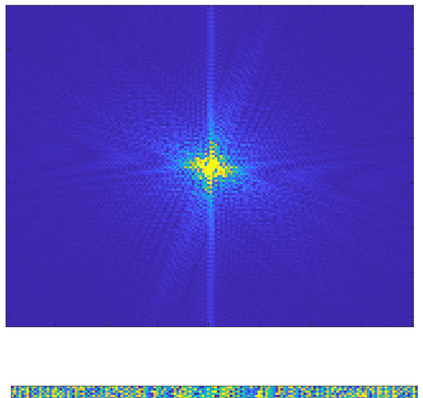
AMPLITUDE

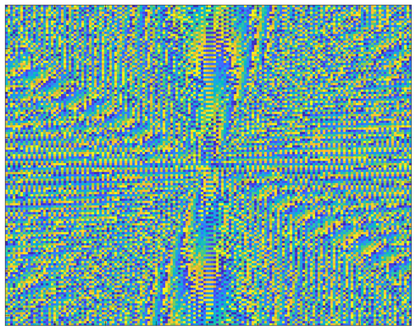


PHASE



2D Fourier transform





Data Processing

2D inverse Fourier transform

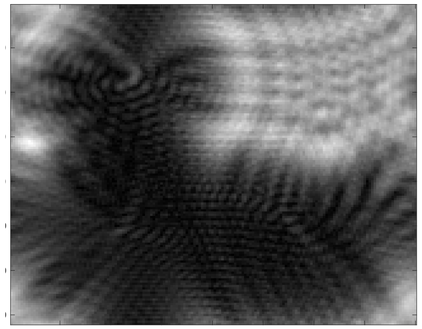
Digital Holography - data processing

Digital hologram

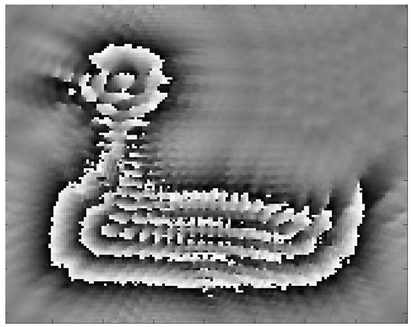
Fourier hologram

Reconstructed image

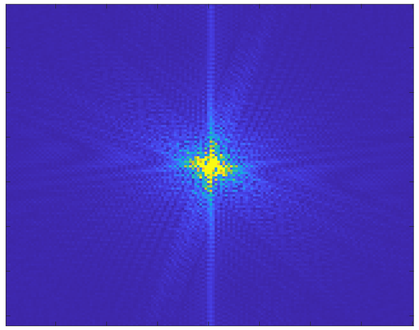
AMPLITUDE

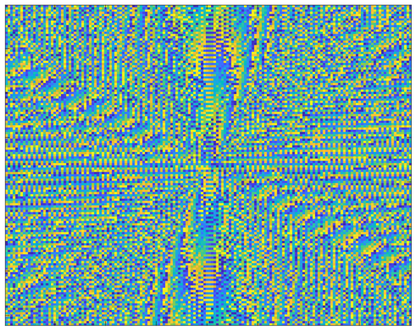


PHASE



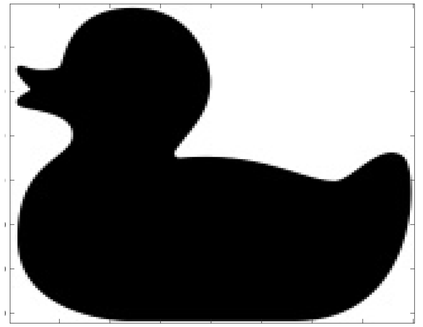
2D Fourier transform



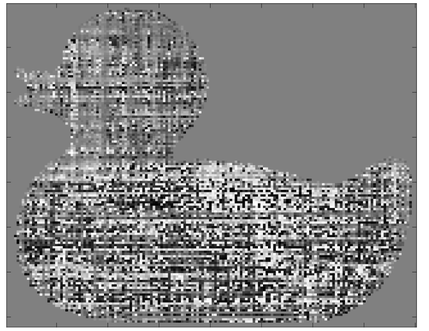


Data Processing

2D inverse Fourier transform



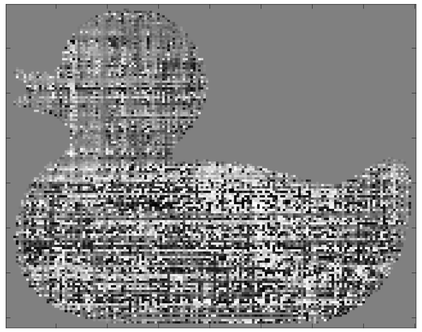
AMPLITUDE



PHASE

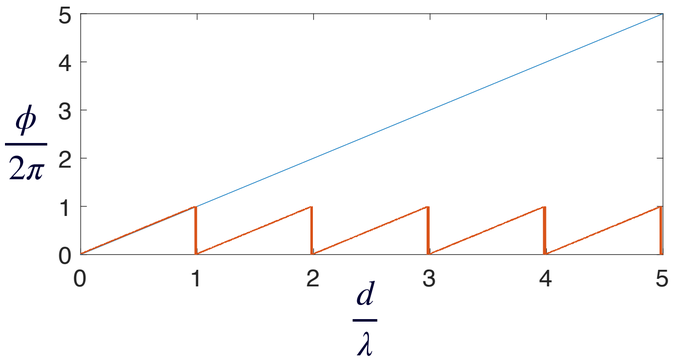
Digital Holography - phase unwrapping

Digital Holography - phase unwrapping



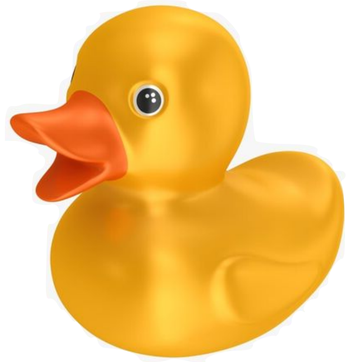
PHASE

Phase unwrap

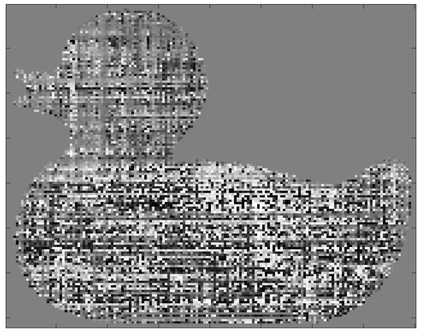


3D profile

TARGET

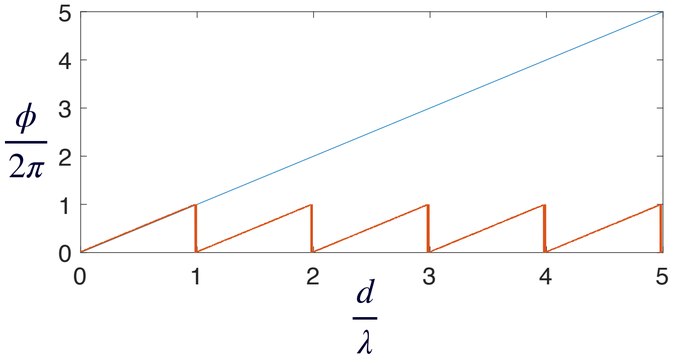


Digital Holography - phase unwrapping



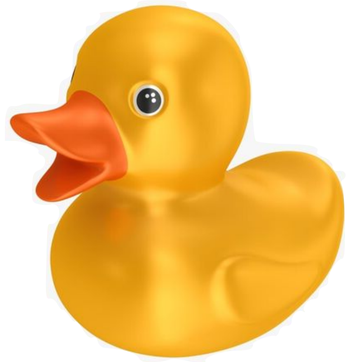
PHASE

Phase unwrap

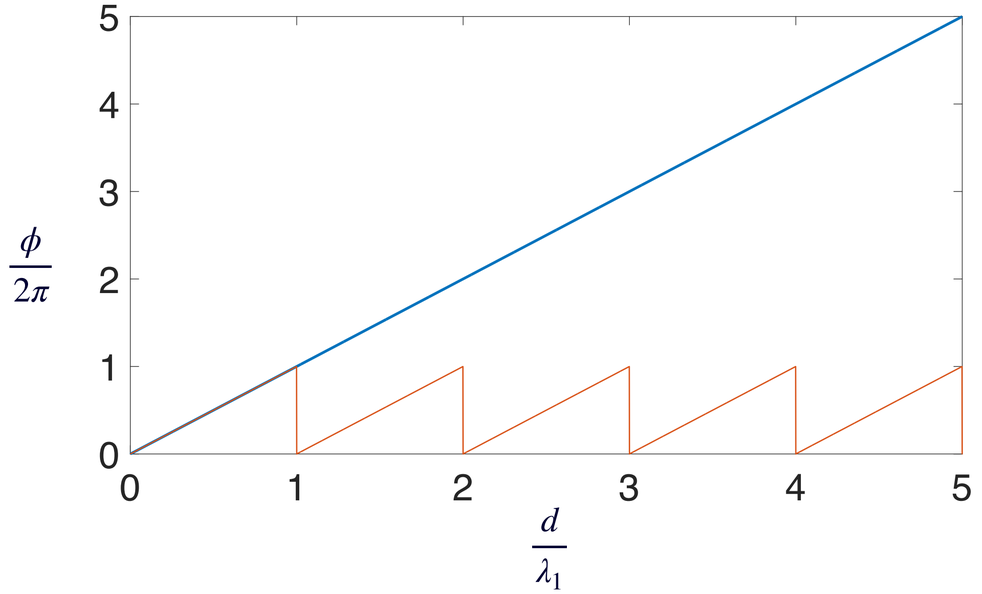


3D profile

TARGET

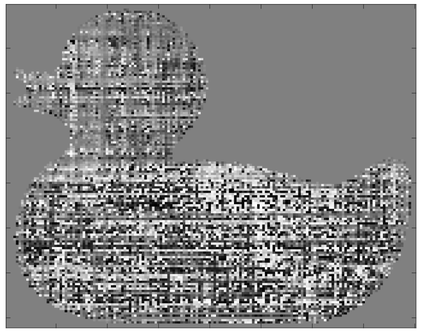


λ_1 $\quad d_{MIN} \approx \frac{\lambda_1}{SNR} \quad d_{MAX} \approx \frac{\lambda_1}{2}$



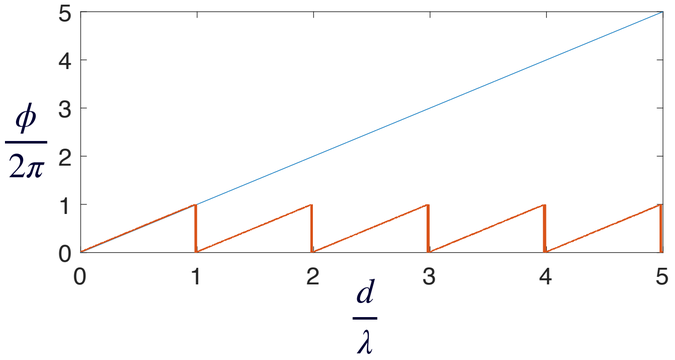
Digital Holography - phase unwrapping

TARGET

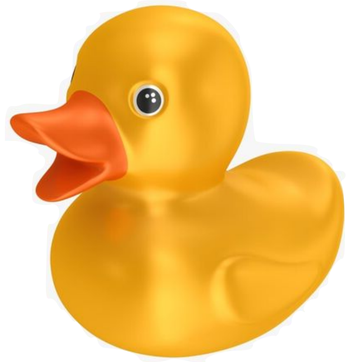


PHASE

Phase unwrap

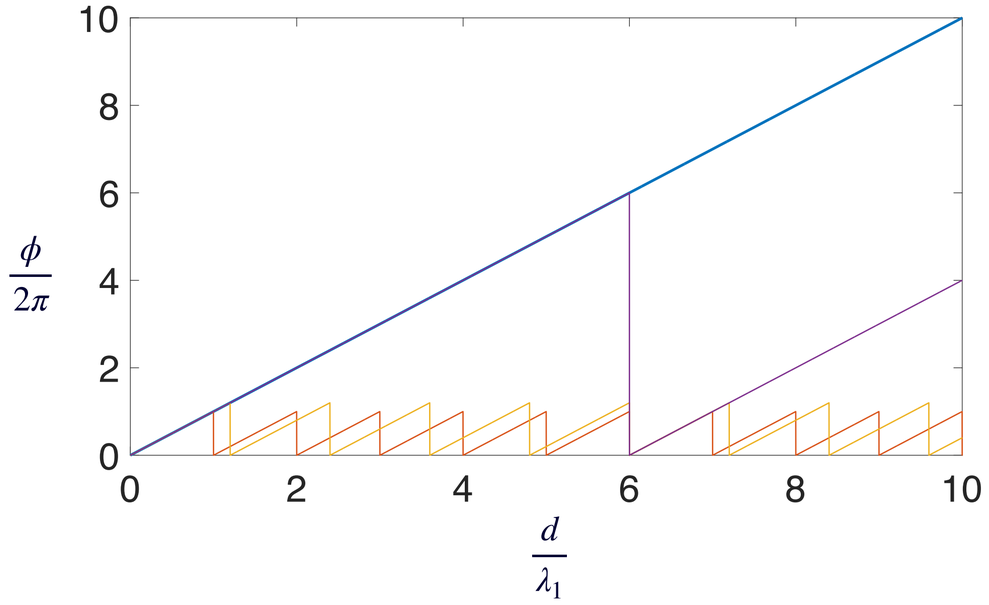


3D profile

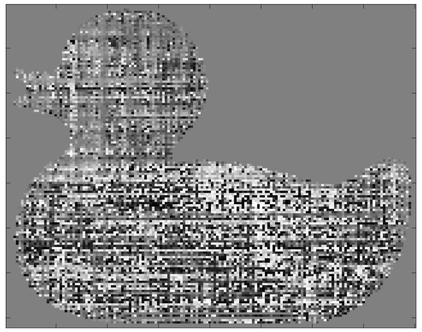


$$\lambda_1 \qquad d_{MIN} \approx \frac{\lambda_1}{SNR} \qquad d_{MAX} \approx \frac{\lambda_1}{2}$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} \qquad d_{MIN} \approx \frac{\lambda_c}{SNR} \qquad d_{MAX} \approx \frac{\lambda_c}{2}$$

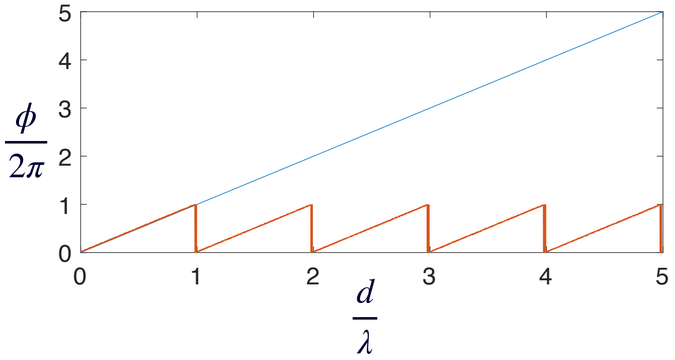


Digital Holography - phase unwrapping



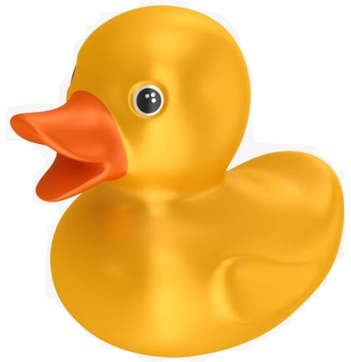
PHASE

Phase unwrap



3D profile

TARGET

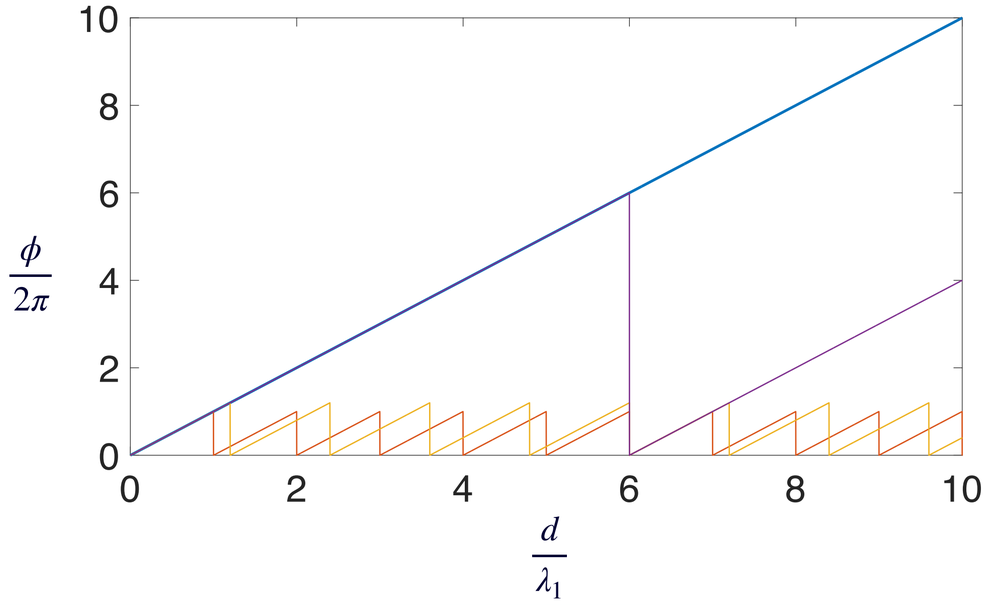


$$\lambda_1$$

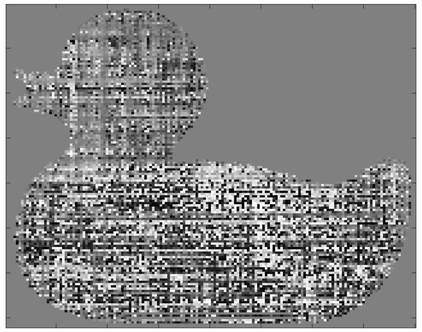
$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

$$d_{MIN} \approx \frac{\lambda_1}{SNR} \qquad d_{MAX} \approx \frac{\lambda_1}{2}$$

$$d_{MIN} \approx \frac{\lambda_c}{SNR} \qquad d_{MAX} \approx \frac{\lambda_c}{2}$$

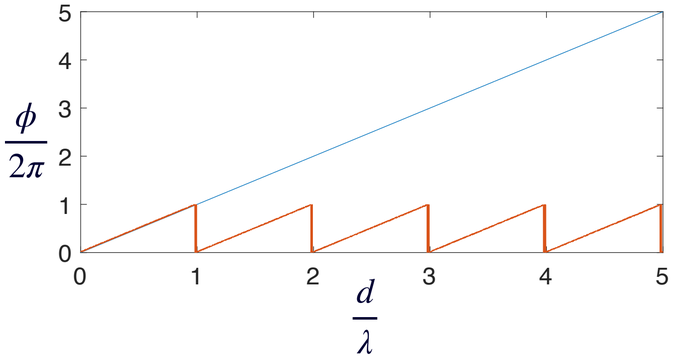


Digital Holography - phase unwrapping



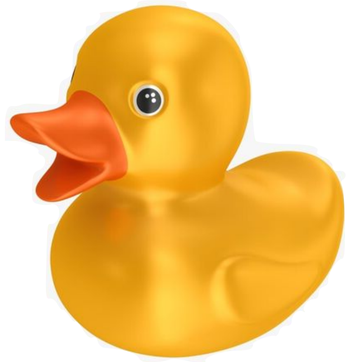
PHASE

Phase unwrap



3D profile

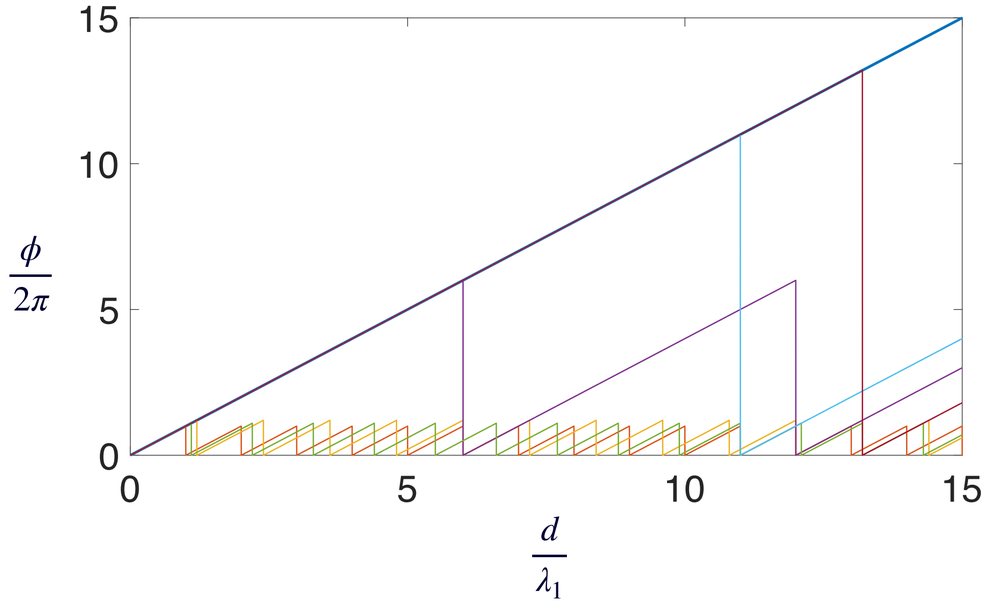
TARGET



$$\lambda_1 \qquad d_{MIN} \approx \frac{\lambda_1}{SNR} \qquad d_{MAX} \approx \frac{\lambda_1}{2}$$

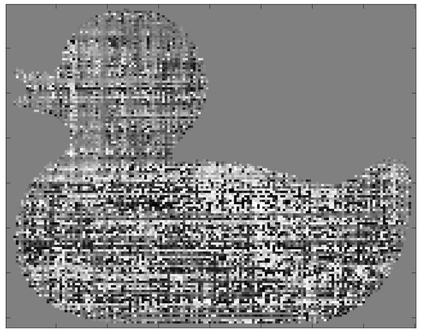
$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} \qquad d_{MIN} \approx \frac{\lambda_c}{SNR} \qquad d_{MAX} \approx \frac{\lambda_c}{2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}} \qquad d_{MIN} \approx \frac{\lambda_K}{SNR} \qquad d_{MAX} \approx \frac{\lambda_K}{2}$$



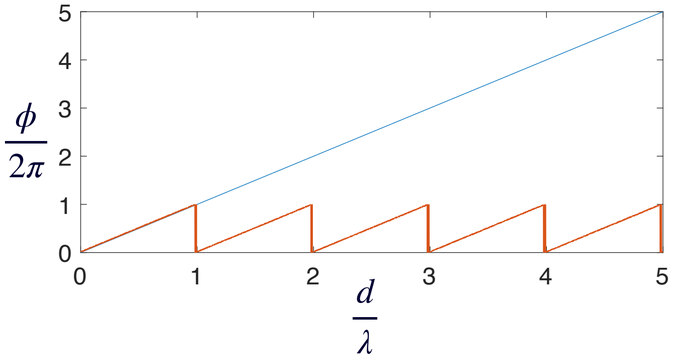
Digital Holography - phase unwrapping

TARGET

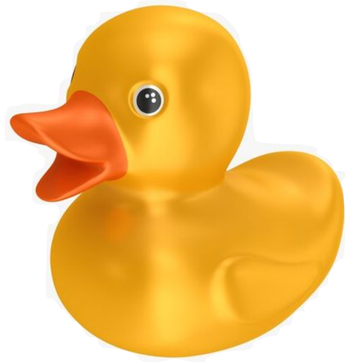


PHASE

Phase unwrap



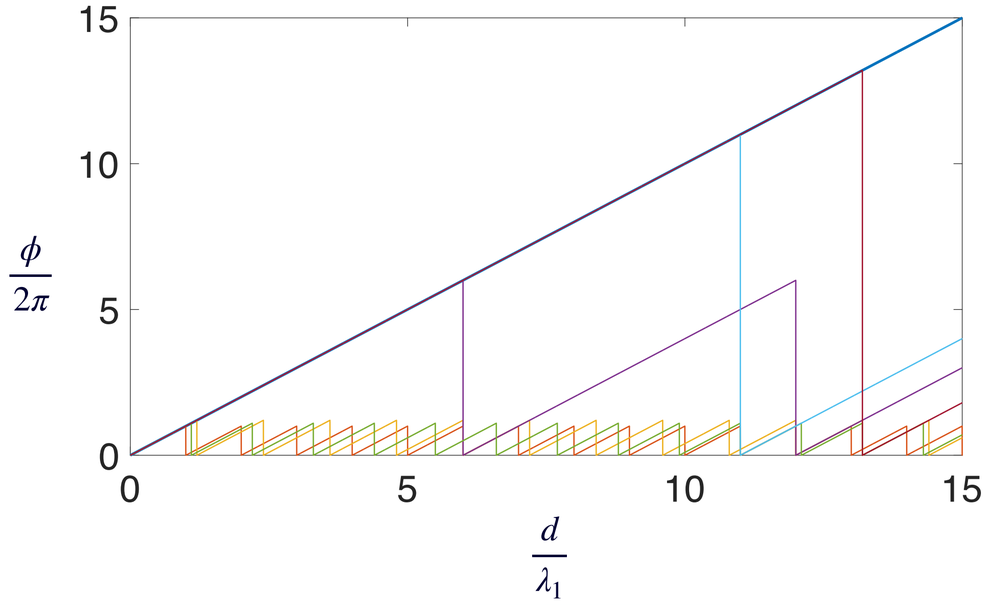
3D profile



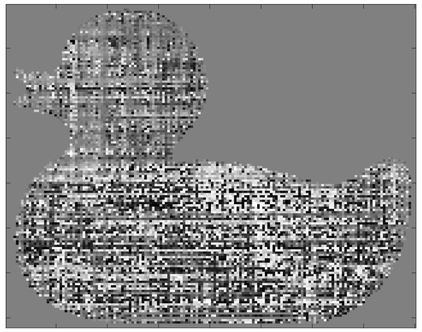
$$\lambda_1 \qquad d_{MIN} \approx \frac{\lambda_1}{SNR} \qquad d_{MAX} \approx \frac{\lambda_1}{2}$$

$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} \qquad d_{MIN} \approx \frac{\lambda_c}{SNR} \qquad d_{MAX} \approx \frac{\lambda_c}{2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}} \qquad d_{MIN} \approx \frac{\lambda_K}{SNR} \qquad d_{MAX} \approx \frac{\lambda_K}{2}$$

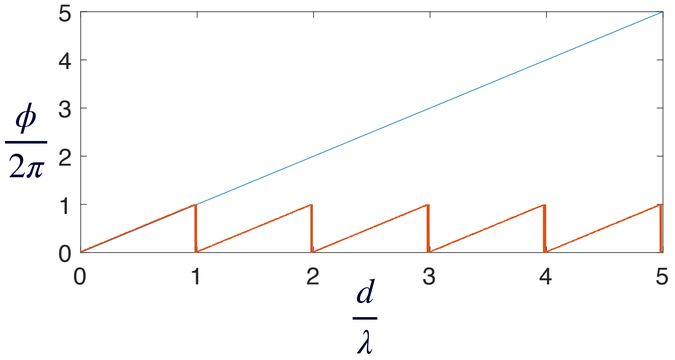


Digital Holography - phase unwrapping



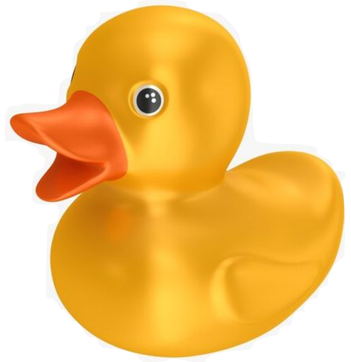
PHASE

Phase unwrap



3D profile

TARGET



$$\lambda_1$$

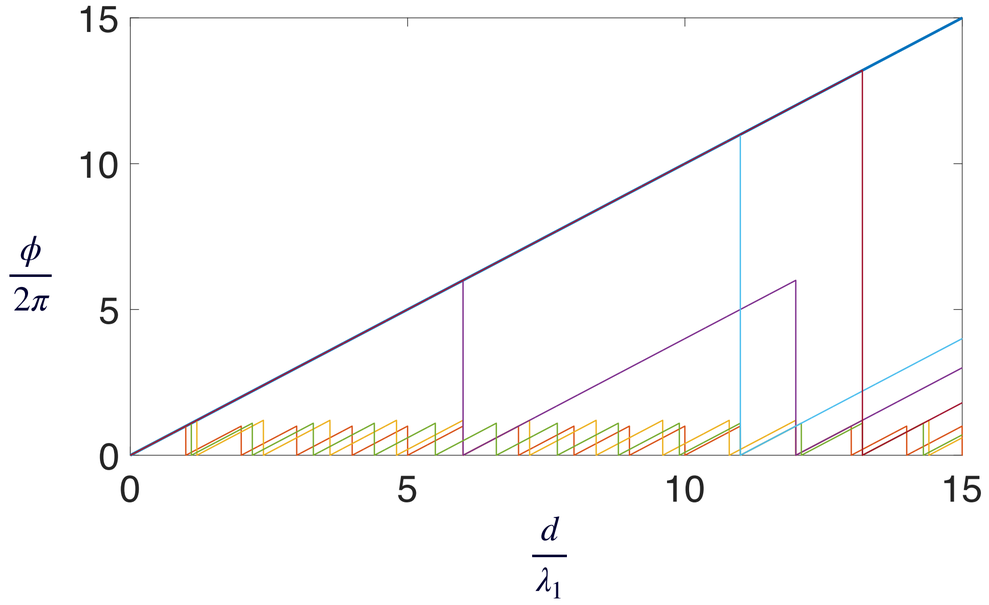
$$\lambda_c = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

$$\lambda_K = \frac{\lambda_{c_1} \lambda_{c_2}}{\lambda_{c_1} - \lambda_{c_2}}$$

$$d_{MIN} \approx \frac{\lambda_1}{SNR} \qquad d_{MAX} \approx \frac{\lambda_1}{2}$$

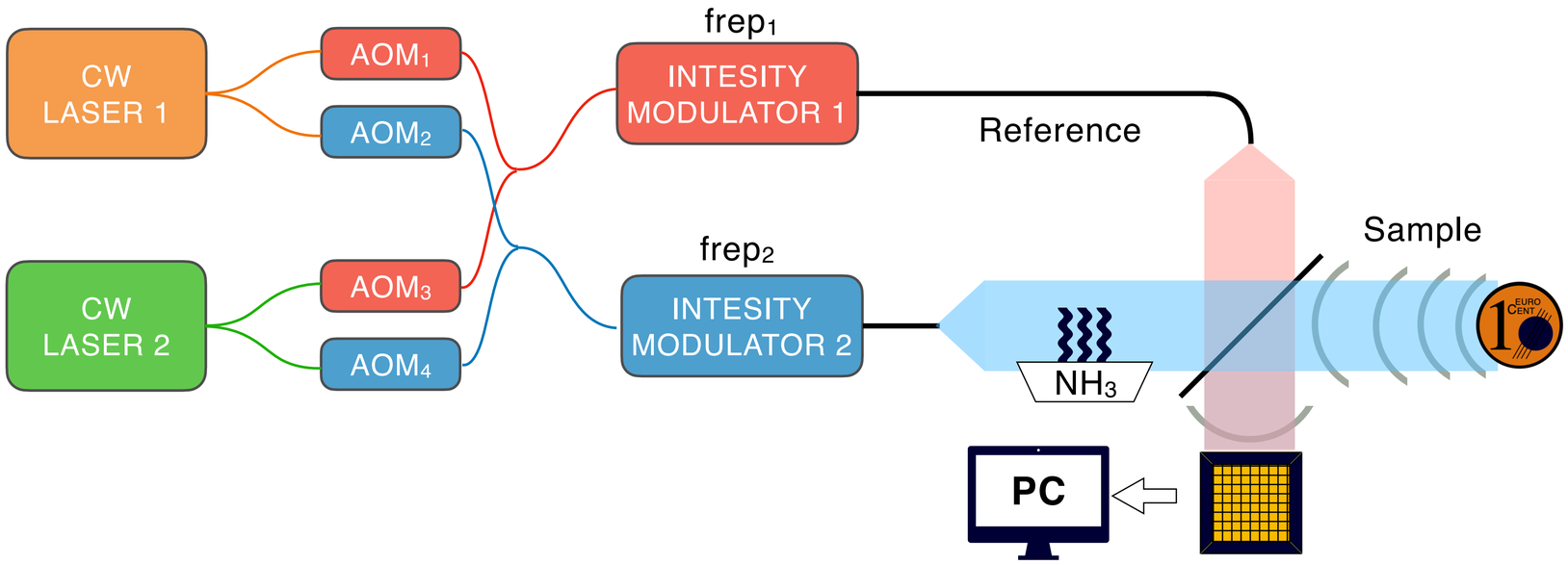
$$d_{MIN} \approx \frac{\lambda_c}{SNR} \qquad d_{MAX} \approx \frac{\lambda_c}{2}$$

$$d_{MIN} \approx \frac{\lambda_K}{SNR} \qquad d_{MAX} \approx \frac{\lambda_K}{2}$$

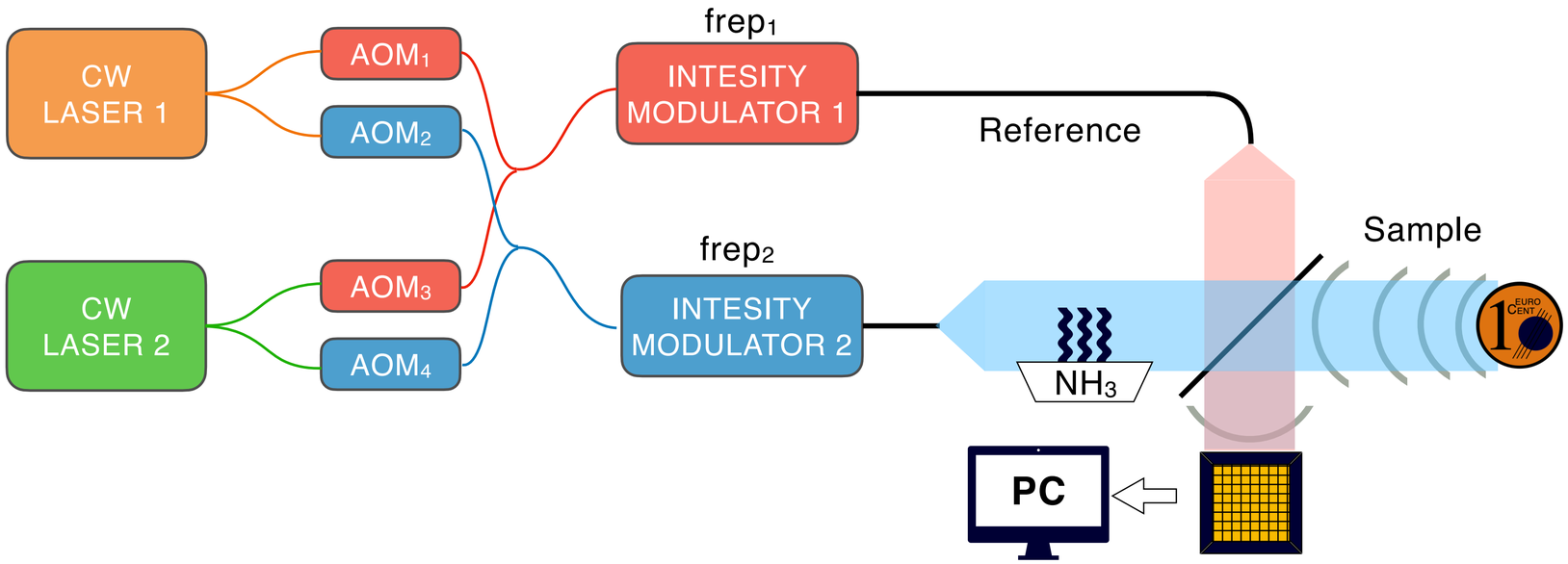


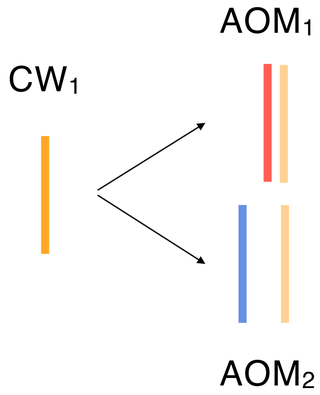
Experimental Setup

Experimental Setup

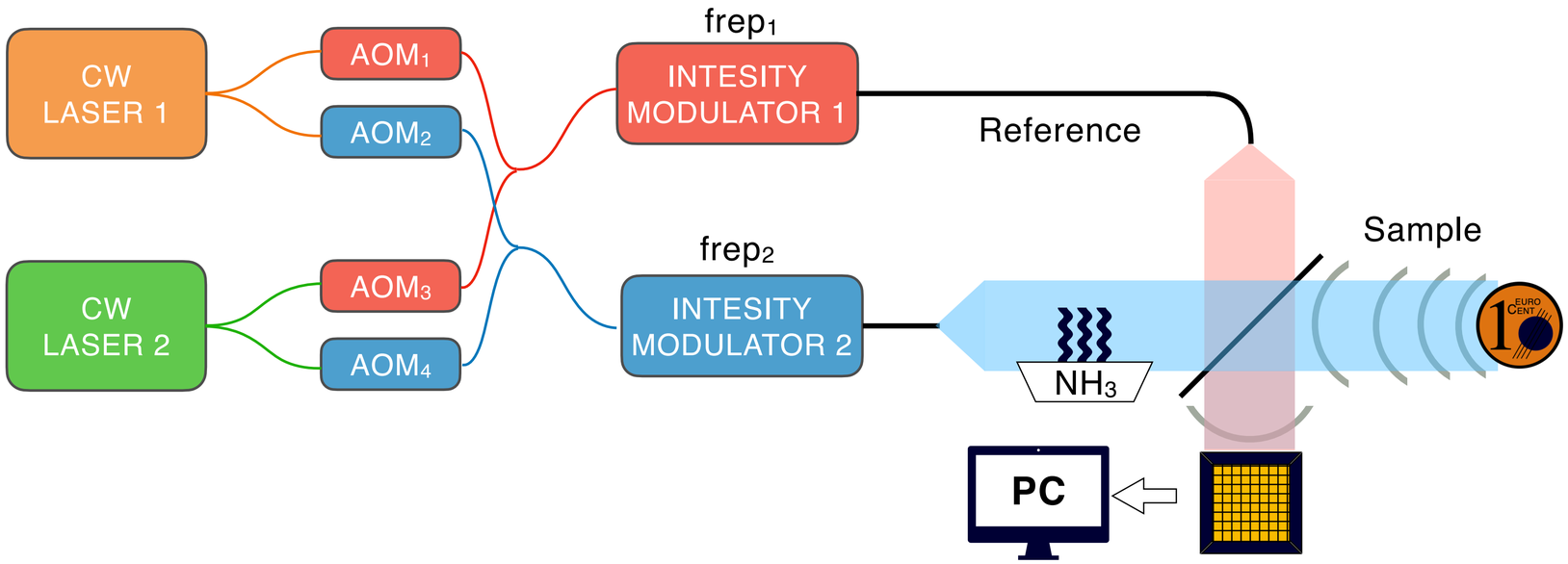


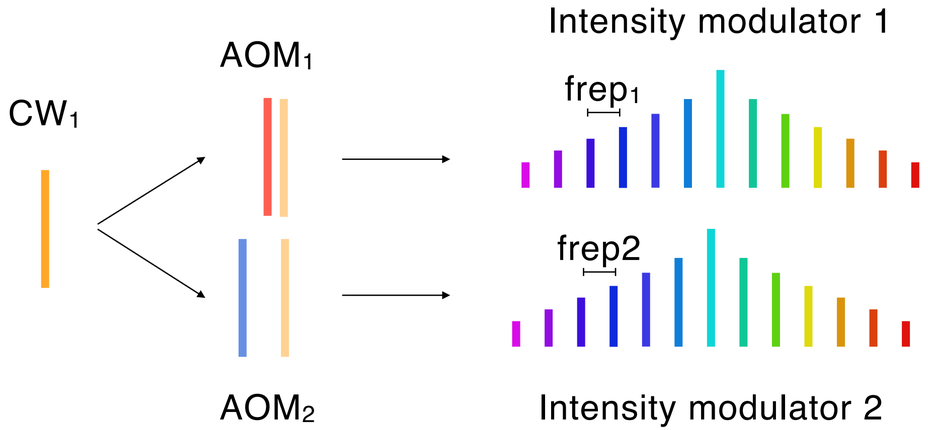
Experimental Setup



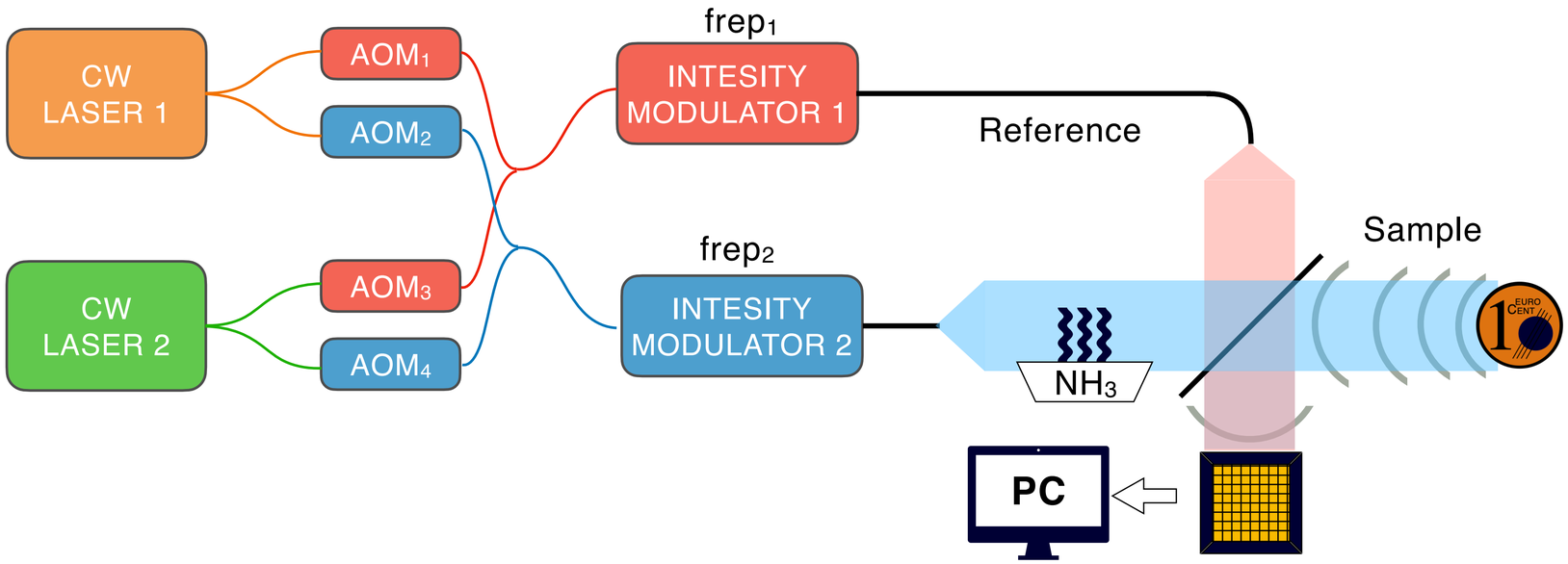


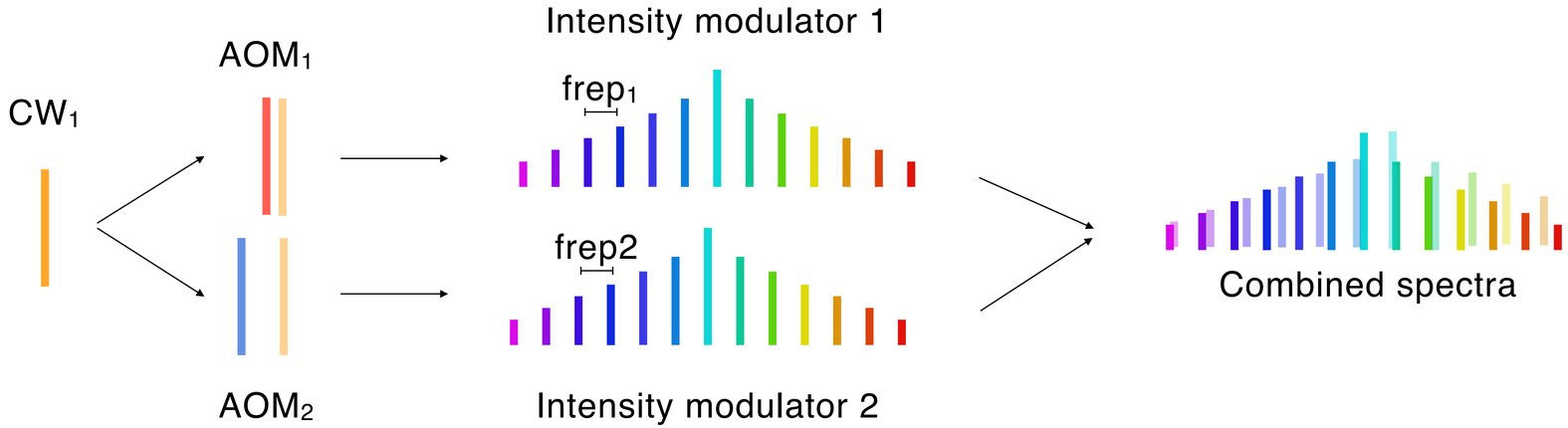
Experimental Setup



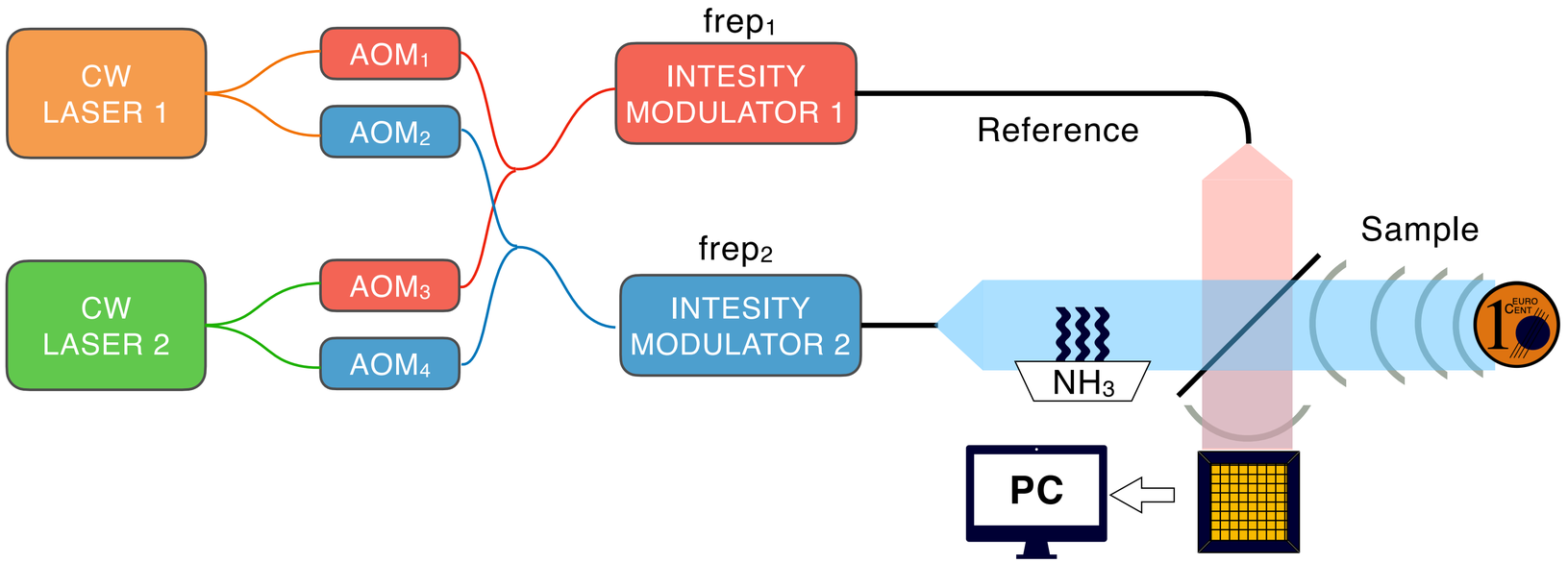


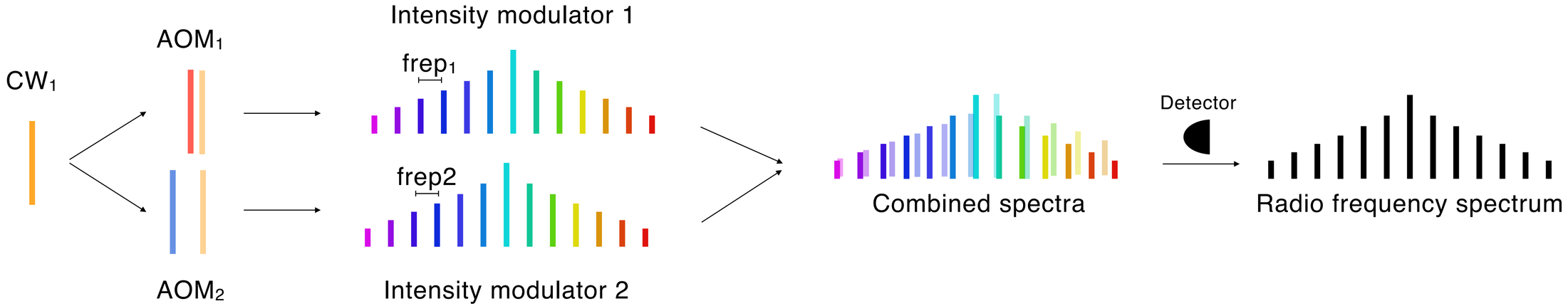
Experimental Setup



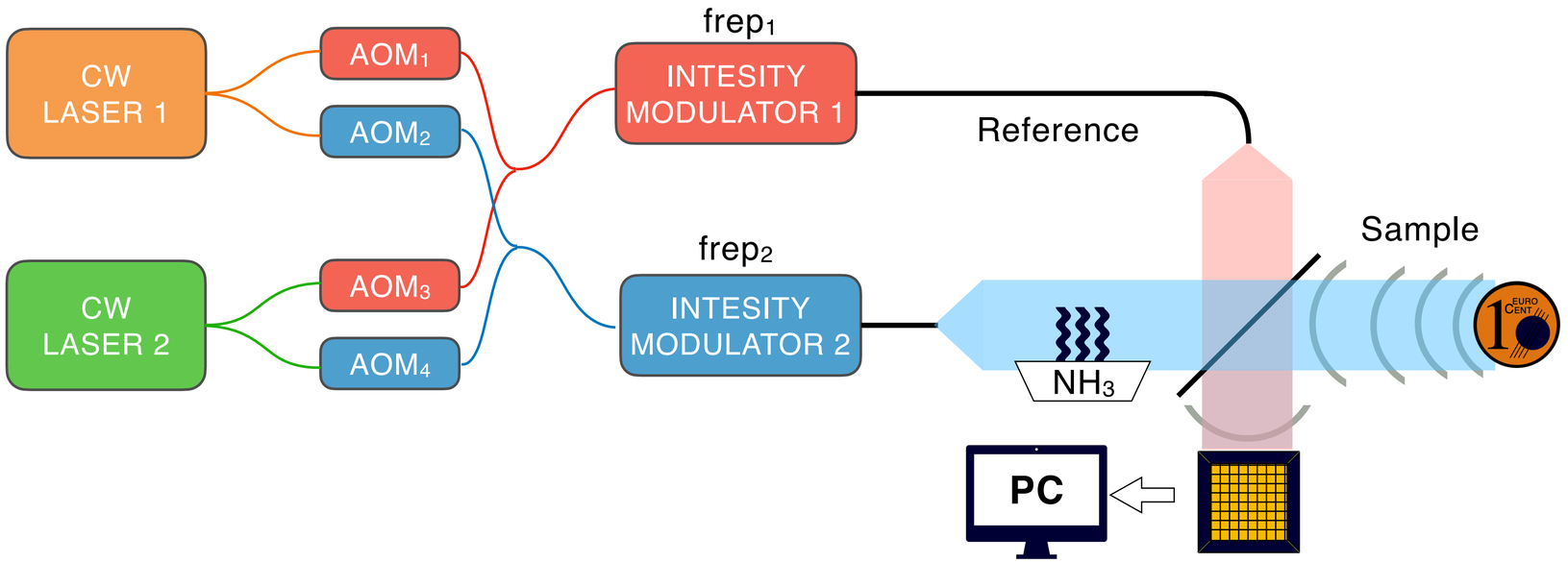


Experimental Setup





Experimental Setup



CW_1 = 195.353 THz

AOM_1 = 25 MHz

AOM_2 = 25 MHz + 40 Hz

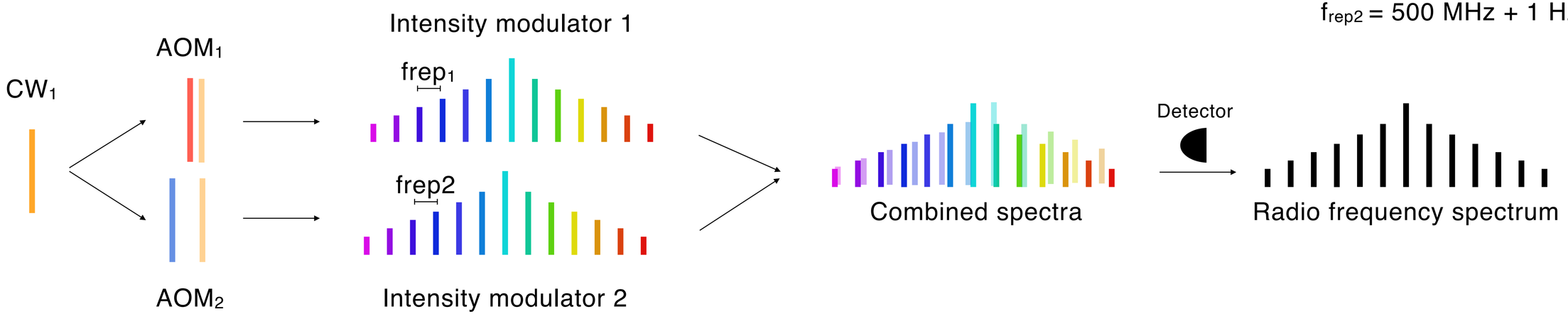
f_{rep1} = 500 MHz

CW_2 = 195.736 THz

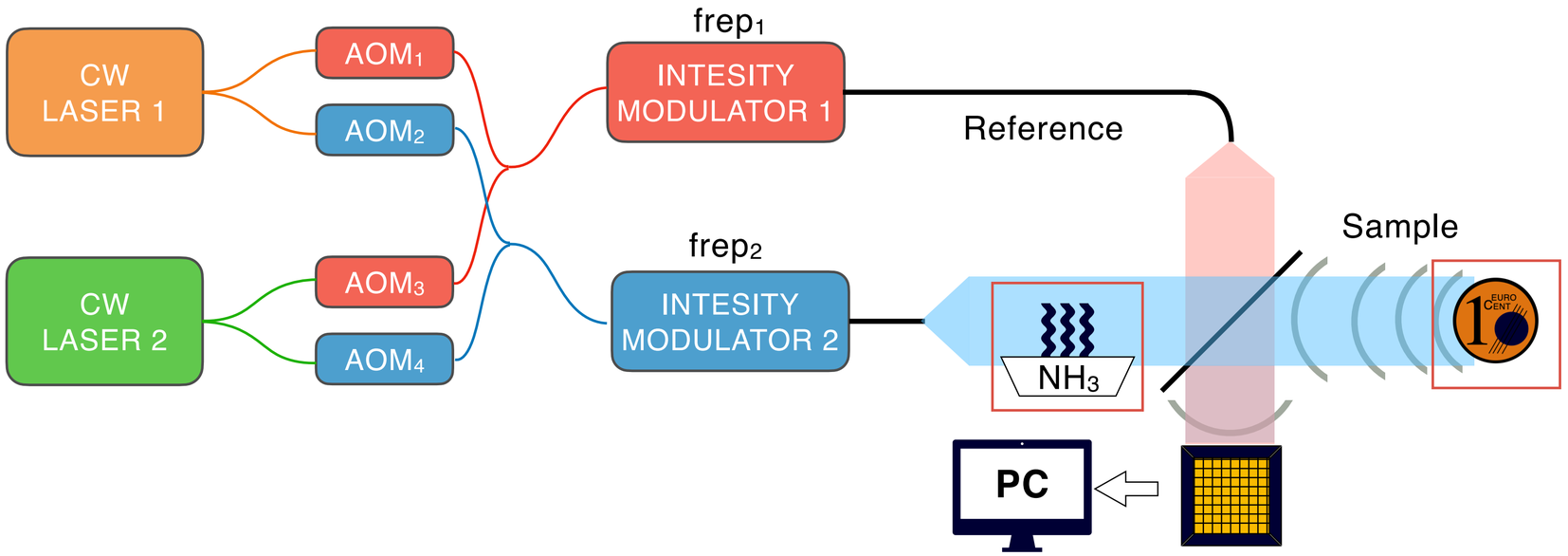
AOM_3 = 40 MHz

AOM_4 = 40 MHz + 120 Hz

f_{rep2} = 500 MHz + 1 Hz



Experimental Setup



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