Interferometric Visualization of High-Power Standing Ultrasound Fields

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1. Motivation

Ultrasound-induced laser beam deflection
at DESY (Fig. 1) [1]

- High-intensity ultrasound waves cause refractive index modulations ⇨ diffraction
- Acousto-optic modulation in ambient air

Requirements:

- High power ultrasound fields ($SPL \approx 140$ dB), individually manufactured
- Contactless characterization method to observe the ultrasound field during the diffraction-based laser beam deflection

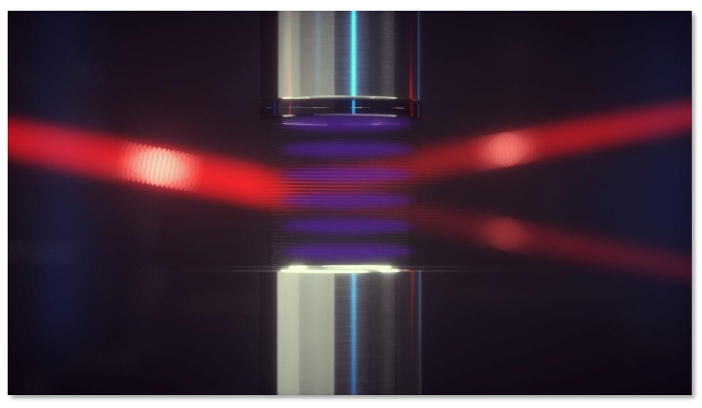
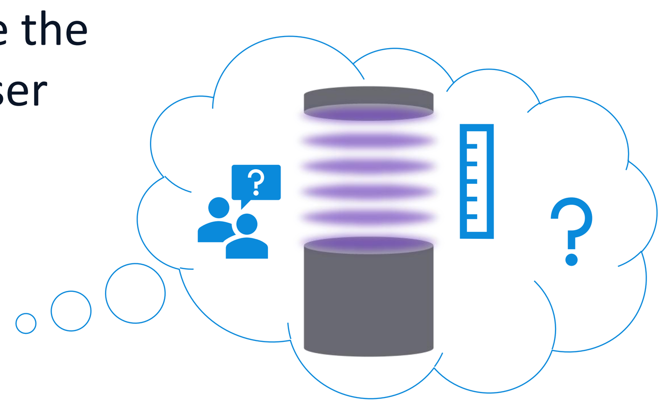


Fig. 1: Visualization of an acousto-optic modulator in ambient air
(image: Science Communication Lab for DESY, modified representation)



Research question:
Is it possible to visualize a standing ultrasound field using a Fizeau interferometer?

2. State of the Art

Typical method for single-shot 2D visualization of sound fields: **Schlieren imaging**

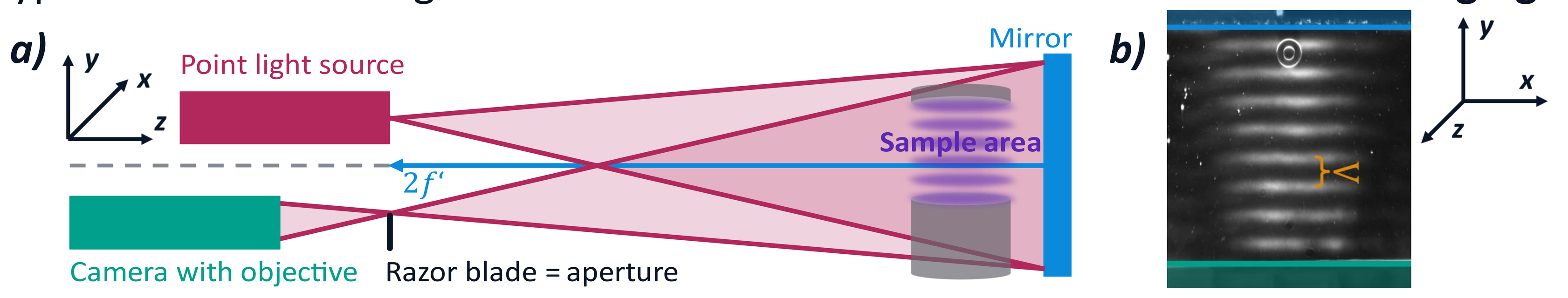


Fig. 2: a) Schematic of the schlieren setup, *modified representation according to [2, p. 871];* ***b) Acquired schlieren image*** *of the ultrasound transducer phased array (green) with reflector (blue) and indicated acoustic wavelength (orange)*

- Visualization of the refractive index gradient (Fig. 2) [2]:
  The refractive index gradients in the sample area cause light refraction which results in brighter and darker regions on the camera due to the aperture
- **Disadvantages:** only qualitative results, gradients in only one direction (perpendicular to the razor blade) can be visualized
- **Goal:** Introduction of a novel non-contact visualization method that enables the observation of ultrasound fields and provides more information than schlieren imaging (e. g. refractive index changes in x and y direction)

3. Tools and Methods

<u>Ultrasound transducer phased array</u> from *TU Darmstadt (Fig. 3) [3]*

- Sound frequency: $F = 40$ kHz, sound wavelength: Λ
- Sound pressure level: $SPL \approx 145$ dB (at 0.3 m distance)
- Array of 64 ultrasound piezoelectric transducers
- Steerable ultrasound beam due to individually controllable phase of each ultrasound transducer
- Acoustic resonator length: $L = k \cdot \frac{\Lambda}{2}$ with $k \in \mathbb{N}$ variable adjustable, in this experiment: $L = 51{,}75$ mm
- Sound pressure distribution of a standing wave [4]:
  $p(x,t) = 2p_0 \cdot \cos\left(\frac{2\pi}{\Lambda} \cdot x\right) \cdot \cos(2\pi F \cdot t)$

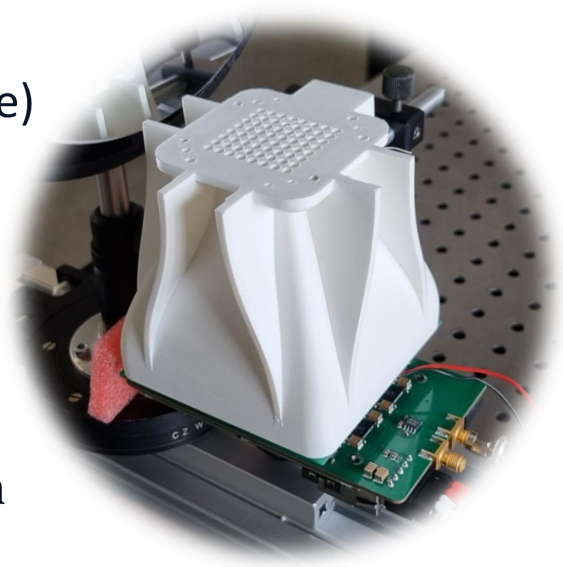


Fig 3: Image of the ultrasound transducer phased array with individually designed waveguide structure [3]

<u>Fizeau Interferometer</u> [5, pp. 49] from Zeiss (Fig. 4): Zeiss DIRECT 100 NT

- Evaluation software based on spatial carrier frequency analysis [5, pp. 107]
- Functionality:

Sound wave induced refractive index modulations in the sample area
⬇
Modulations of the sample wavefront
⬇
Optical path differences (OPD) between the reference and the sample beam
⬇
Measurable using the Fizeau interferometer

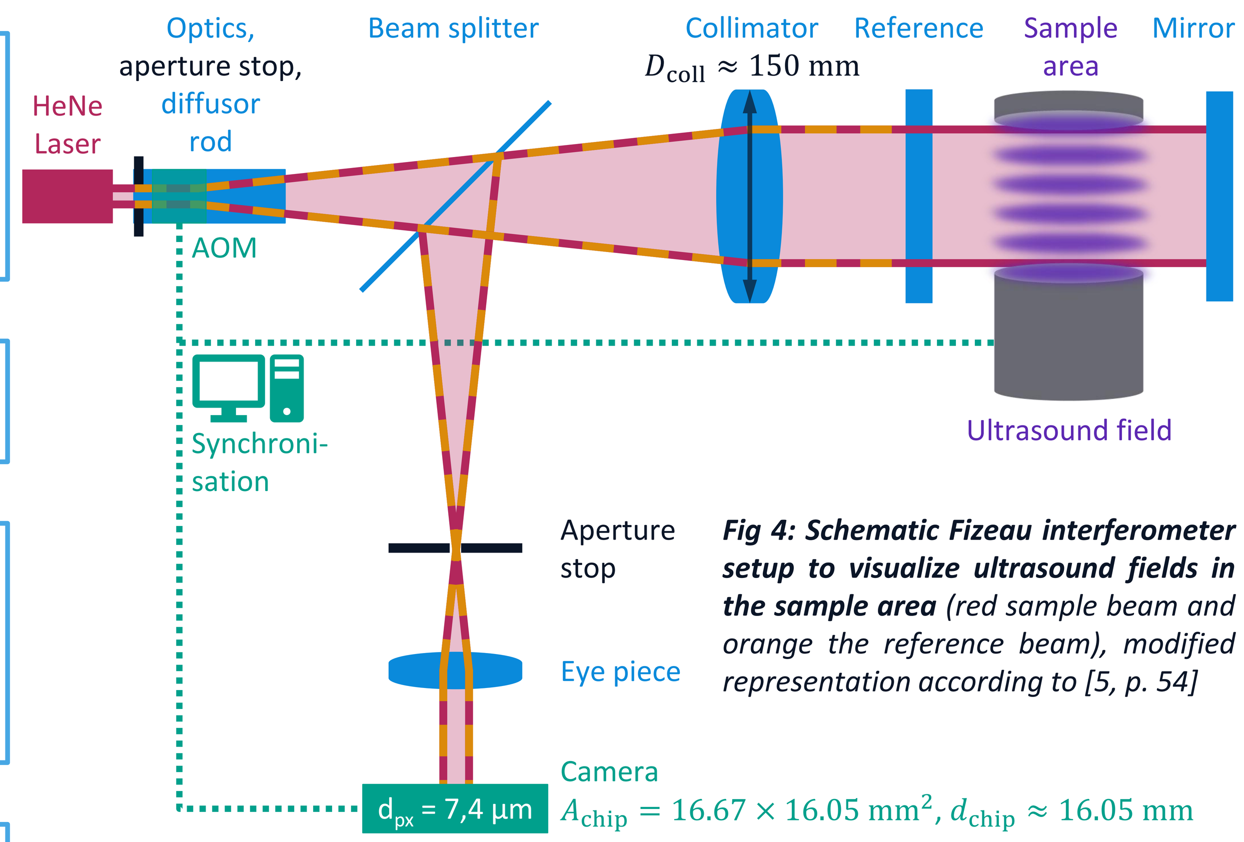


Fig 4: Schematic Fizeau interferometer setup to visualize ultrasound fields in the sample area *(red sample beam and orange the reference beam), modified representation according to [5, p. 54]*

- Synchronization of the sound frequency to the illumination of the interferometer using a standard acousto-optic modulator (AOM)
- Estimation of resolution: minimal resolvable sound wavelength with this setup
  $\Lambda_{min} \approx 2 \frac{\text{samples}}{\text{period}} \cdot 10\ \text{px} \cdot d_{px} \cdot \frac{D_{coll}}{d_{chip}} = 1.38\ \text{mm}\ ⇨\ F_{max} \approx 250\ \text{kHz}$

Ambient conditions

- Temperature: $T = 22.6$ °C ⇨ speed of sound: $c_{sound} = 345 \frac{\text{m}}{\text{s}}$
- Relative humidity: $H_{rel} = 15\%$

4. Result and Discussion

<u>Visualized standing ultrasound field</u> (Fig. 5) generated by the ultrasound transducer phased array:

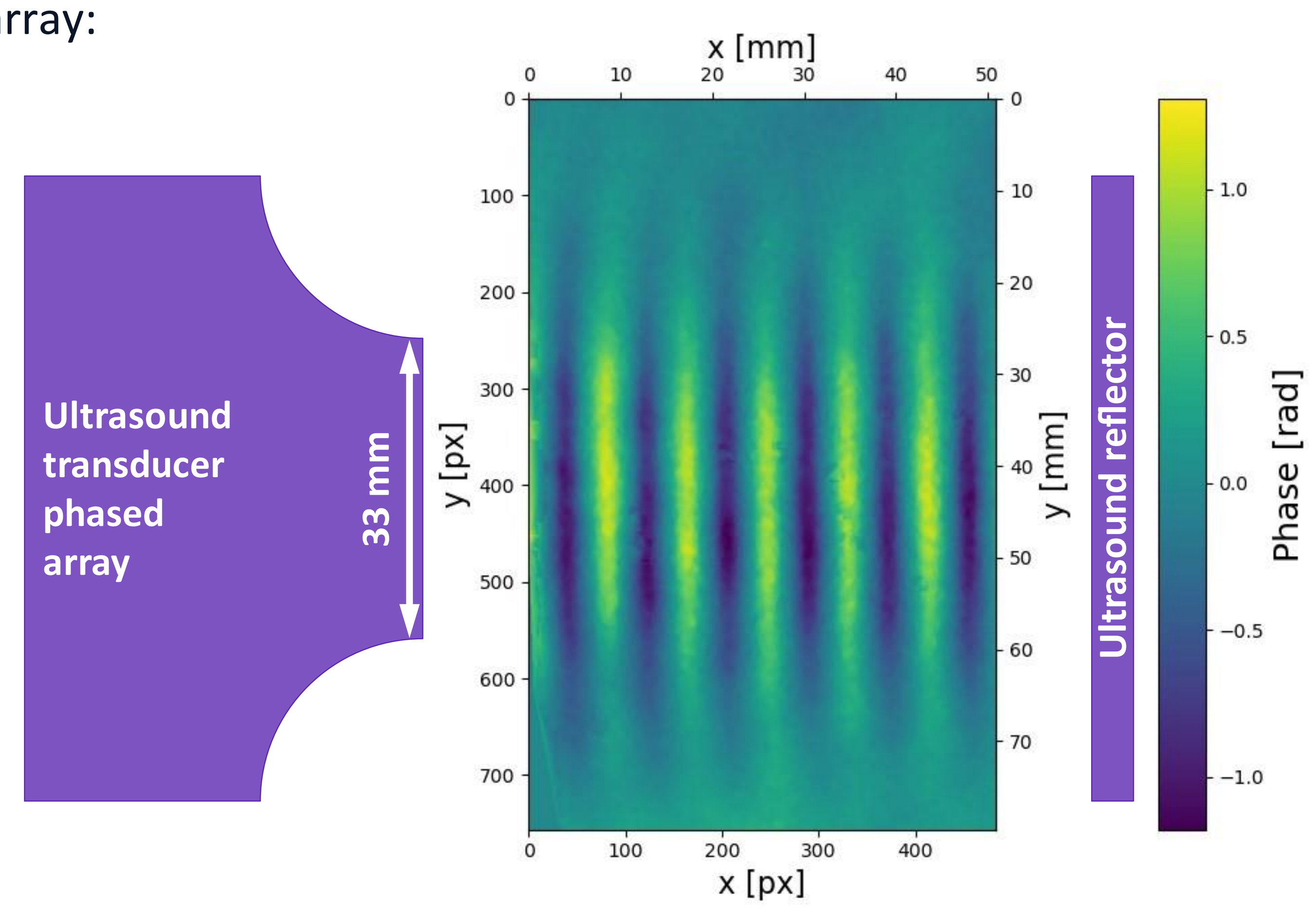


Fig 5: Visualized measurement data of the ultrasound field with schematically illustrated ultrasound source (left) and reflector (right)

- Optical path difference between reference and sample beam, shown as phase
- Two dimensional image of the sound field in a single acquisition
- Background subtraction to eliminate temperature changes
- Collimated sound waves result in a planar acoustic wavefront
- Cosine-shaped sound field distribution along the propagation direction x
- Evaluation of the sound wavelength using Fourier transformation
  $F = 40.7\ \text{kHz} \pm 3.4\ \text{kHz}\ ⇨\ \Lambda \approx 8.5\ \text{mm} \pm 0.8\ \text{mm}$

5. Conclusion and Outlook

- It is possible to visualize high-power standing ultrasound fields with a Fizeau interferometer
- Single-shot images of the ultrasound field are directly visible in the interferometer software
- Evaluations such as acoustic frequency analysis can be carried out
- Various sound fields generated by the ultrasound transducer phased array can be investigated using this interferometric visualization method
- Relevant regions can be observed during the ultrasound-induced laser beam deflection
- Optical path difference [nm] can be converted into sound pressure
  ⇨ Potential for quantitative and single-shot measurements of sound pressure

References:
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