Ultrasound-Mediated Biophotonic Imaging

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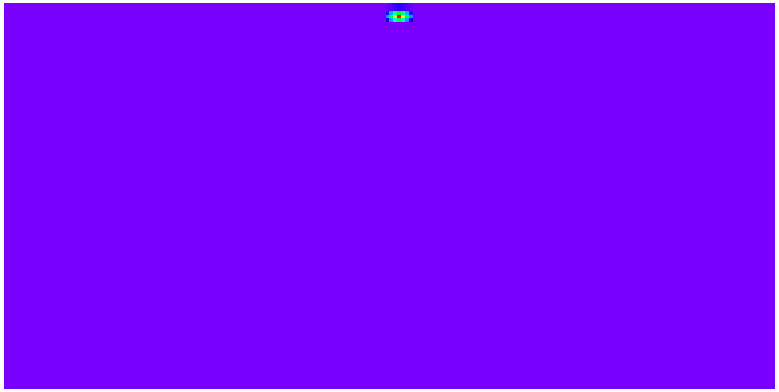
URL: http://oilab.tamu.edu



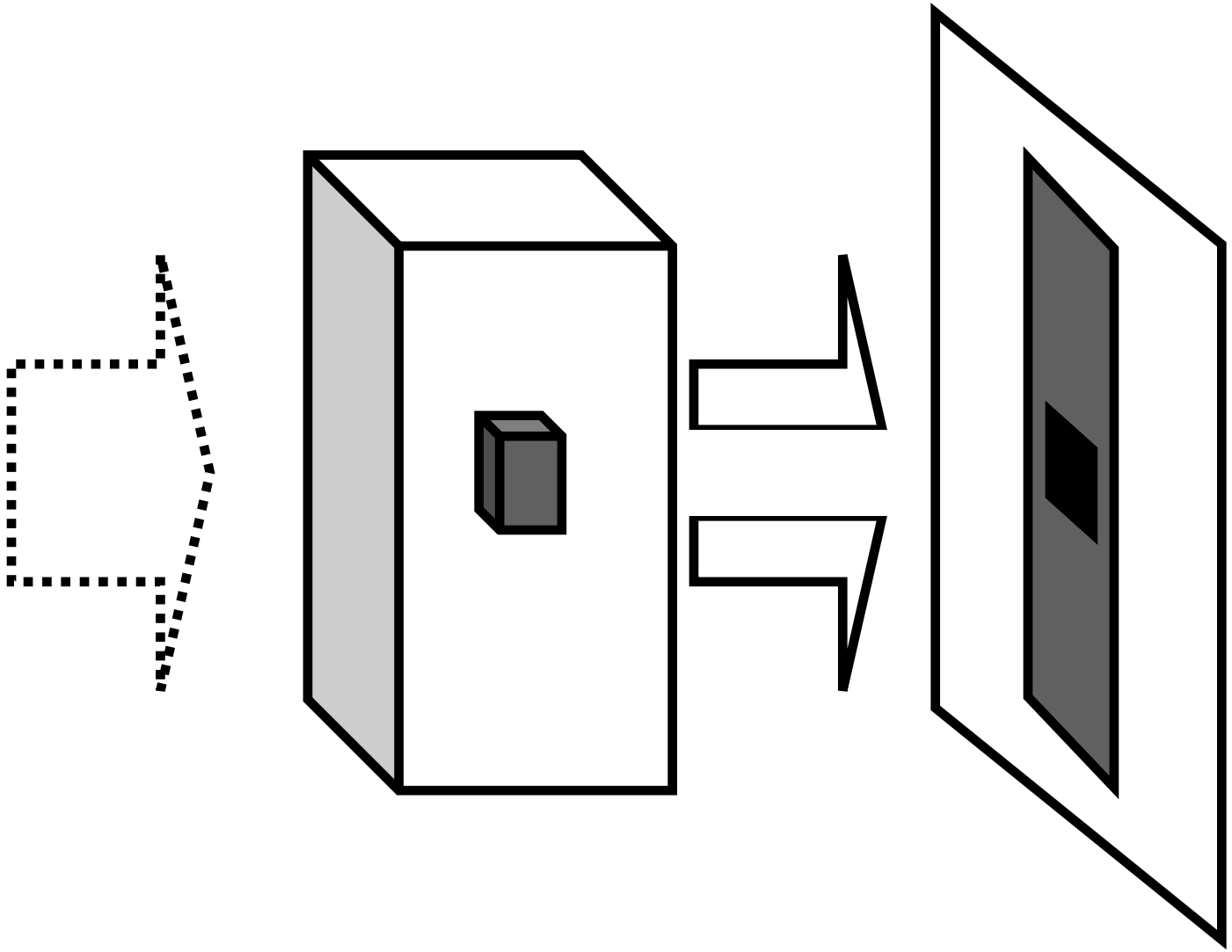
Outline

- Introduction
- Superficial imaging: Mueller OCT
- Acousto-optical tomography
- Thermo-acoustic tomography
- Summary

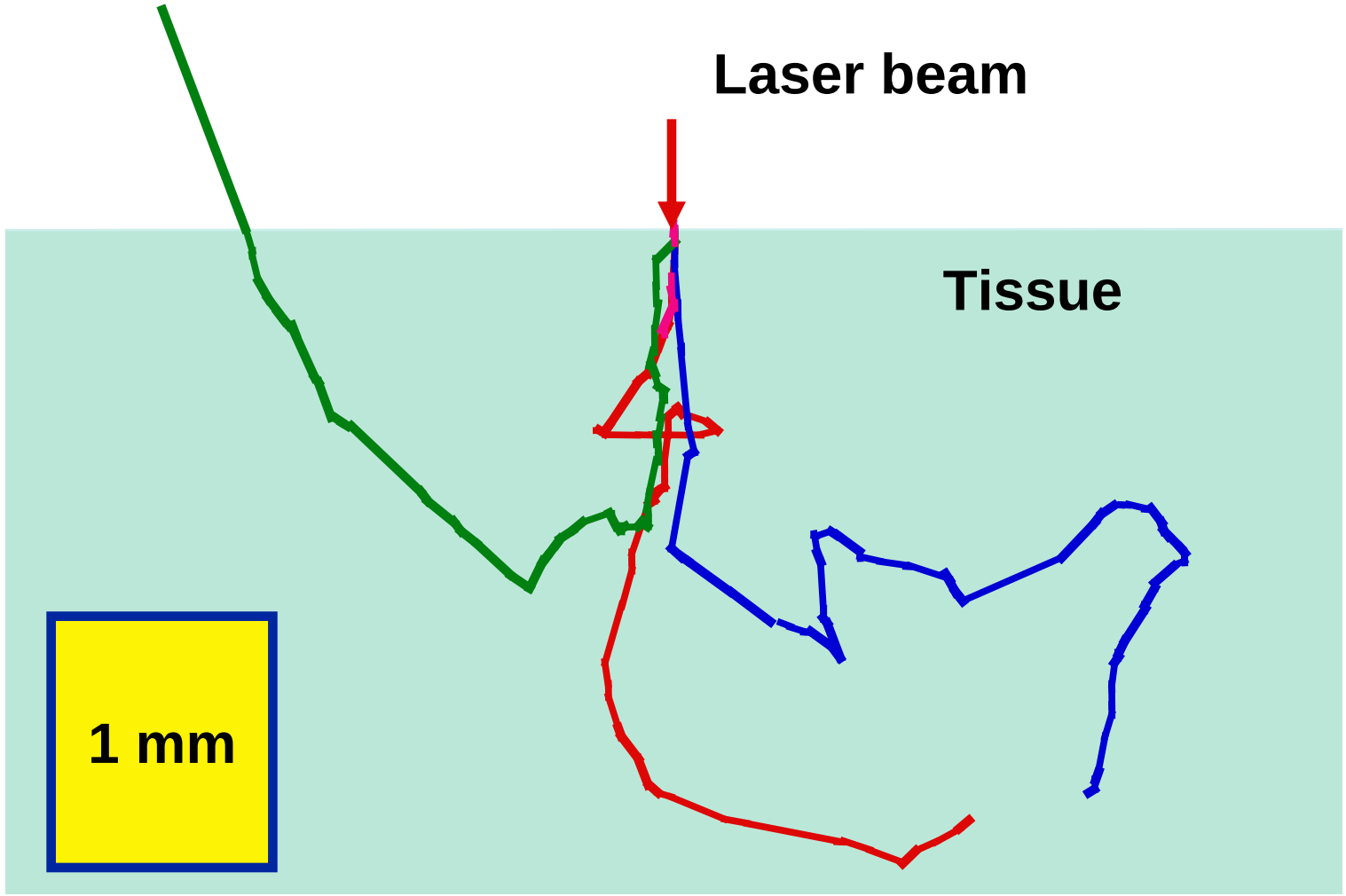
First X-Ray Image by Roentgen [Nature 53, 274 (1896)]

- Good resolution
- Ionizing radiation: potentially carcinogenic
- Small soft tissue contrast
- No functional information

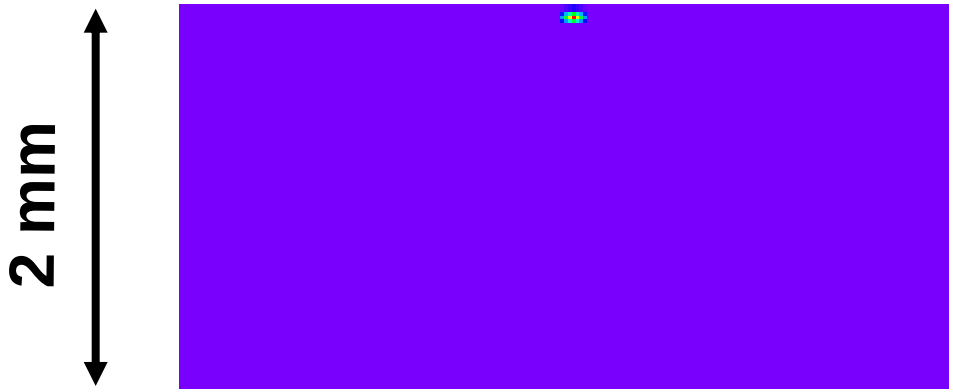
X-Ray Projection



Photon Traces in Biological Tissue



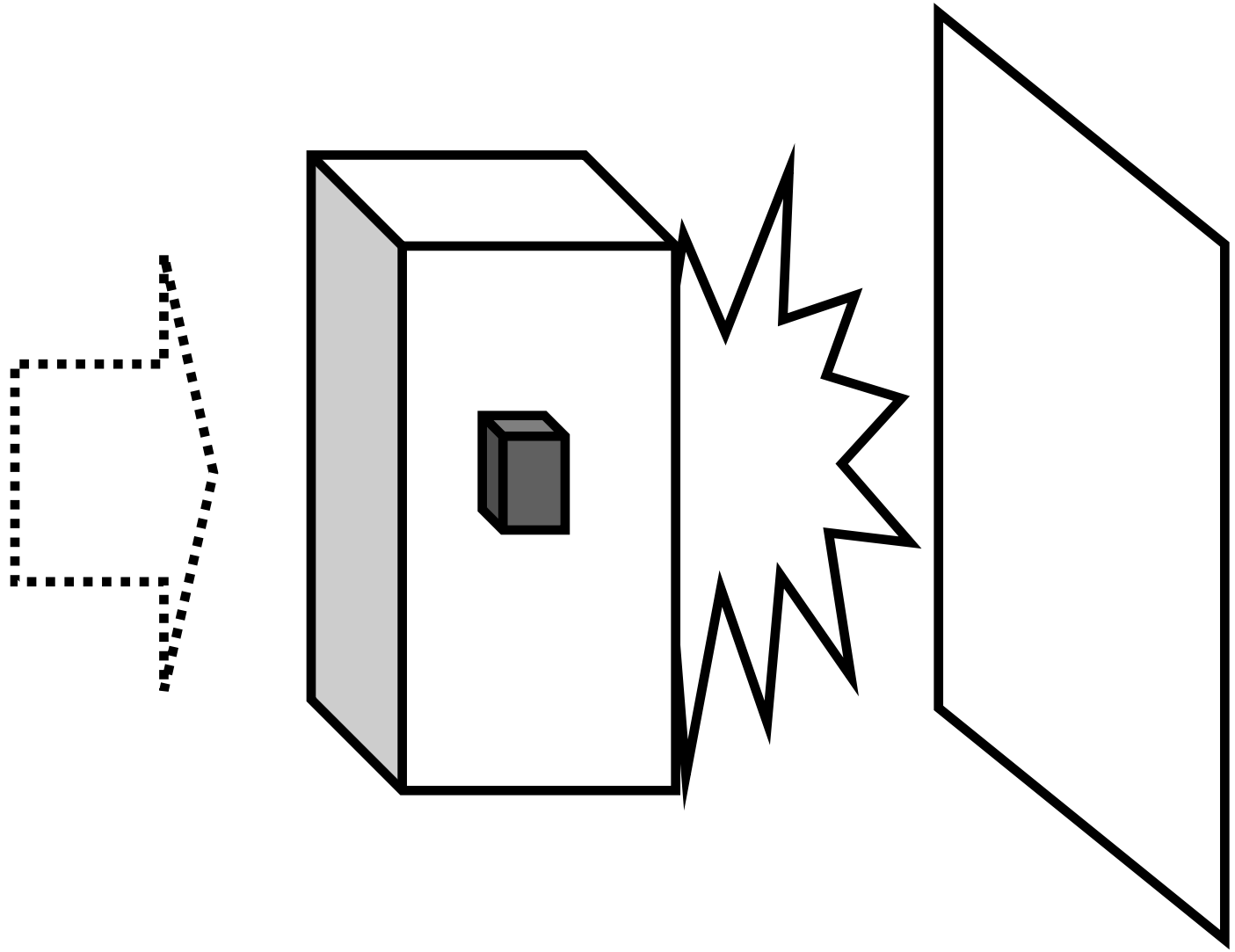
Propagation of Light in Biological Tissue



Click on the following file to see the movie:
http://oilab.tamu.edu/epub/MCMovie.avi

- **Our public-domain software is available online.**
- ***Computer Methods and Programs in Biomedicine 47, 131 (1995).***

Light Encounters Multiple Scatterings



Motivation for Optical Imaging

- Non-ionizing radiation: Photon energy is ~2 eV.
- Good soft-tissue contrast between cancers and benign/normal lesions:
  - Optical spectra are related to the molecular conformation of the tissue.
  - Optical absorption: Angiogenesis, apoptosis, necrosis, and hyper-metabolism.
  - Optical scattering: Size of cell nuclei.
- Functional imaging by quantification of physiological parameters: Oxygen saturation of hemoglobin and blood flow.

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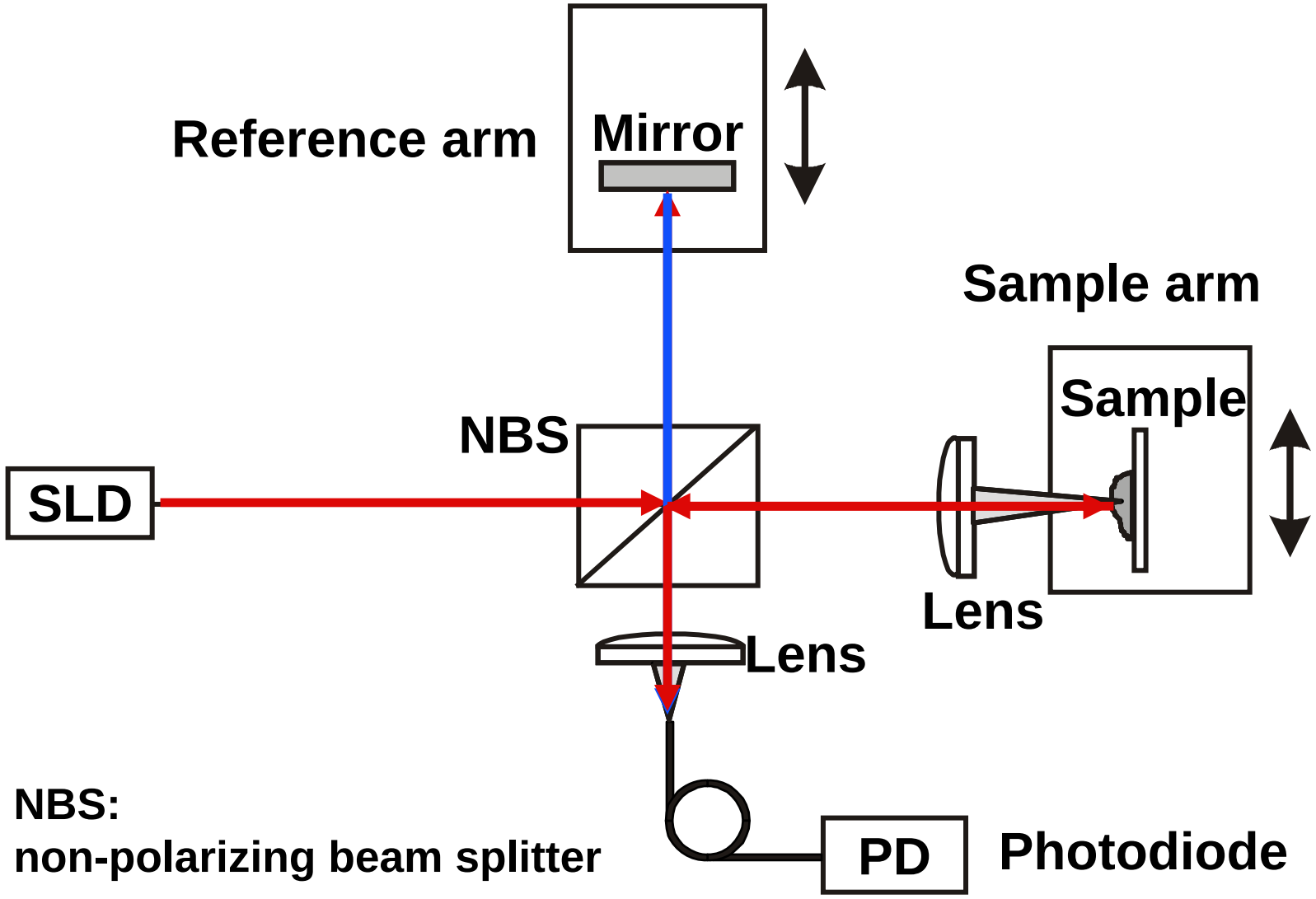
Conventional Optical Coherence Tomography

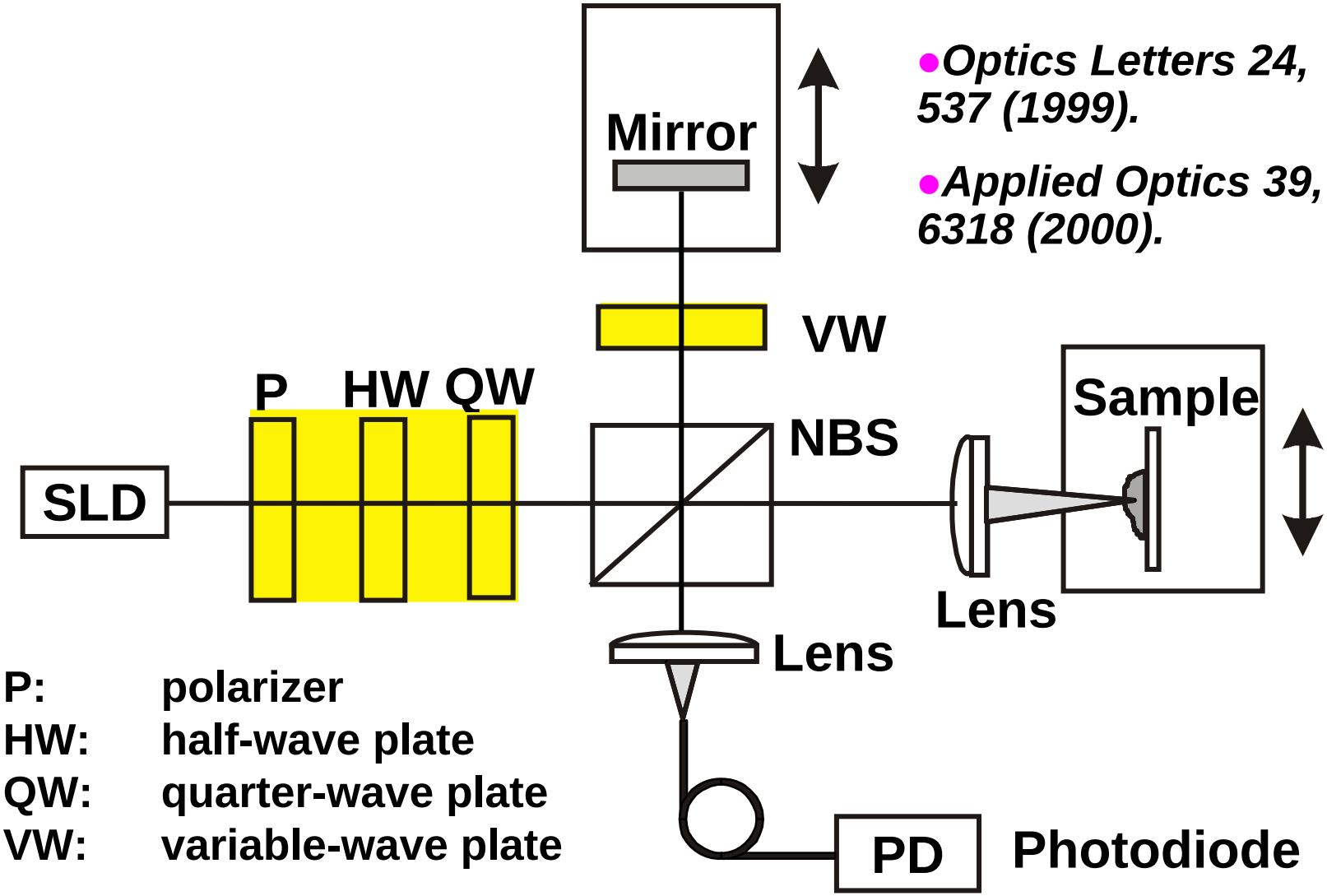


NBS:
non-polarizing beam splitter

Motivation for Polarization OCT

- Conventional OCT has artifacts caused by polarization.
- Polarization provides new contrast mechanisms.
- Sources of birefringence include epidermal keratin, dermal collagen, and muscle fibers.
- Neoplasia or coagulation alters birefringence.
- Stress induces polarization.

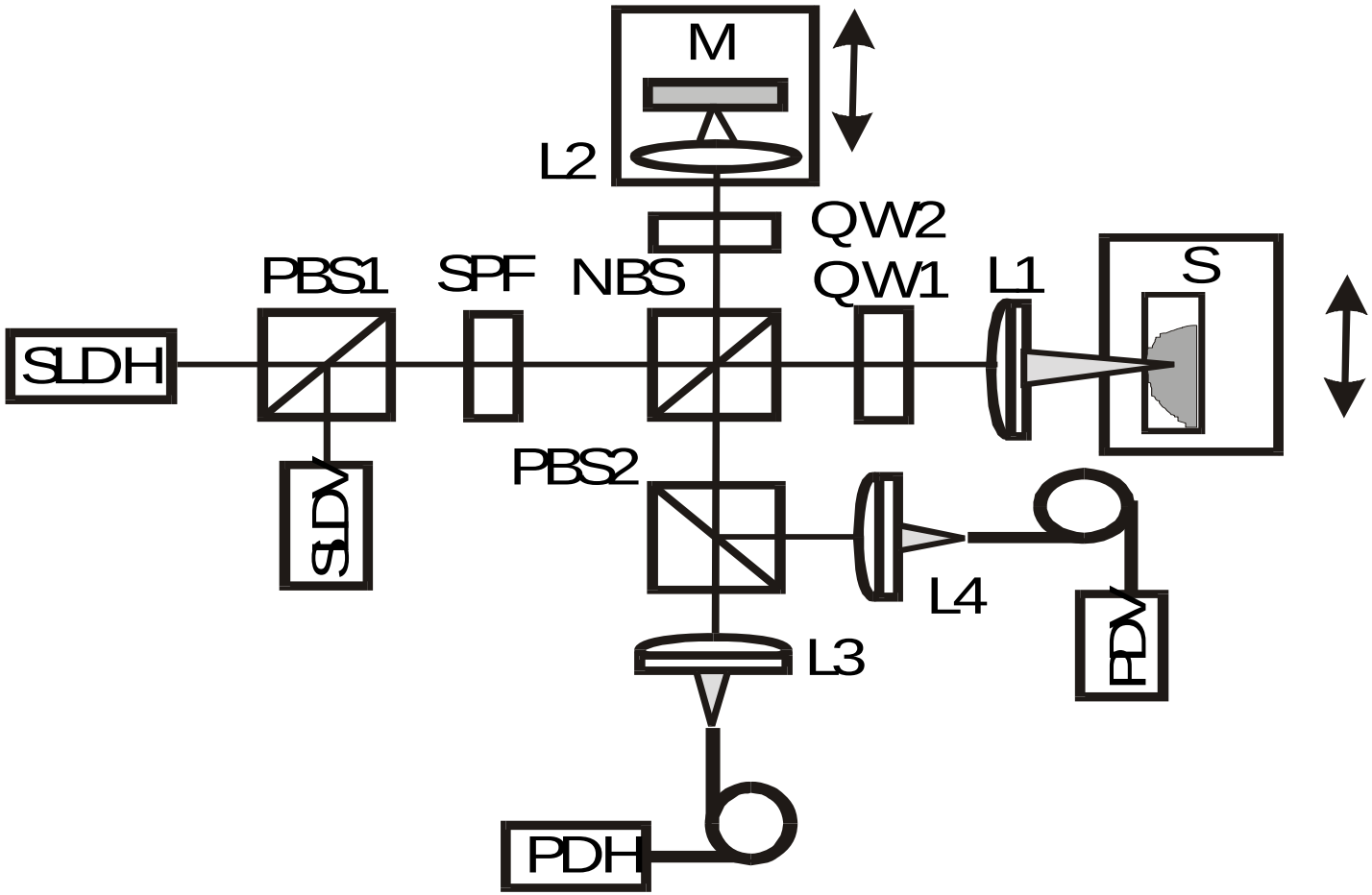
Mueller-Matrix Optical Coherence Tomography



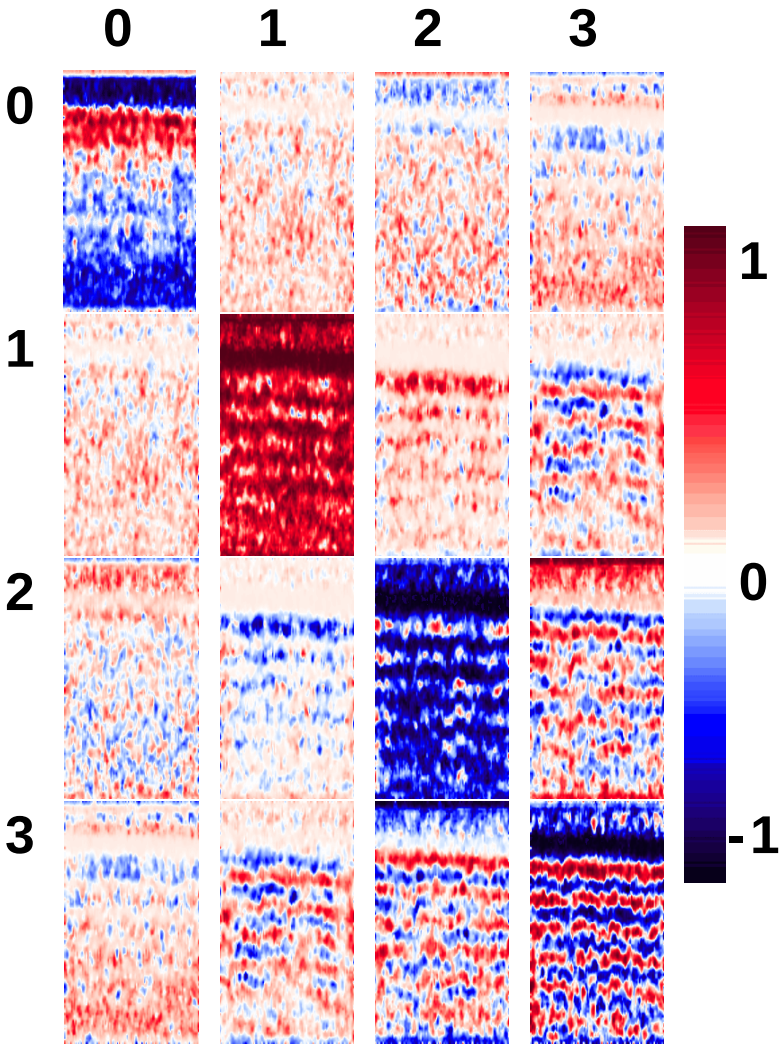
- *Optics Letters 24, 537 (1999).*
- *Applied Optics 39, 6318 (2000).*

P: polarizer
HW: half-wave plate
QW: quarter-wave plate
VW: variable-wave plate

Mueller-Matrix Optical Coherence Tomography: Dual-Source and Dual-Detector System



Mueller Images of Porcine Tendon (0.5 mm × 1 mm)

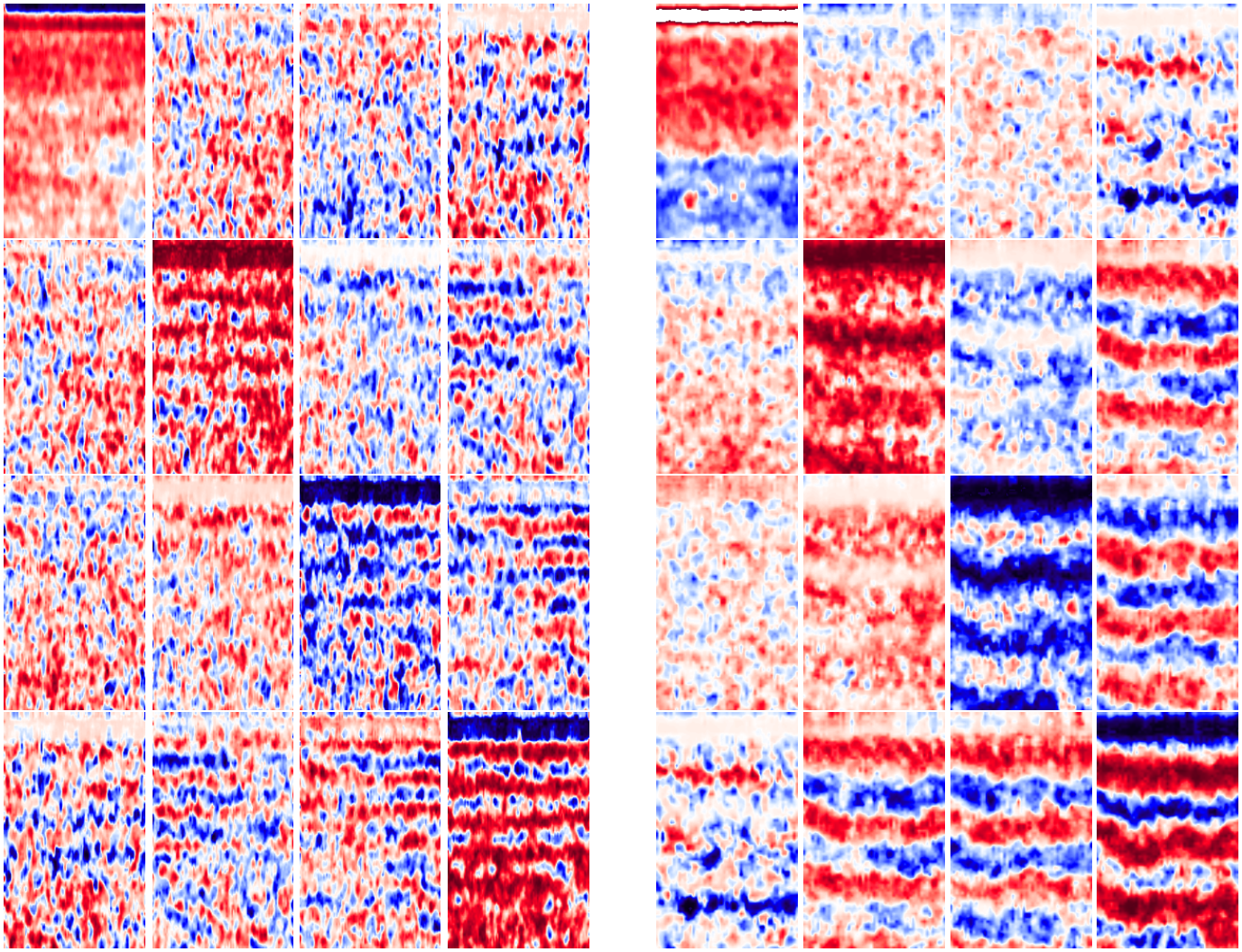


- 10 micron resolution
- ~1 mm imaging depth

- Birefringence: $(4.2 \pm 0.3) \times 10^{-3}$
- Orientation: accurate to <5°
- Diattenuation: 0.26/mm

- *Optics Letters, in press (2001).*

Before and After Coagulation in Porcine Tendon (0.5 mm × 1 mm)



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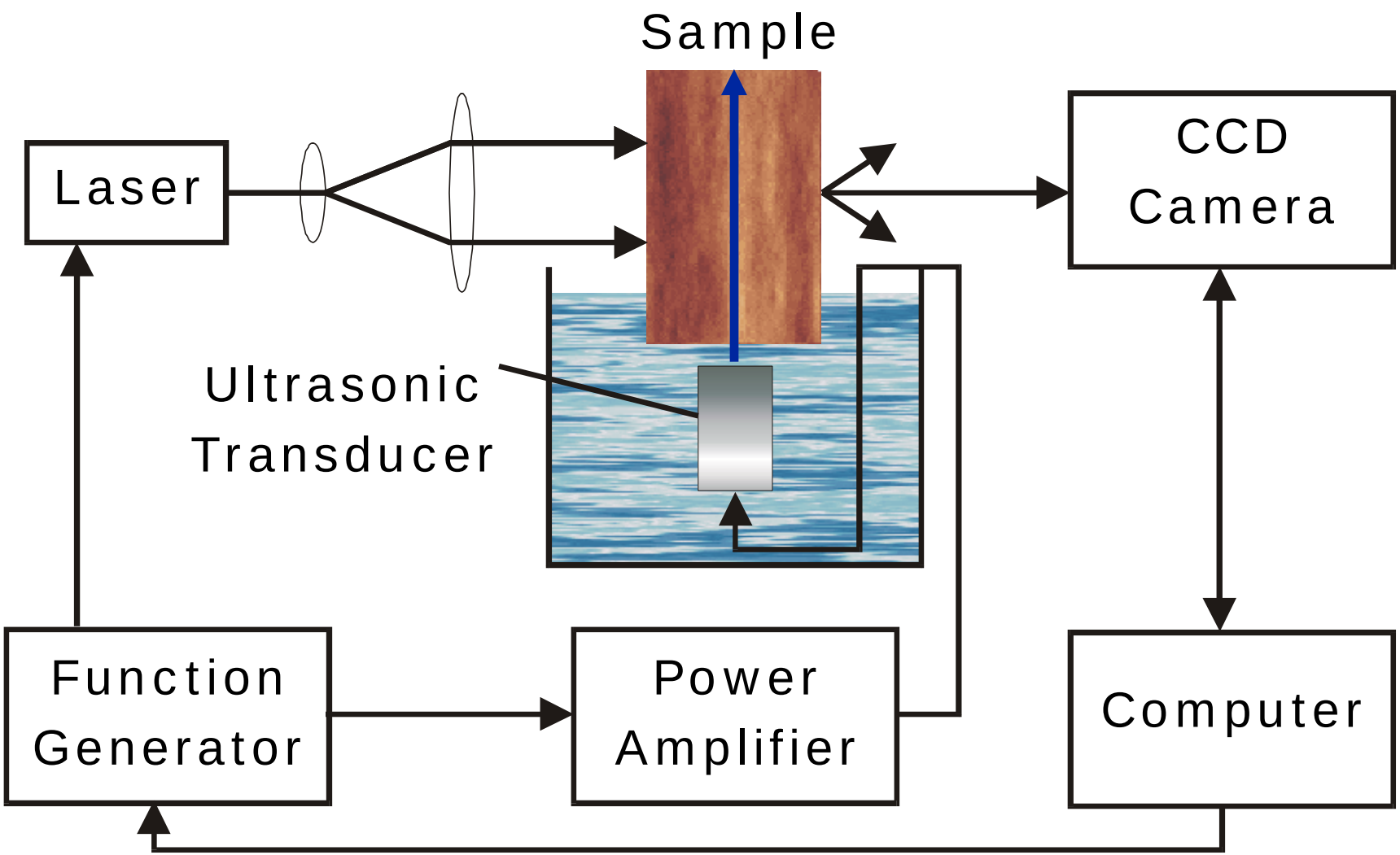
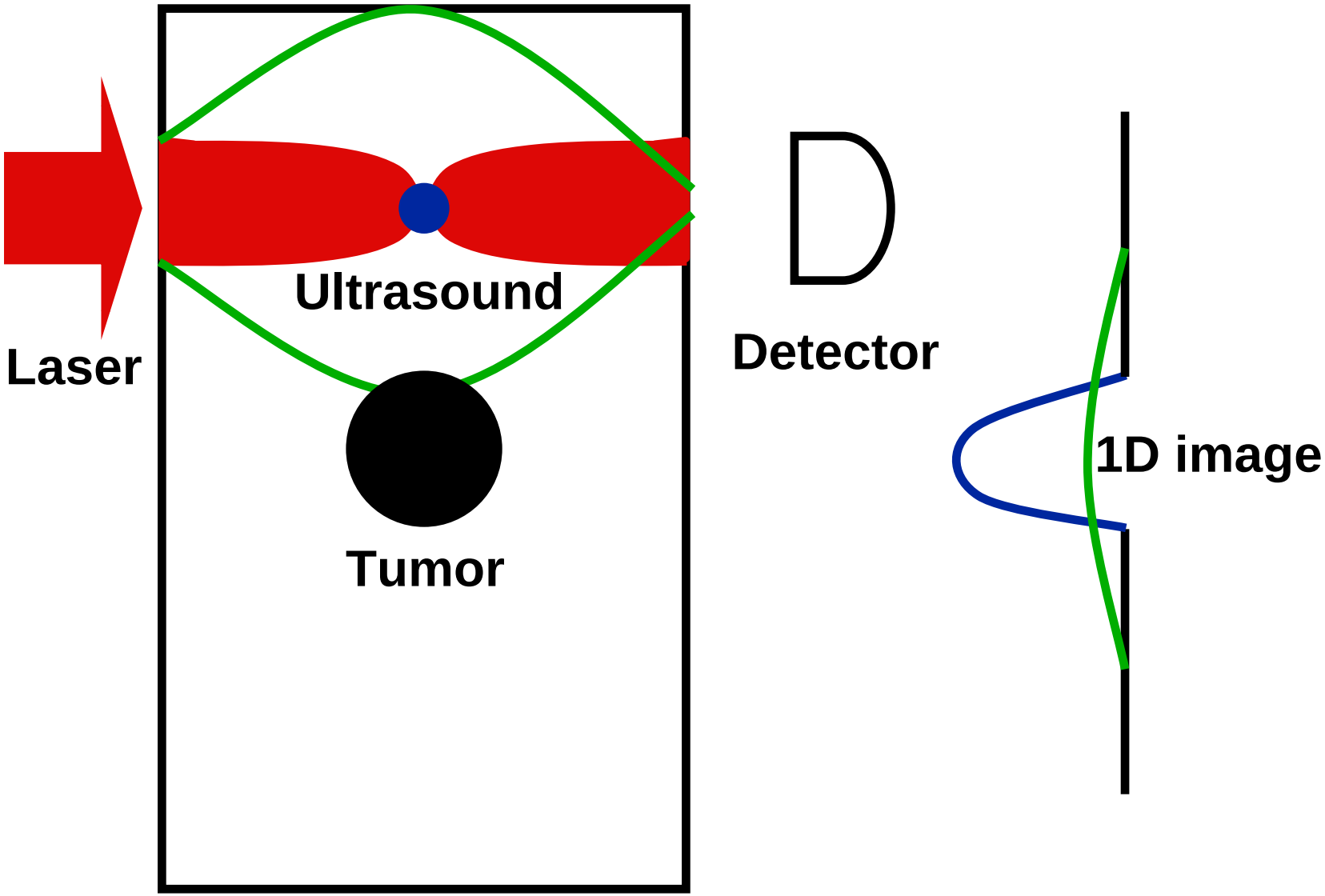
Motivation for Combining Light with Ultrasound

- Both are non-ionizing radiation.
- Optical signal provides good contrast, even physiological information for functional imaging.
- Light is highly scattering in biological tissue (~100 /cm). Poor imaging resolution for thick tissue.
- Ultrasound is much less scattering in biological tissue (~0.3 /cm @ 7 MHz). Good imaging resolution.
- Ultrasound has limited contrast for early-stage tumors.
- Ultrasound brings order to chaos in photon diffusion.
- <u>Optical contrast + Ultrasonic resolution.</u>

Parallel Lock-In Detection of Speckles -- Synchronous Illumination



Top View of a Cross Section



Full-Field Mapping of Acoustic Amplitude in Clear Media

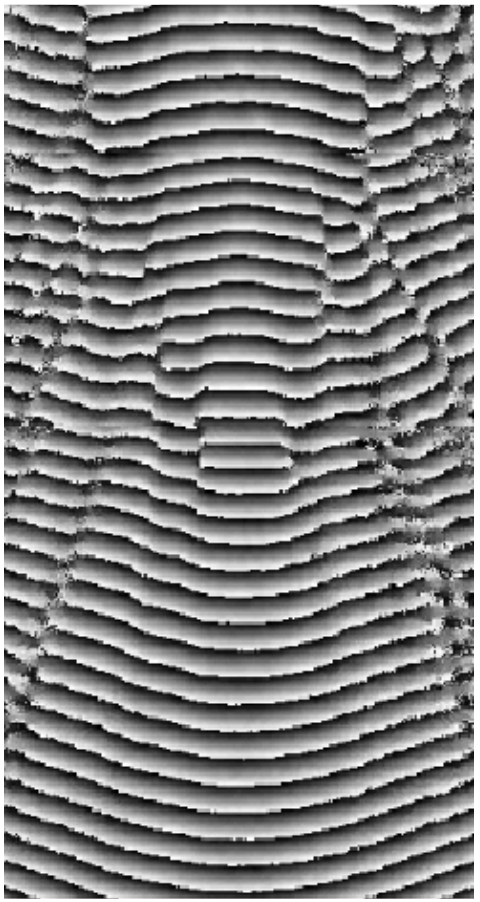
Experimental

1 cm

Simulated

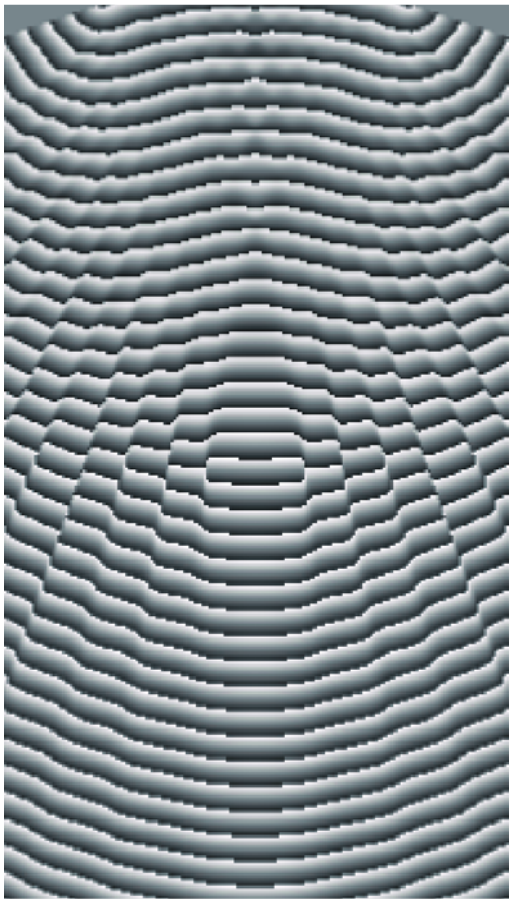
- *J of Acoustical Society of America 106, L36 (1999).*

Full-Field Mapping of Acoustic Phase in Clear Media



Experimental

1 cm



Simulated

- *J of Acoustical Society of America 106, L36 (1999).*

Experimental Data vs. Theoretical Data

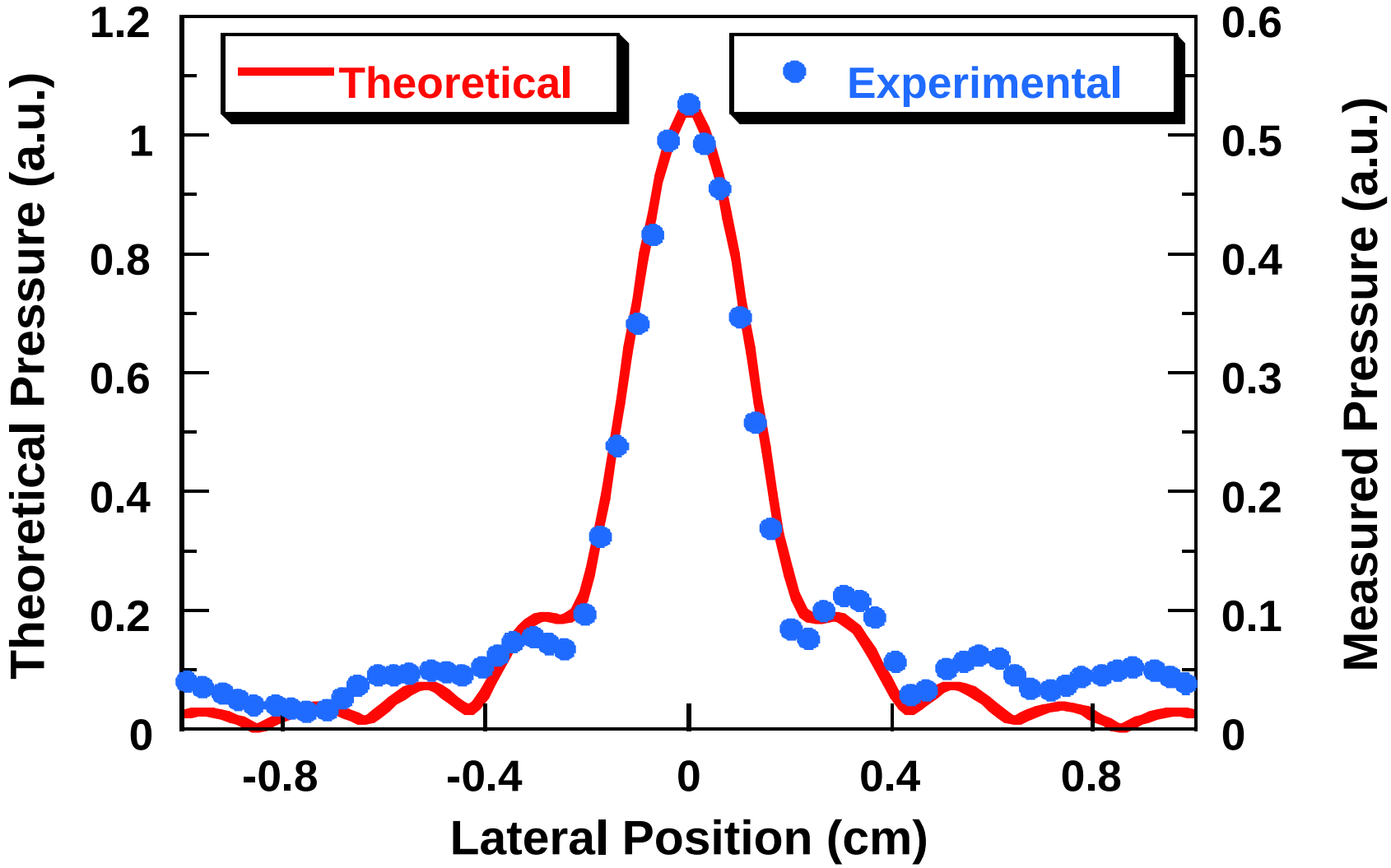
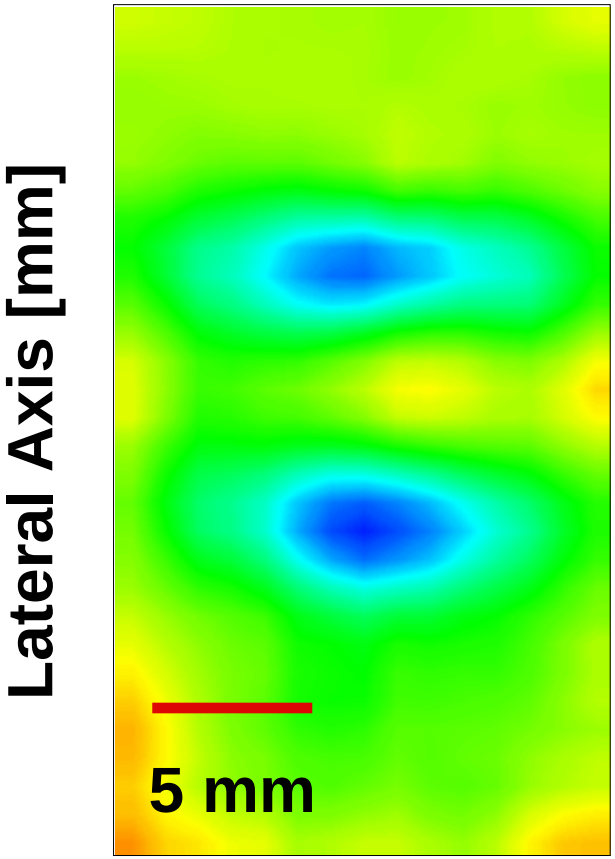
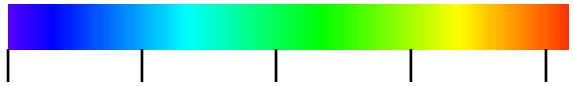


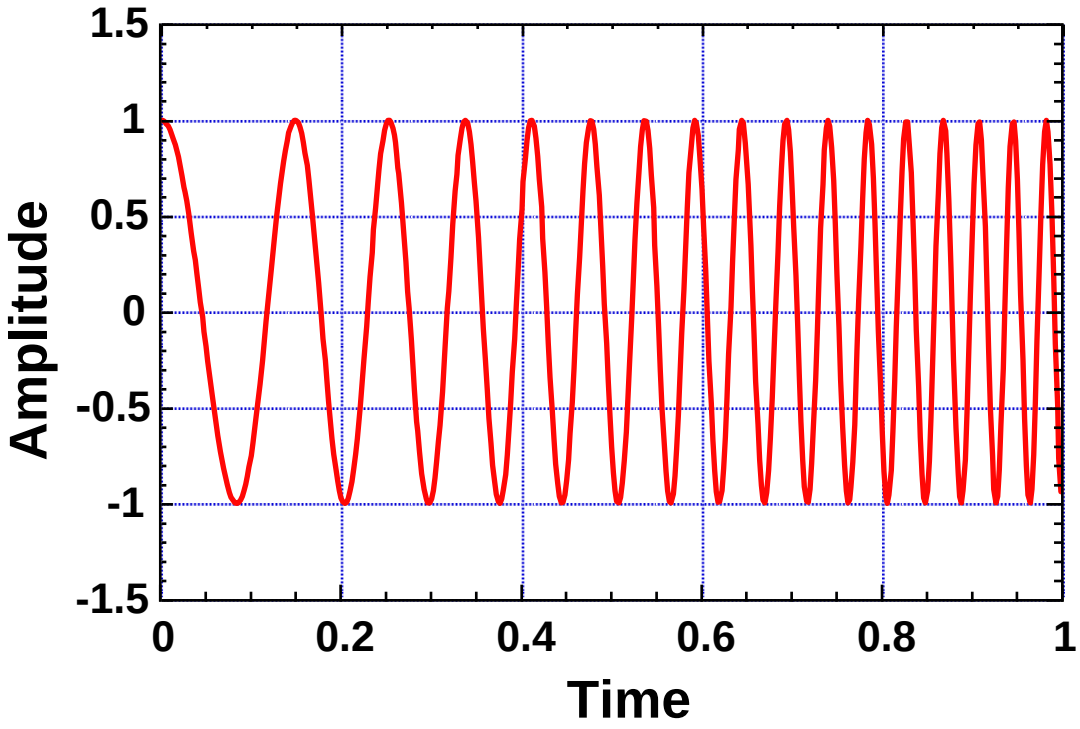
Image of Two Objects Buried in Tissue





- *Applied Optics 39, 659 (2000).*

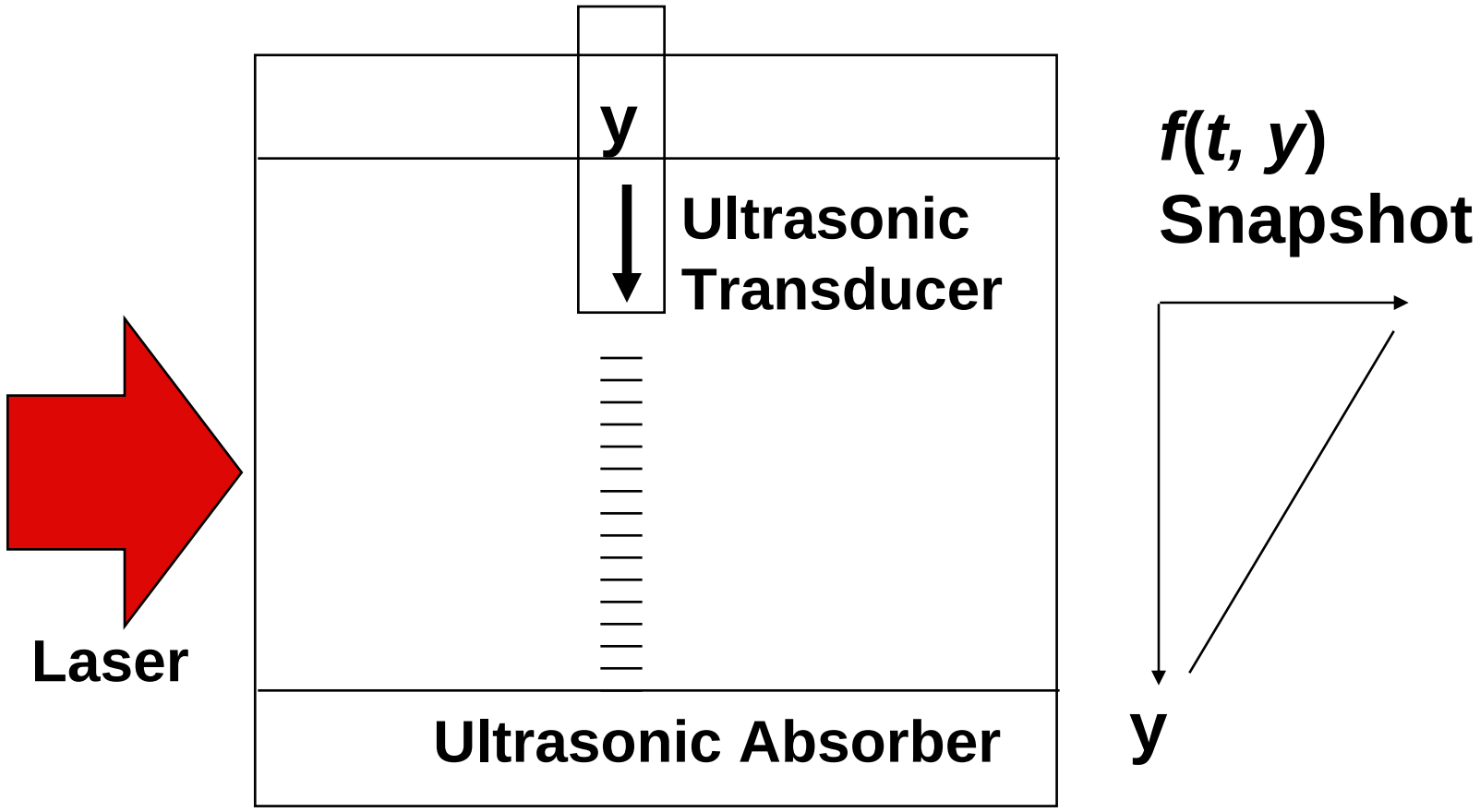
Frequency-Swept Signal (Chirp)



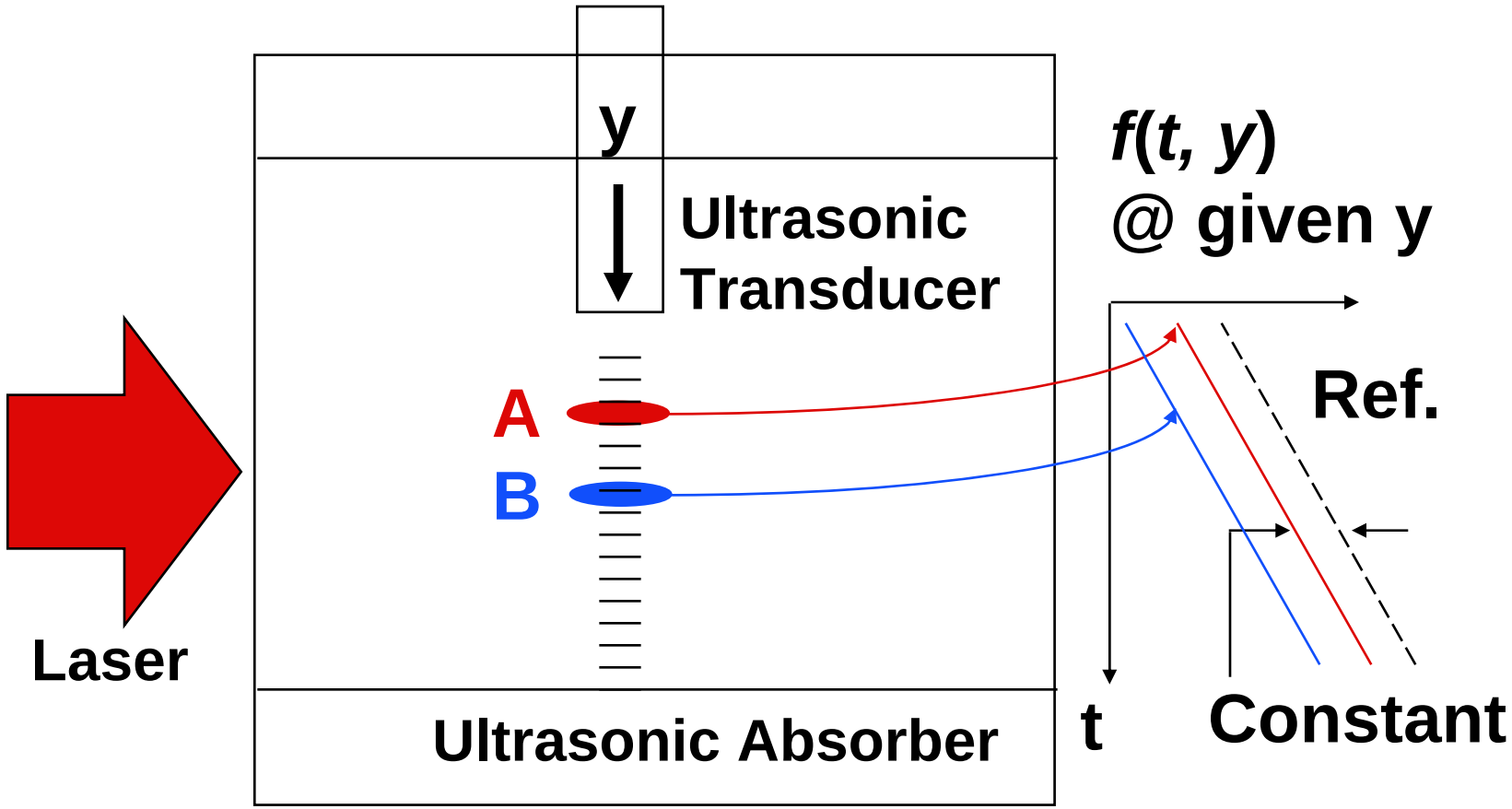
$$f(t) = a + bt$$

- ***f(t)*** **Instantaneous frequency**
- ***a*** **Starting frequency**
- ***b*** **Sweep rate**

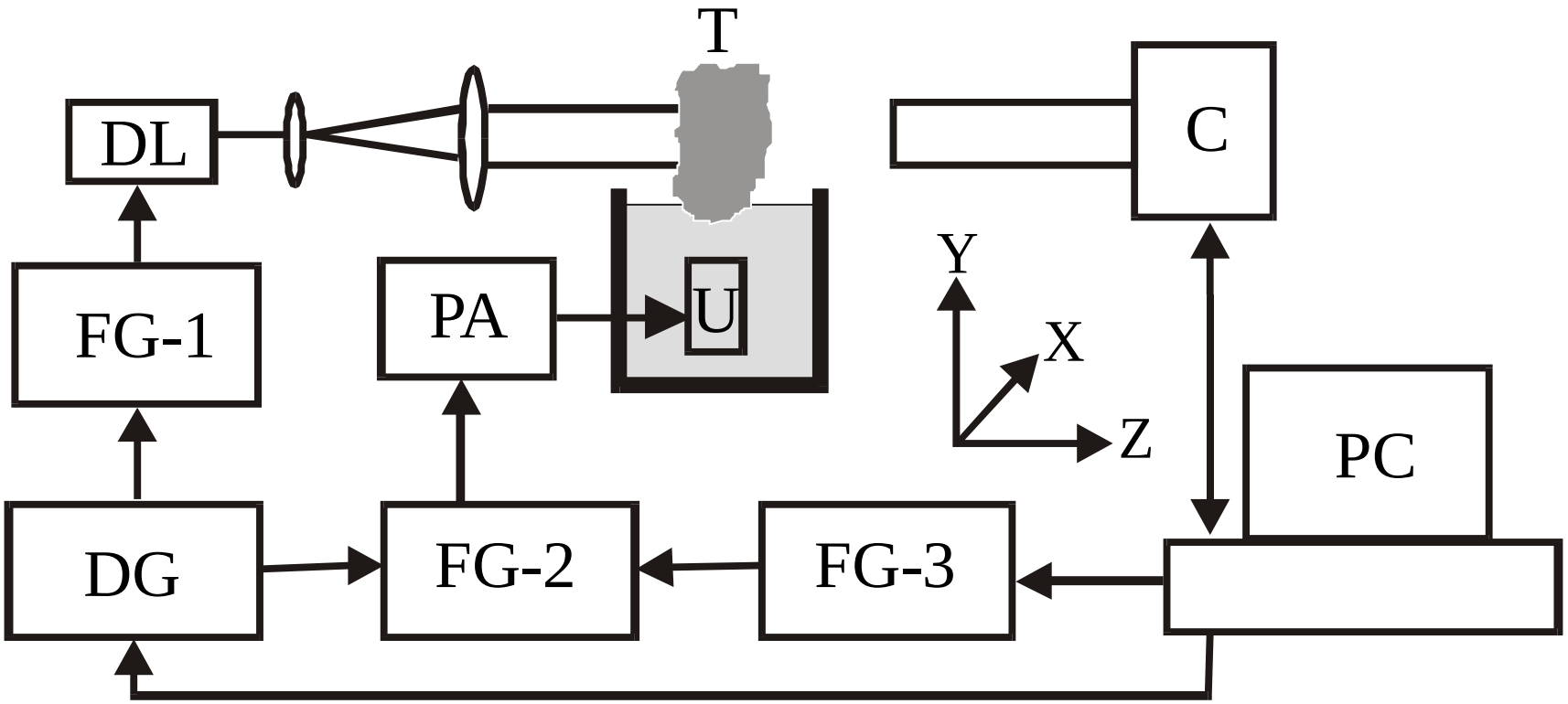
Instantaneous Frequency along the Ultrasonic Axis (y)



Instantaneous Frequency vs. Time

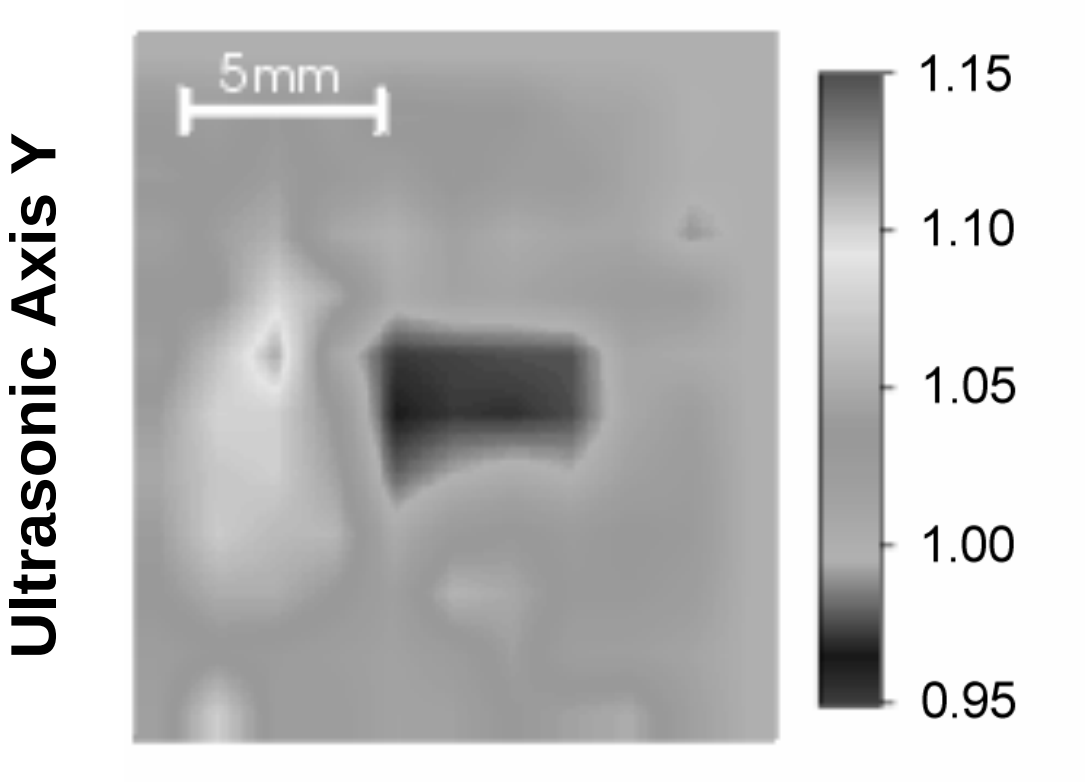


Frequency-Sweep for Axial Resolution



- DL: diode laser
- FG: function generator
- DG: delay generator
- PA: power amplifier
- C: CCD

Image Obtained with Frequency Sweep



- ***Optics Letters 25, 734 (2000).***

Mechanisms of Ultrasonic Modulation of Coherent Light in Scattering Media

Plan of Attack:
Autocorrelation Function → Fourier Transform

$$G_1(\tau) = \left\langle E(t)E^*(t+\tau) \right\rangle$$

$$G_1(\tau) \xrightarrow{\text{Fourier Transform}} I_n = S(n\omega_a)$$

Autocorrelation: Analytic Solution

$$G_1(t) = \frac{L}{l} \frac{\sinh\left\{\varepsilon\left[1-\cos\left(\omega_a t\right)\right]\right\}^{1/2}}{\sinh\left[(L/l)\left\{\varepsilon\left[1-\cos\left(\omega_a t\right)\right]\right\}^{1/2}\right]}$$

$$\varepsilon = 6(\delta_n + \delta_d)\left(n_0 k_0 A\right)^2$$

- L: **thickness of slab**
- l: **scattering mean free path**

- ***Wang, Physical Review Letters 87, 043903 (July 23, 2001).***

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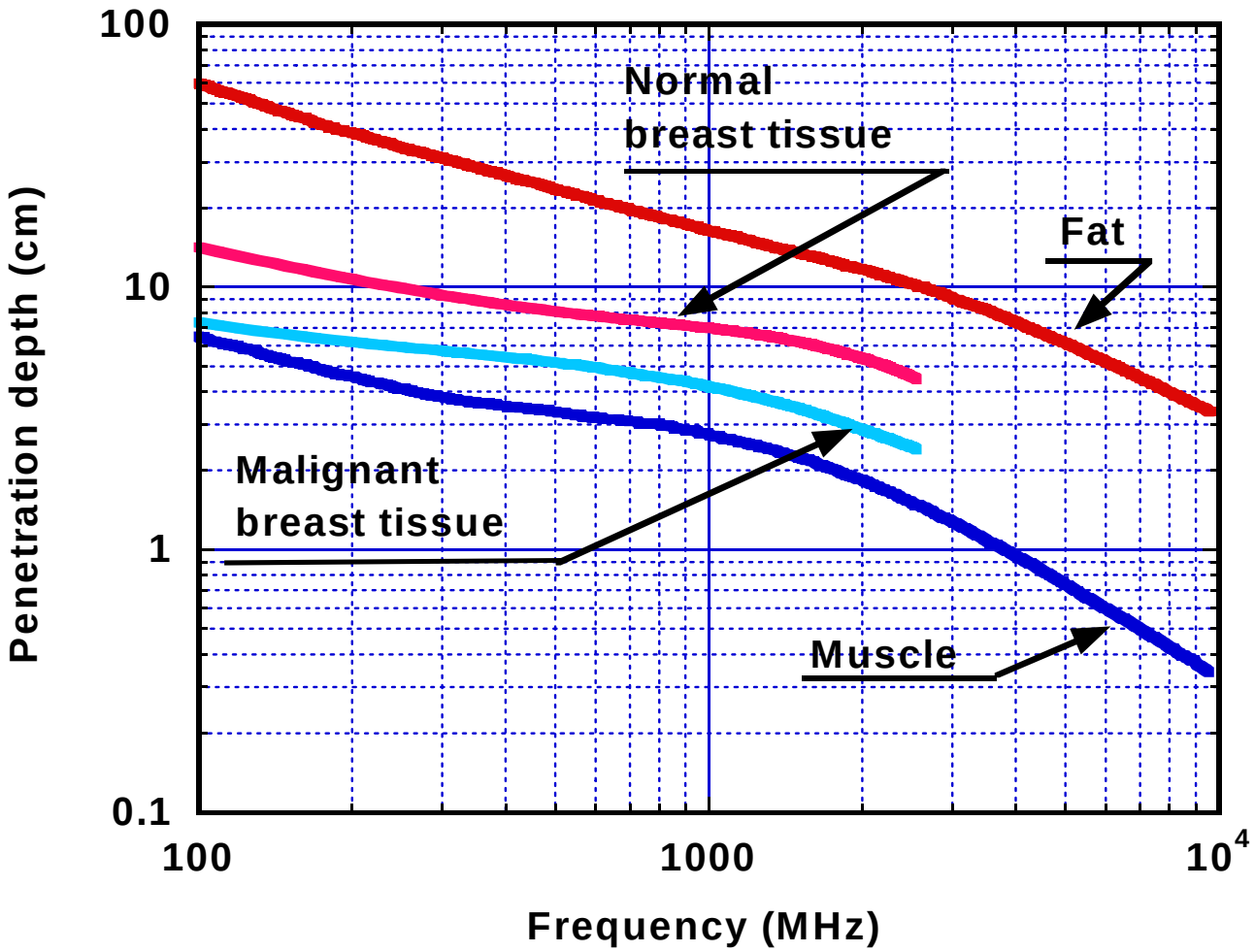
- Summary

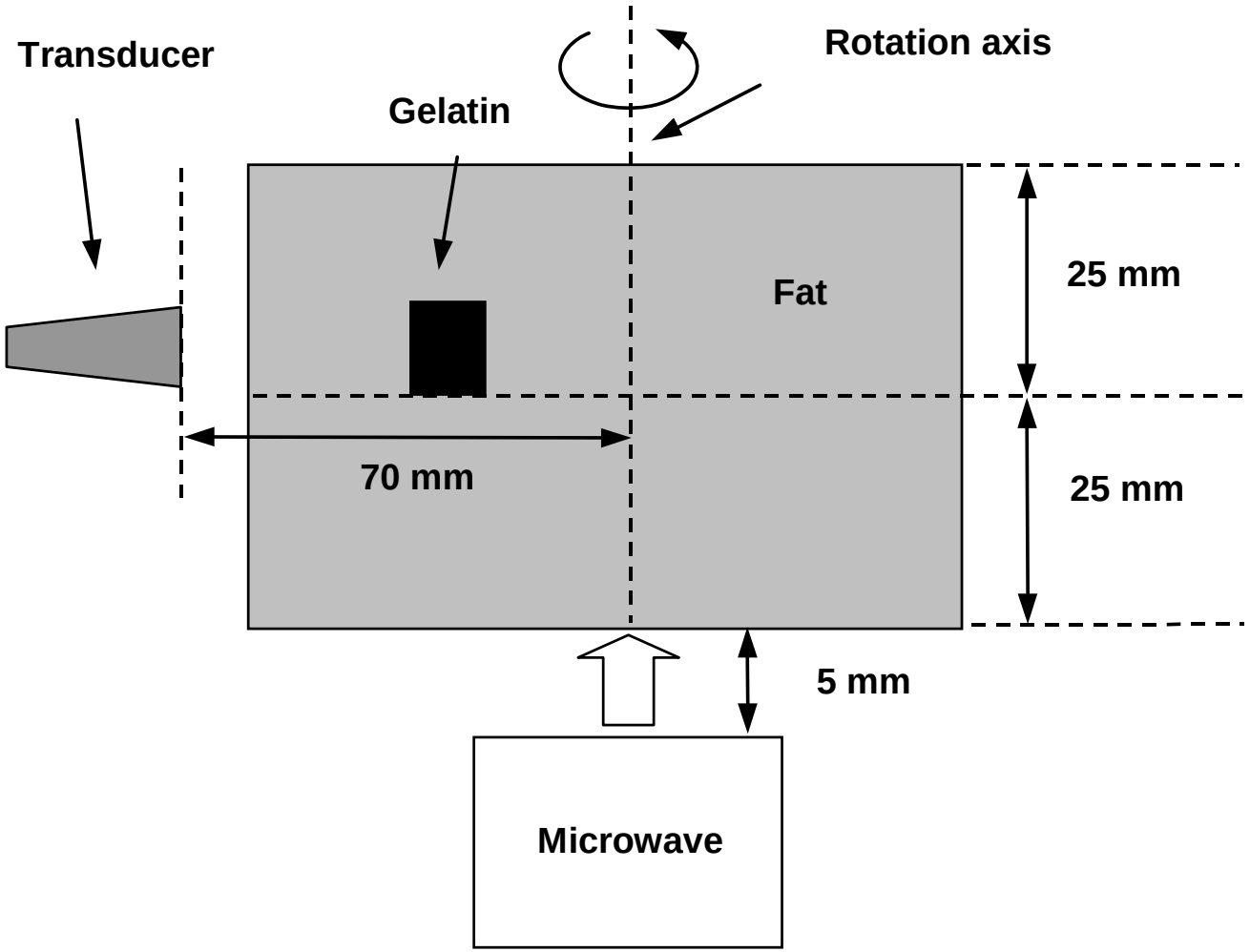
Motivation for Combining Microwave and Ultrasound

- Both are non-ionizing radiation.
- Both have deep penetrating power.
- Microwave provides good contrast, related to protein-bound water, ionic conductivity of cytoplasm, and tissue water.
- Microwave alone has poor imaging resolution due to its long wavelength.
- Ultrasound provides good imaging resolution due to its short wavelength and low scattering.
- Ultrasound has limited contrast for early-stage tumors.
- Microwave contrast + Ultrasonic resolution.

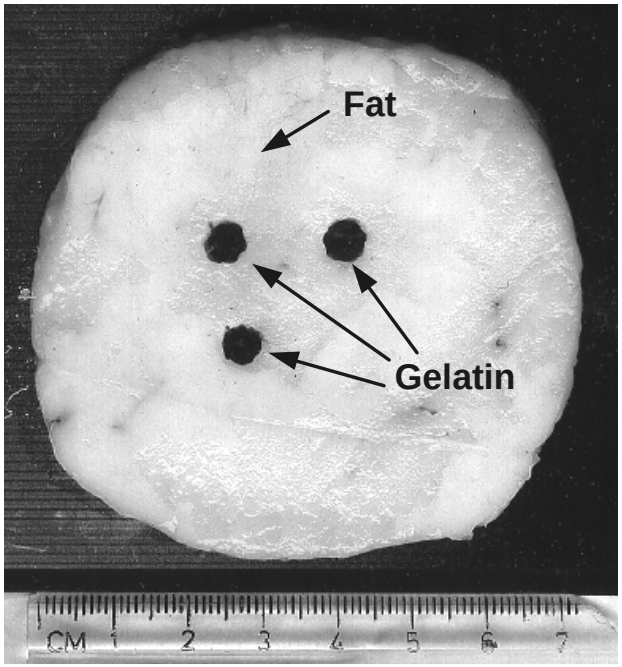
Microwave Penetration

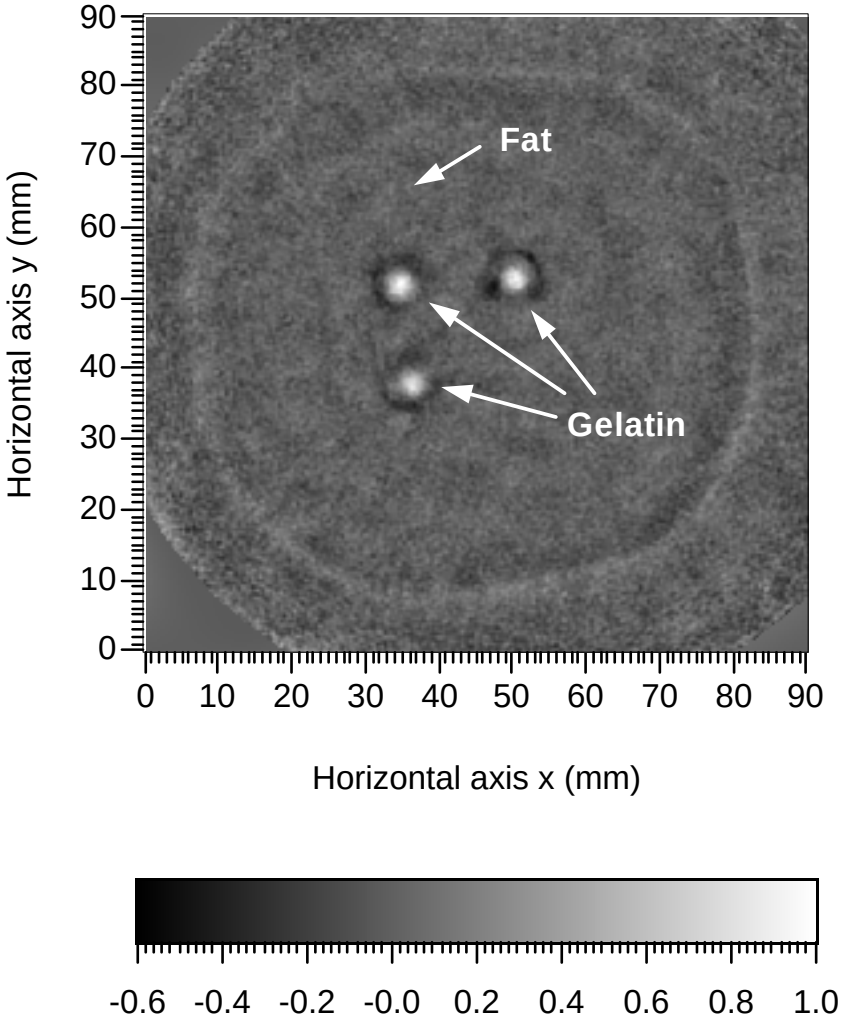


Reconstruction-based Thermoacoustic Tomography



Photograph and Thermoacoustic Image





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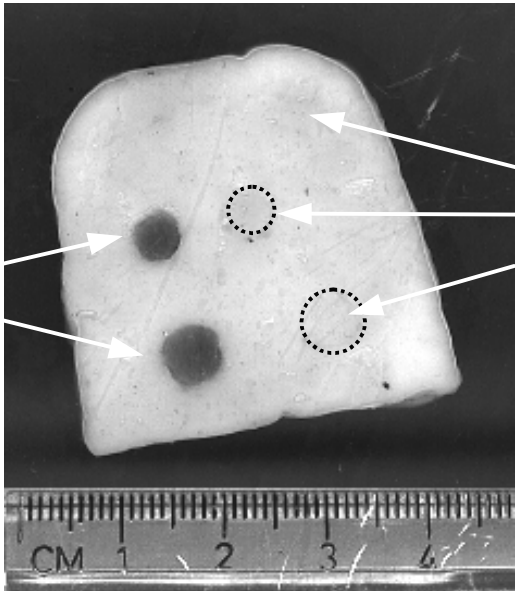

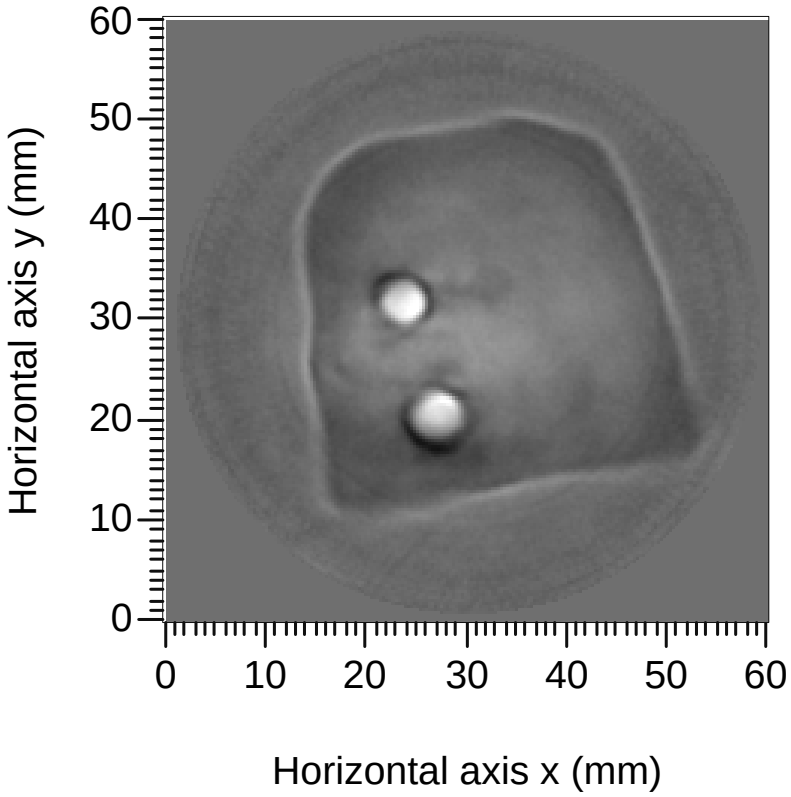

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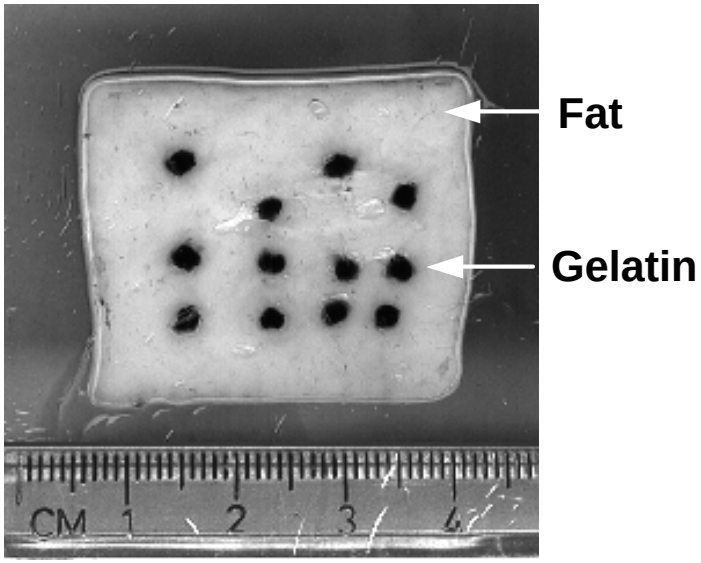
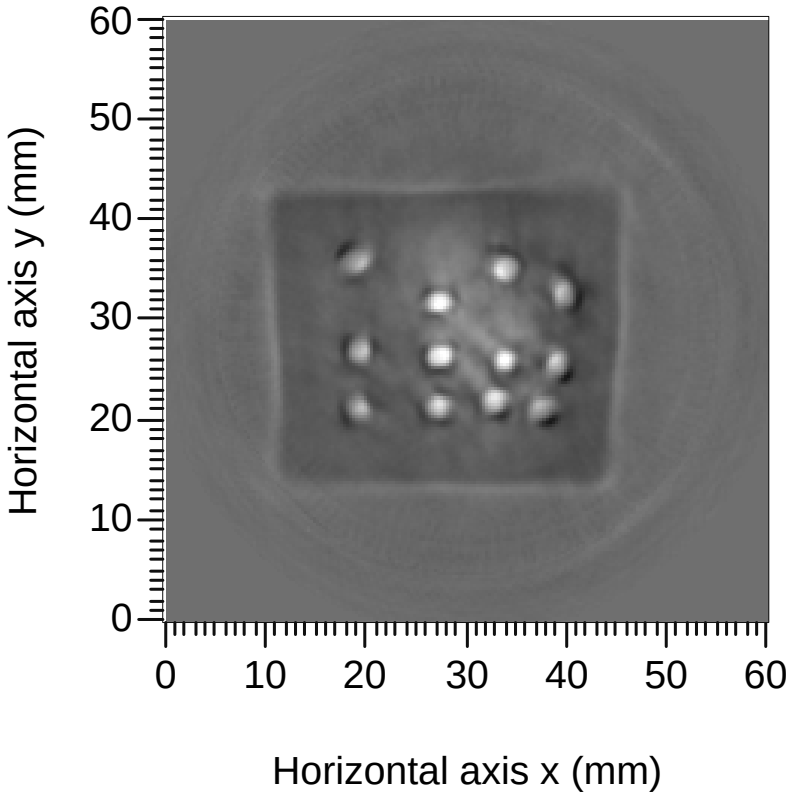
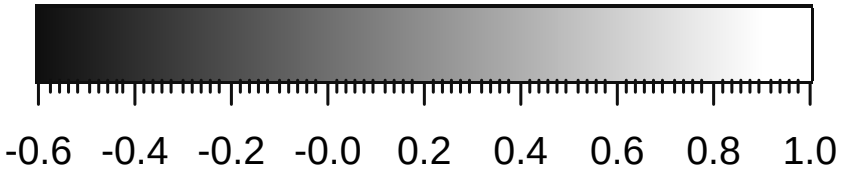




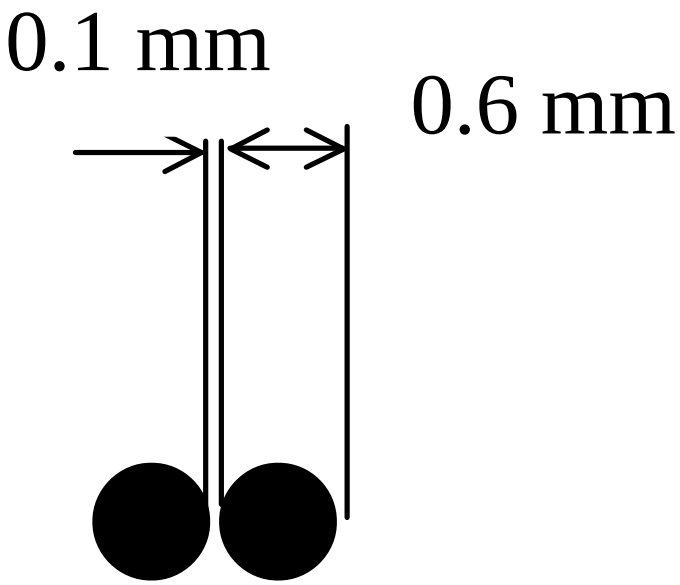
- **0.5 mm resolution**
- **Low speckle artifacts**

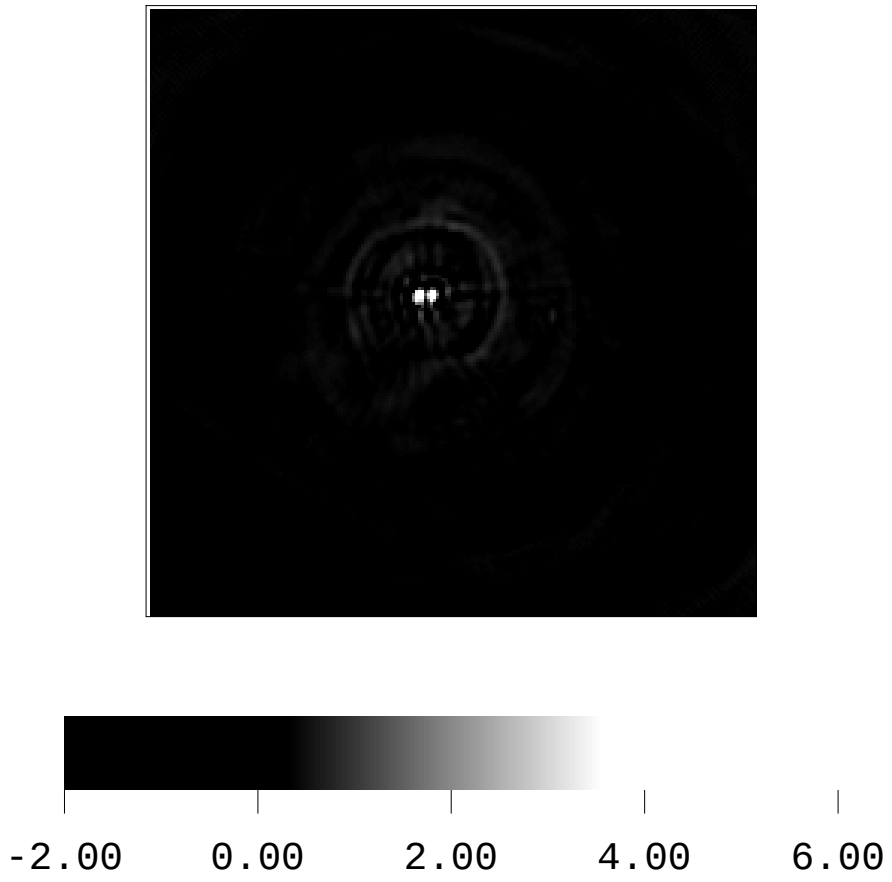


Advantages of Thermoacoustic Tomography

- Compared with MRI
  - Comparable or better resolution
  - Lower cost
  - Faster image acquisition
  - Non-magnetic
  - Complementary contrast mechanism
- Compared with X-ray imaging
  - Non-ionizing radiation
  - Better soft-tissue contrast
- Compared with ultrasonography
  - Better soft-tissue contrast
  - Weaker speckle artifacts
  - Compatible with each other
- Compared with pure-microwave tomography
  - Better resolution

Laser-Induced Thermoacoustic Tomography: Quantification of Resolution





Summary

- Combining ultrasonic and electromagnetic waves (light & microwave) provides good imaging resolution and new contrast mechanisms.
- Resolution is determined by the ultrasonic parameters.
- Contrast is provided by the electromagnetic properties even if the ultrasonic contrast does not exist.
- Functional imaging can be potentially accomplished with optical contrast.
- Non-ionizing radiation is used.

Funding Sources

- National Institutes of Health (X4)
- National Science Foundation
- US Army Medical Research
- The Whitaker Foundation
- Texas Higher Education Board

Acknowledgments/Downloadable Reprints

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