BU Engineering College of Boston University

Time Resolved Measurement of Transient Acoustic Waves using A Frequency Domain Photoacoustic Microscopy System

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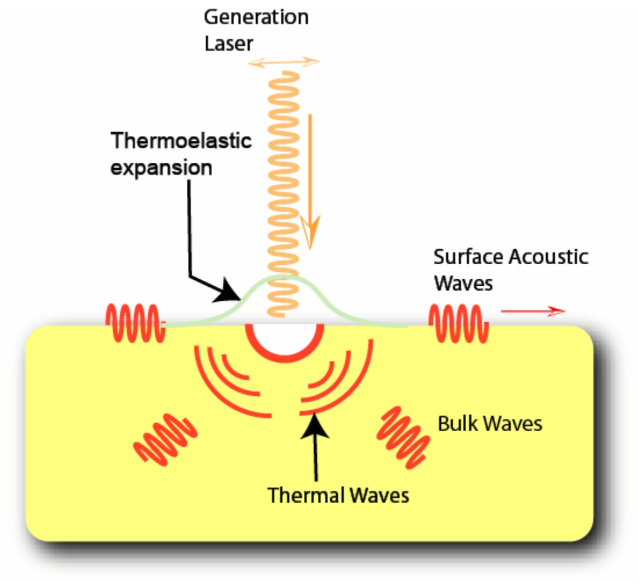
OUTLINE

- Photoacoustic Microscopy: Background and Applications
- Motivation - Signal to Noise Ratio Considerations
- Experimental Setup
- Time Domain Signal Analysis
- Conclusions

PHOTOACOUSTIC MICROSCOPY
(Laser Based Ultrasonics)



- Pulsed or modulated CW laser illuminates the sample surface
- Absorption of incident light leads to local heating of the sample
- Thermoelastic expansion of the heat active region generates coherent acoustic waves
- Generated acoustic waves are detected by measuring the sample surface displacement or elastic strain using optical detection systems

Advantages of Photoacoustic Microscopy over Conventional Acoustic Microscopy

- Non-contact, remote materials inspection
- Extremely high fidelity (generation and detection of acoustic waves over GHz bandwidth possible)
- High spatial resolution (important for the characterization of MEMS and nanoscale structures)
- Rapid scanning possible leading to reduced inspection time

Applications Include the Measurement of:

- Dimensional properties such as thickness or density of thin films and membranes
- Mechanical properties such as residual stress, elastic modulus, Poisson's ratio
- Micro- structural properties such as grain-size and texture
- Surface properties, surface defects, coating quality

Laser Sources used for Acoustic Wave Generation

GENERATION OF BROADBAND ACOUSTIC WAVES

- **Nanosecond sources: Q- switched lasers**

- **Femtosecond and picosecond sources: Mode-locked lasers**

GENERATION OF NARROWBAND ACOUSTIC WAVES

- **Temporally modulated pulsed laser sources: Mode-locked or Q switched pulse trains, AO modulated Q switched lasers, Laser array Sources**

OTHER:

- **Direct modulated CW laser: Generated with Pseudo-random Sequence**

(Pierce *et. al.*, Appl. Phys. Lett. 72(9), 1030, 1997, Madaras and Anastasi, AIP (509) 303, 2000)

Signal to Noise Ratio (SNR) of an Optical Detection System

Noise Sources: Thermal noise, shot noise, intensity and wavelength instabilities, etc (**Wagner and Spicer, J. Opt. Sc. Am B 4(8), 1316, 1997, Wagner, *Physical Acoustics***)

Shot Noise Limited SNR: $SNR \ \alpha \ \delta \sqrt{\frac{P}{B}}$

δ = Acoustic wave amplitude

P = Optical power incident on the photodetector

B = Bandwidth of the detection system

Approach Used to Improve the SNR: Focus the acoustic energy into an extremely narrow frequency band and match the bandwidth of the detection system to the acoustic spectrum.

Towards the Development of a Photoacoustic Microscopy System with an Improved Signal to Noise Ratio (SNR)

High resolution Measurements Require:

- ❑ tightly focused excitation source
- ❑ generation of high frequency acoustic waves

Pulsed Lasers Can be Used BUT:

- ❑ energy must be kept low: δ↓
- ❑ acoustic energy distributed over a large bandwidth: B↑

NET RESULT

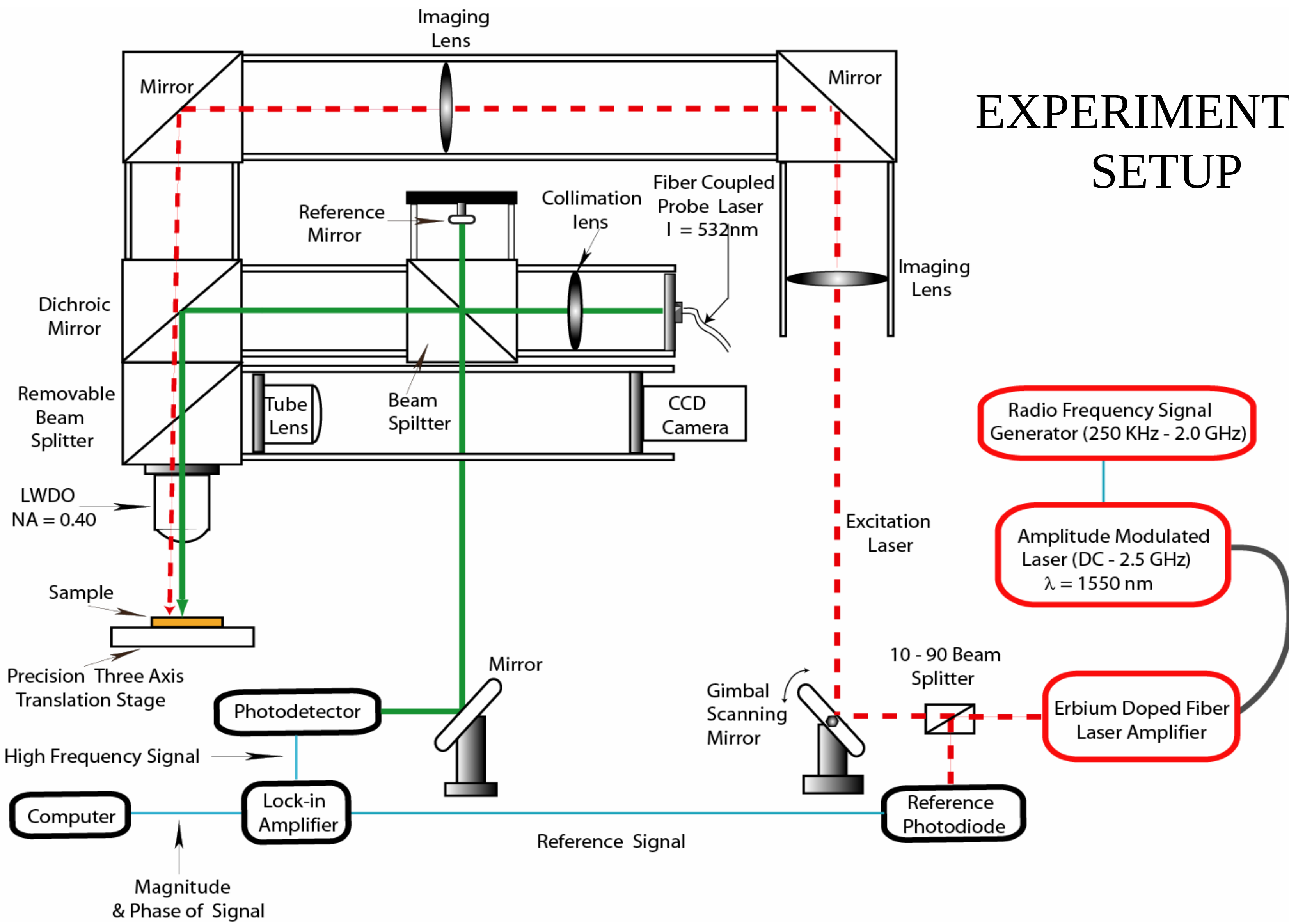
$$SNR \ \alpha \ \delta\sqrt{\frac{P}{B}}$$ ↓

Our Approach: Low power, sinusoidally modulated CW laser source

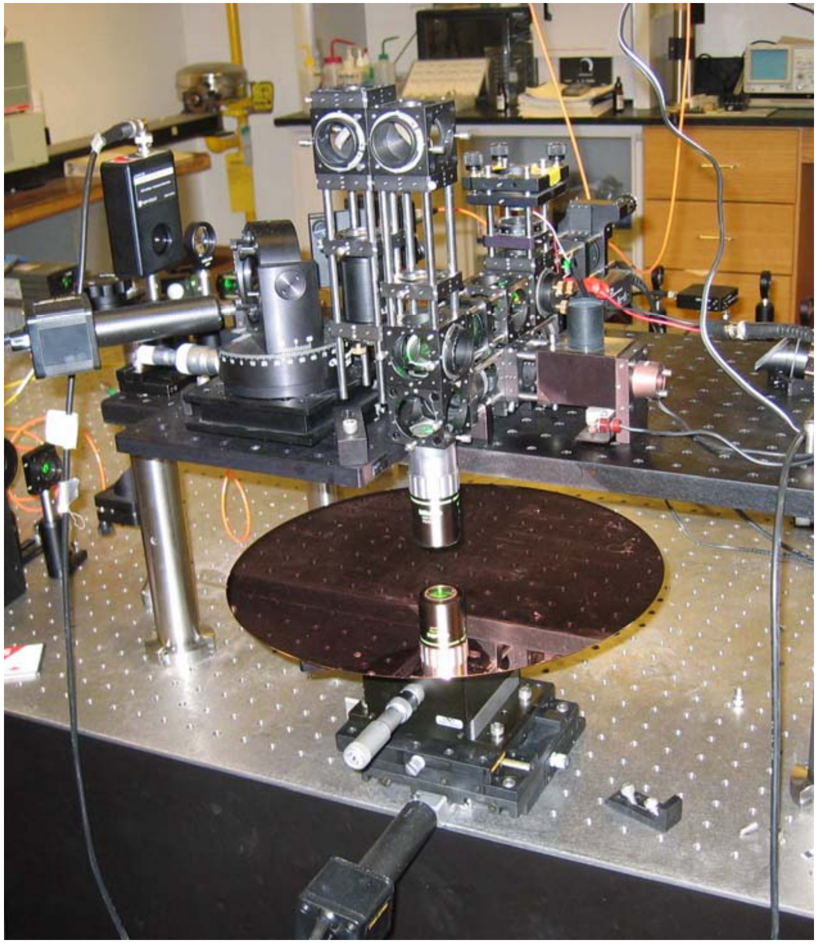
- ❑ power low: δ↓
- ❑ acoustic energy focused into extremely narrow frequency band: B↓↓↓

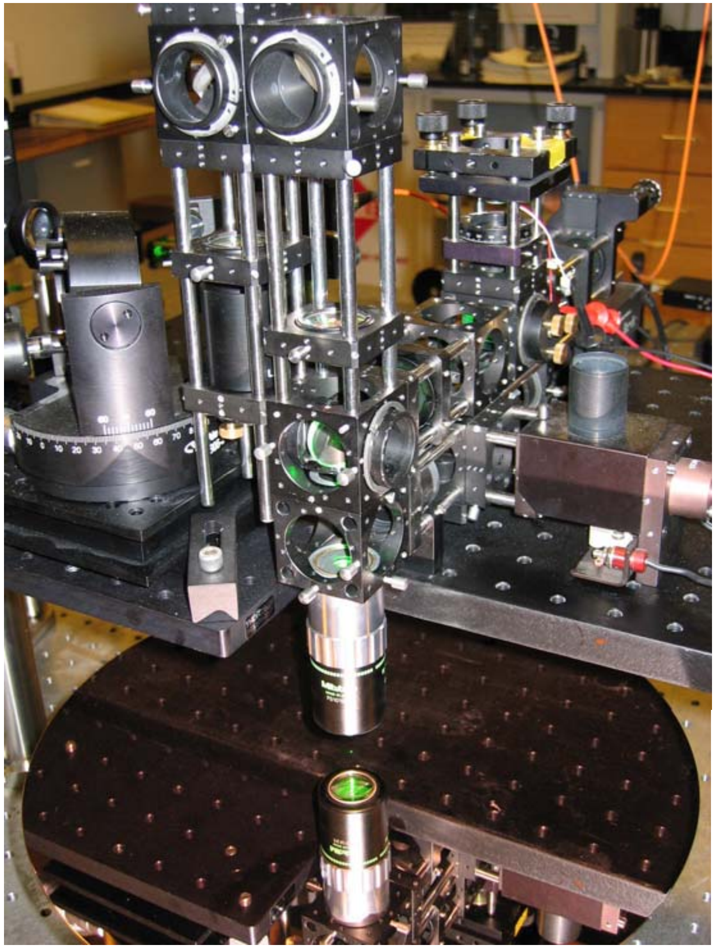
NET RESULT $SNR \ \alpha \ \delta\sqrt{\frac{P}{B}}$ ↑

EXPERIMENTAL SETUP



EXPERIMENTAL SETUP





CHALLENGE: EXTRACT QUANTITATIVE INFORMATION

- Measured magnitude and phase of the signal at *f* are influenced by the entire acoustic field
- Extraction of materials properties/ quantitative NDE difficult

TIME DOMAIN RECONSTRUCTION

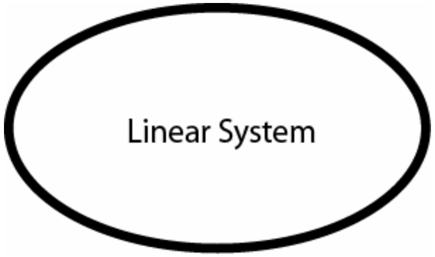
- Material is excited using sinusoidal modulation at given frequency (*f*) and at a fixed source to receiver distance
- Magnitude and phase of the signal at *f* is recorded
- Measurement is repeated over the frequency range of interest
- A time domain “pulsed” response is constructed

FREQUENCY DOMAIN

$$f_1(t) = I_1(f_1)\cos(2\pi f_1 t)$$

$$\vdots$$

$$f_N(t) = I_N(f_N)\cos(2\pi f_N t)$$



$$u_1(t) = A(f_1)\cos(2\pi f_1 t + \varphi(f_1))$$

$$\vdots$$

$$u_N(t) = A(f_N)\cos(2\pi f_N t + \varphi(f_N))$$

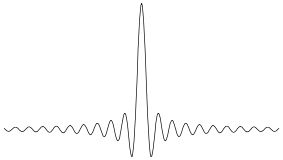
SUM (INPUT)

SUM (OUTPUT)

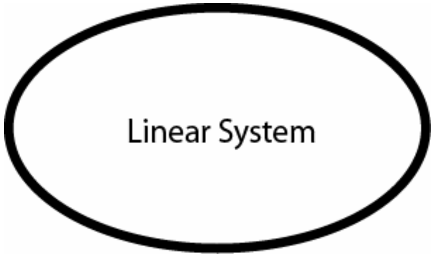
$$i(t) = \frac{1}{N}\sum_{n=1}^{N} I_n(nf_0)\cos(2\pi n f_0 t)$$

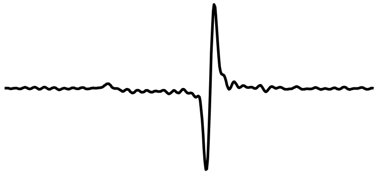
$$S(t) = \frac{1}{N}\sum_{n=1}^{N} A_n(nf_0)\cos\left[2\pi n f_0 t + \varphi(nf_0)\right]$$

TIME DOMAIN



INPUT “PULSE”





OUTPUT SIGNAL

Murray and Balogun, Appl. Phys. Lett. 85(14), 2974, 2004, Balogun and Murray, J. Appl. Phys., 100, 034902, 2006

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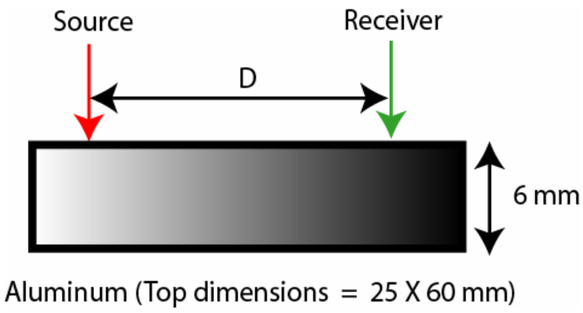
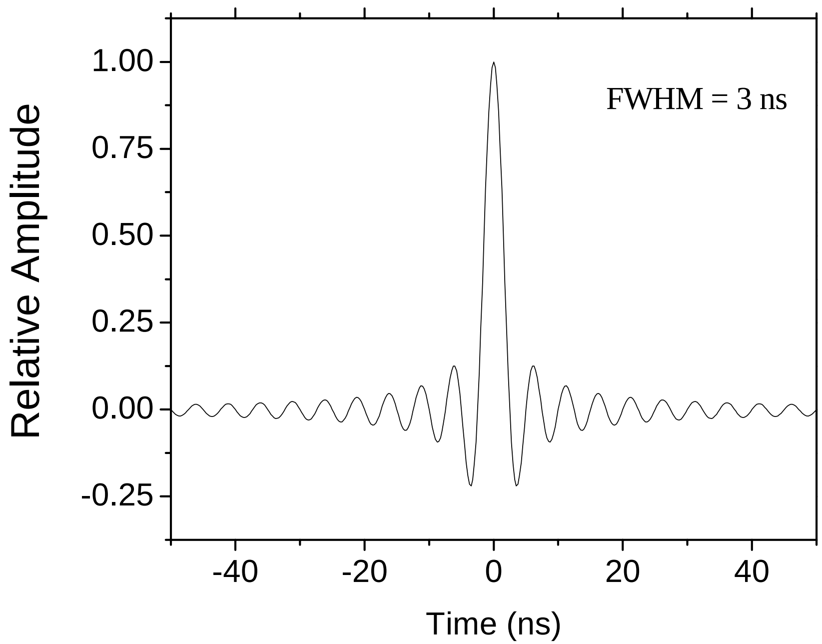
TIME DOMAIN RECONSTRUCTION

Frequency range = 1 – 200 MHz

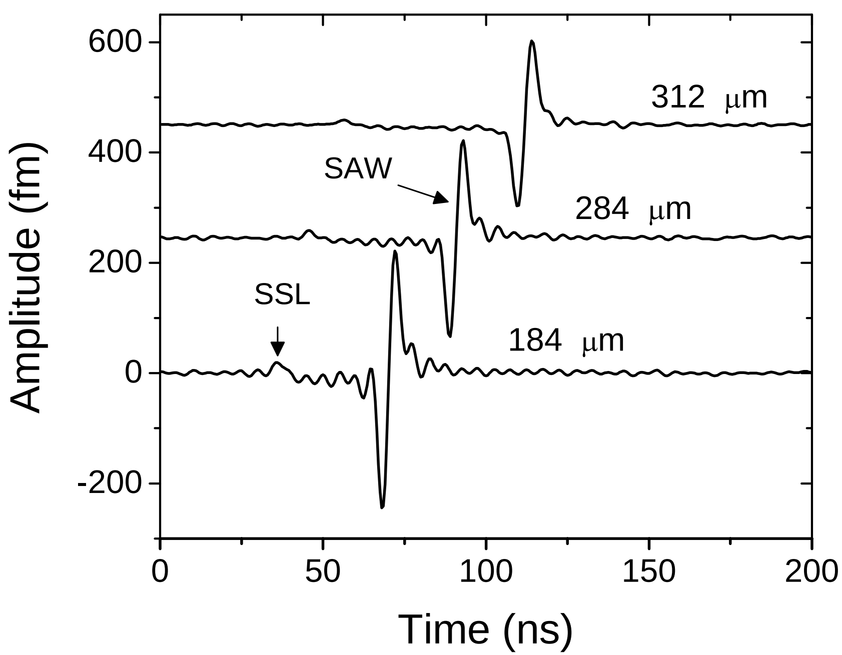
f_0 = 1.0 MHz



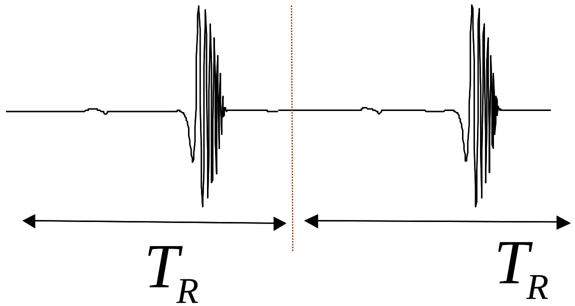
SYNTHESIZED INPUT "PULSE"



SYNTHESIZED RESPONSE



Choice of Frequency Resolution f_0



TIME DOMAIN ALIASING

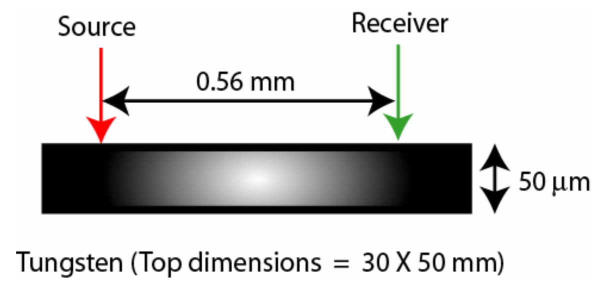
- Reconstructed time window repeats after $T_R = \frac{1}{f_0}$
- Arrivals after T_R will appear as "alias arrivals" at T < T_R
- f_0 must be chosen such that T_R is greater than the decay time (τ) of the acoustic field to unambiguously reconstruct the time domain response.

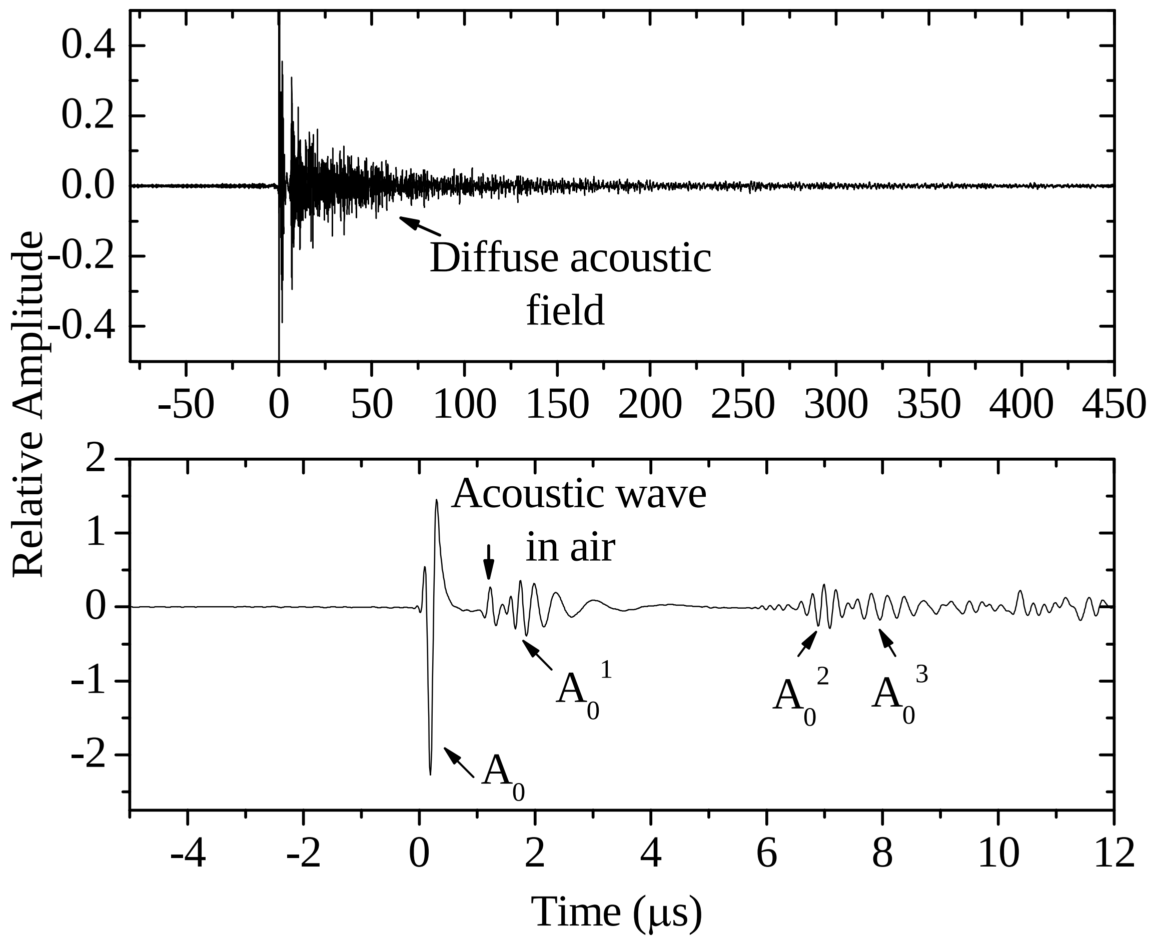
SIGNAL TO NOISE RATIO (SNR)

- SNR improves with number of frequency samples acquired (N) $SNR \propto N^{\frac{1}{2}}$
- τ allows for selection of minimum f_0, oversampling is analogous to averaging in the time domain

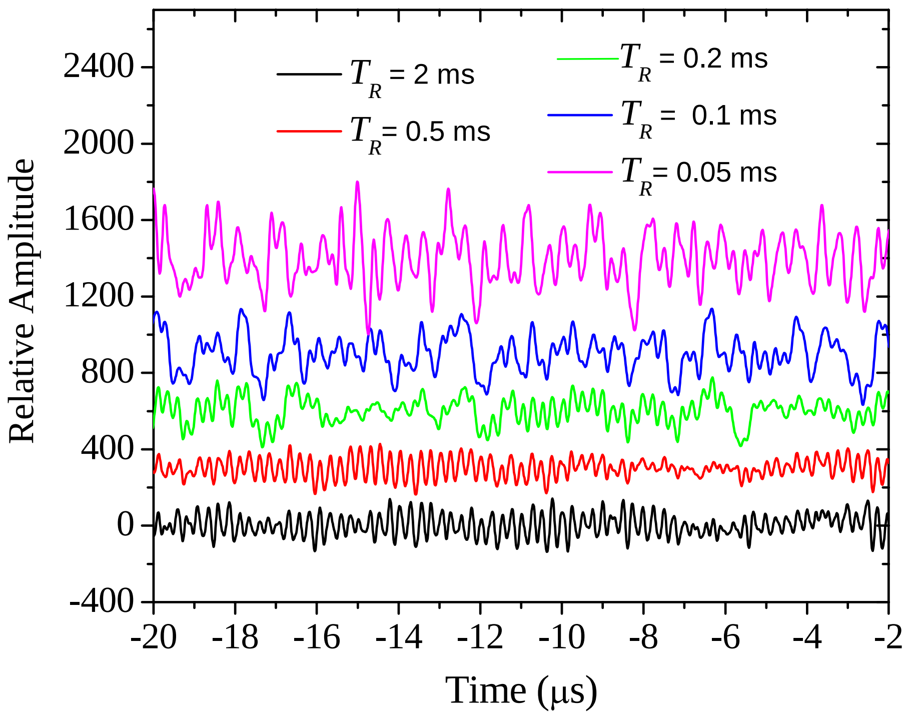
TIME DOMAIN ALIASING

Frequency range = 0.2 –10 MHz, f_0 = 0.5 KHz, T_R = 2 ms

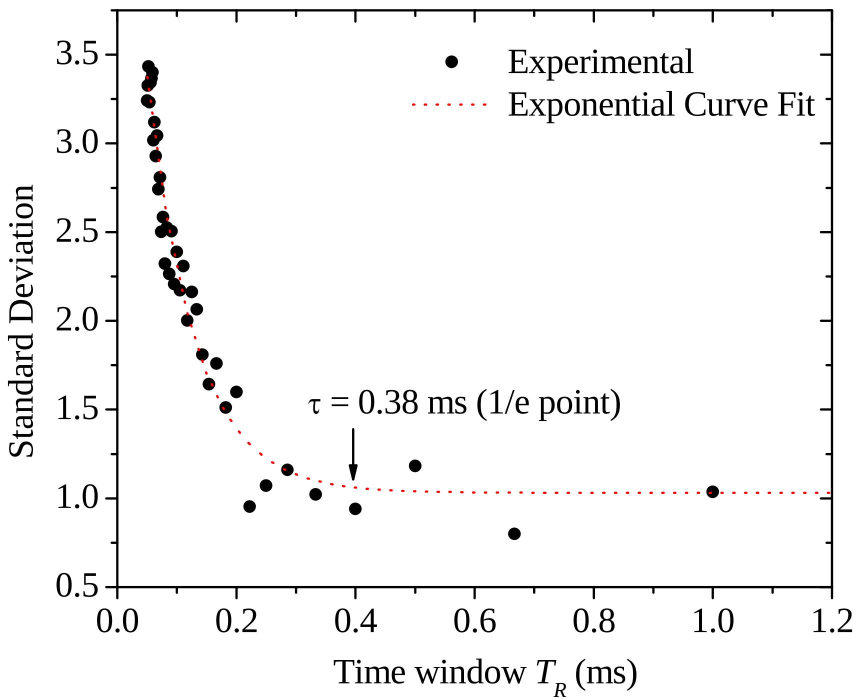




NOISE IN SYNTHESIZED WAVEFORMS



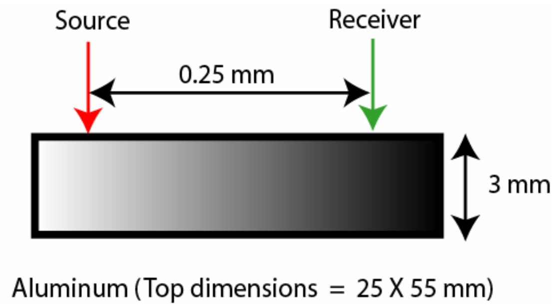
NOISE AS A FUNCTION OF TIME WINDOW



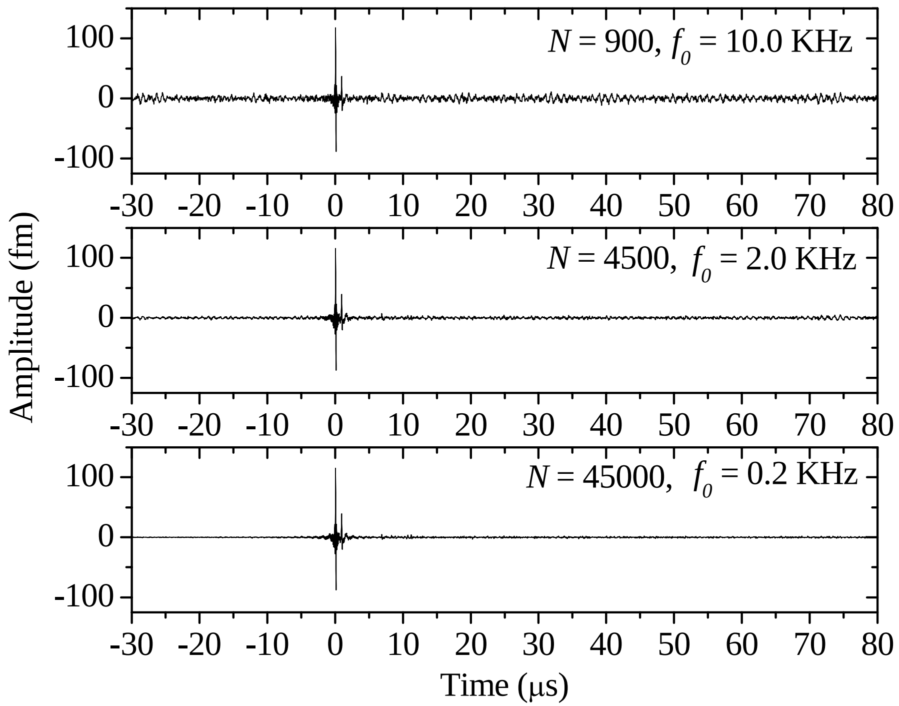
SIGNAL TO NOISE RATIO (SNR)

- Here the acoustic decay time is < 20μs
- SNR dependence on *N* confirmed

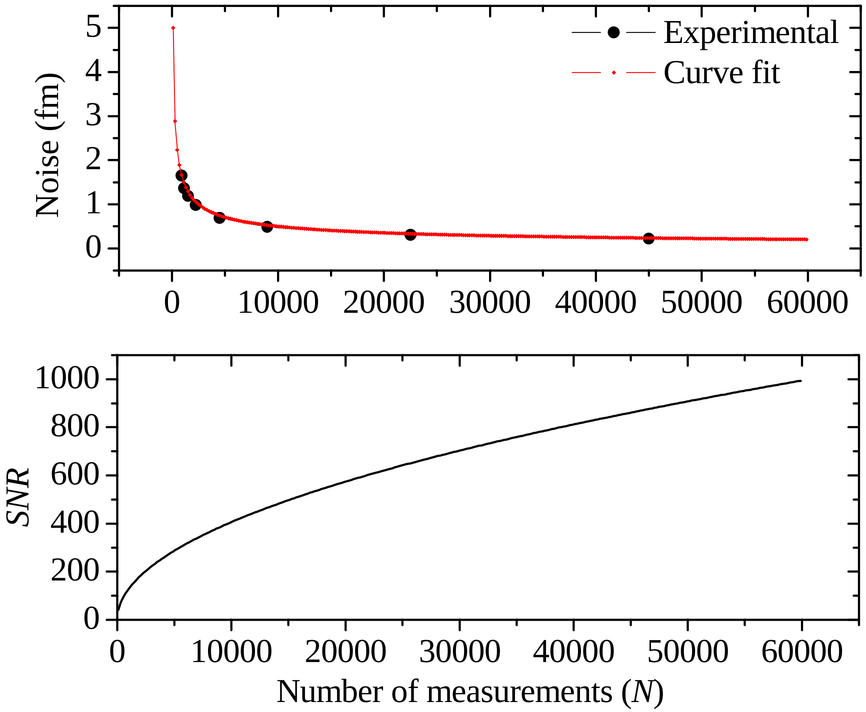
Frequency range = 1 – 10 MHz



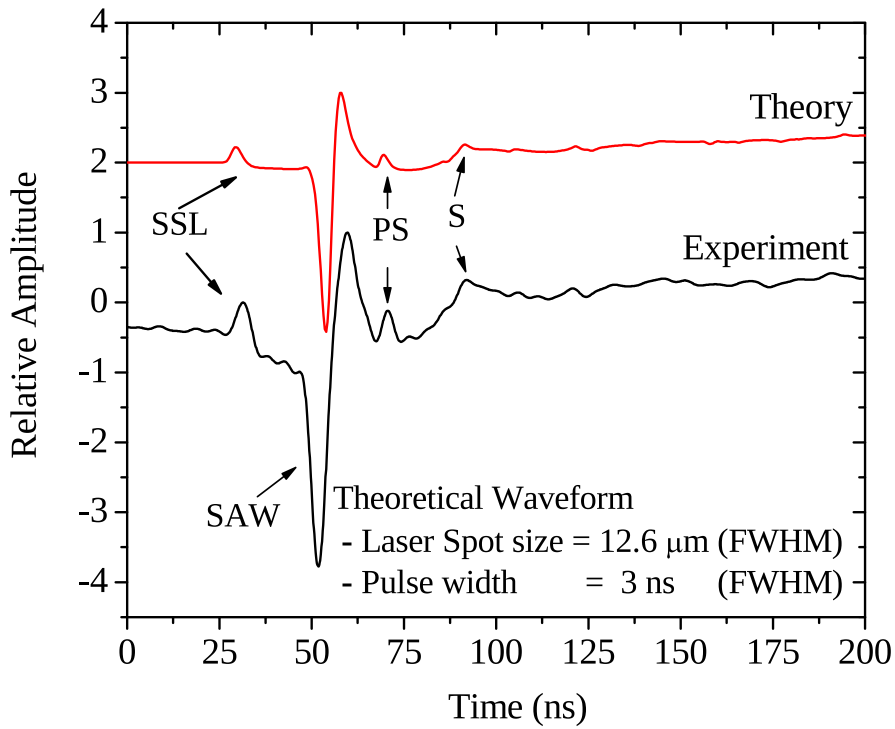
SYNTHESIZED WAVEFORMS

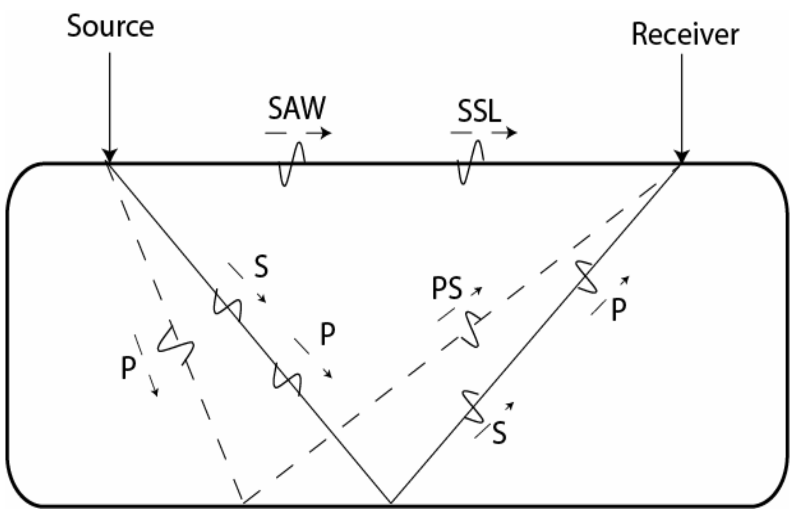


SNR



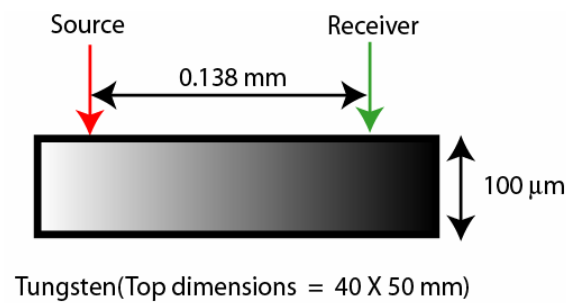
High Frequency Measurements: Theory and Experiment





Frequency range = 1 –200 MHz

f_0 = 10.0 KHz, T_0 = 0.1 ms



CONCLUSIONS

- A frequency domain photoacoustic microscopy system was developed for the characterization of micro- and nanoscale materials.
- The displacement sensitivity of the optical detection system was shown to be in the femtometer range for a detection bandwidth of 1 Hz.
- Temporal resolution of transient acoustic waves was obtained by synthesizing a pulse response from the frequency domain data