Surface characterisation using combined ultrasound and low coherence interferometry

Chunhui Li[1], Sinan Li[1], Zhihong Huang[1], Ruikang Wang[2]
[1]School of Engineering, Physics and Mathematics, University of Dundee, UK
[2]Department of Bioengineering, University of Washington, US

introduction

- This paper describes a novel optical acoustic system for skin characterisation based on its elasticity.
- A broadband surface acoustic wave (SAW) impulses is generated by A focused laser source.
- SAW detected with a optical low coherence interferometer.
- The measured SAW velocity dispersion spectrum was used to characterise the elasticity of the specimen

Laser Ultrasonics

Absorption of Electromagnetic (light) energy into Mechanical (acoustic wave) energy

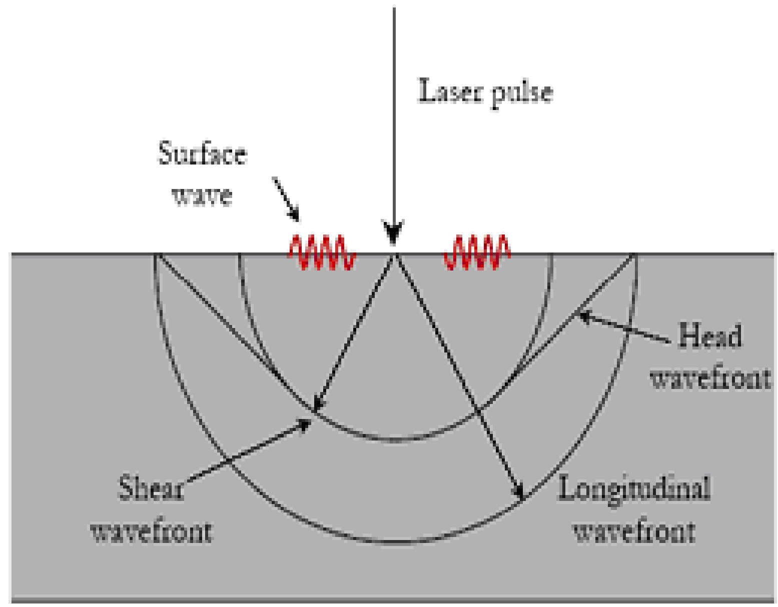
- **Laser Generation of Ultrasound**

  - absorption of optical energy;

  - thermal expansion;

  - Generation of elastic waves;

- **Widely used in industry**
  - surface materials and thin films



Waves generated by a laser pulse incident on an infinite half-space of solid.

Surface acoustic waves

- Domain by Rayleigh wave

  - *Low frequency content*

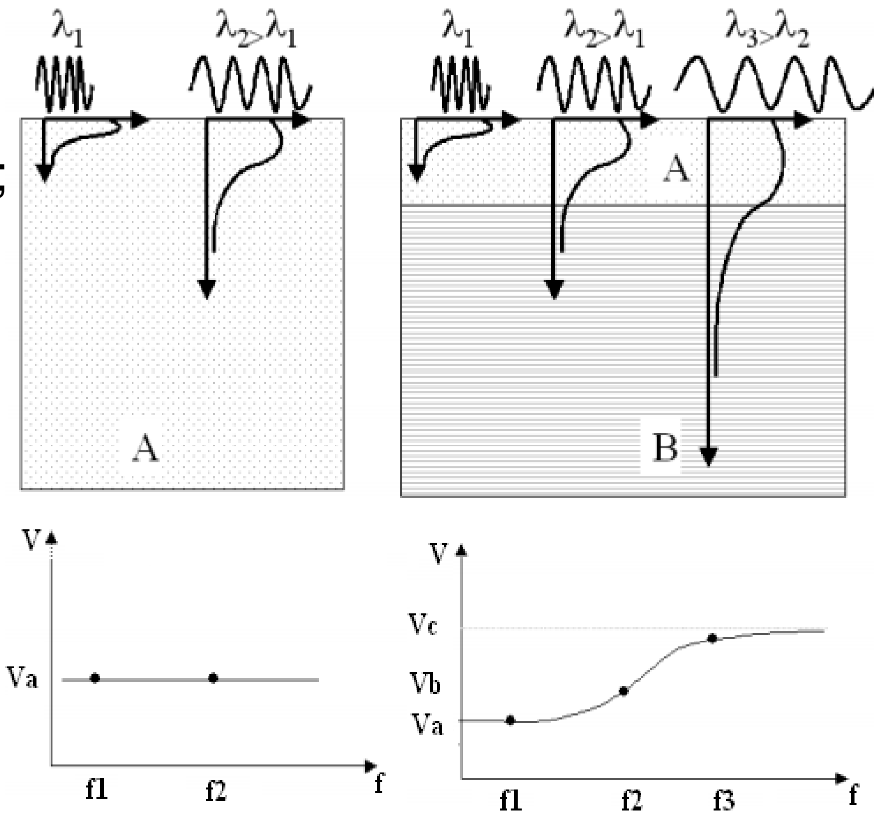
    Deep penetration;

    Substrate layer determines wave velocity;

  - *High frequency*

    Low penetration;

    Surface layer determines wave velocity;



- Rayleigh wave and elastic properties

$$c = \frac{0.87 + 1.12v}{1+v}\left(\frac{E}{2\rho(1+v)}\right)^{\frac{1}{2}}$$

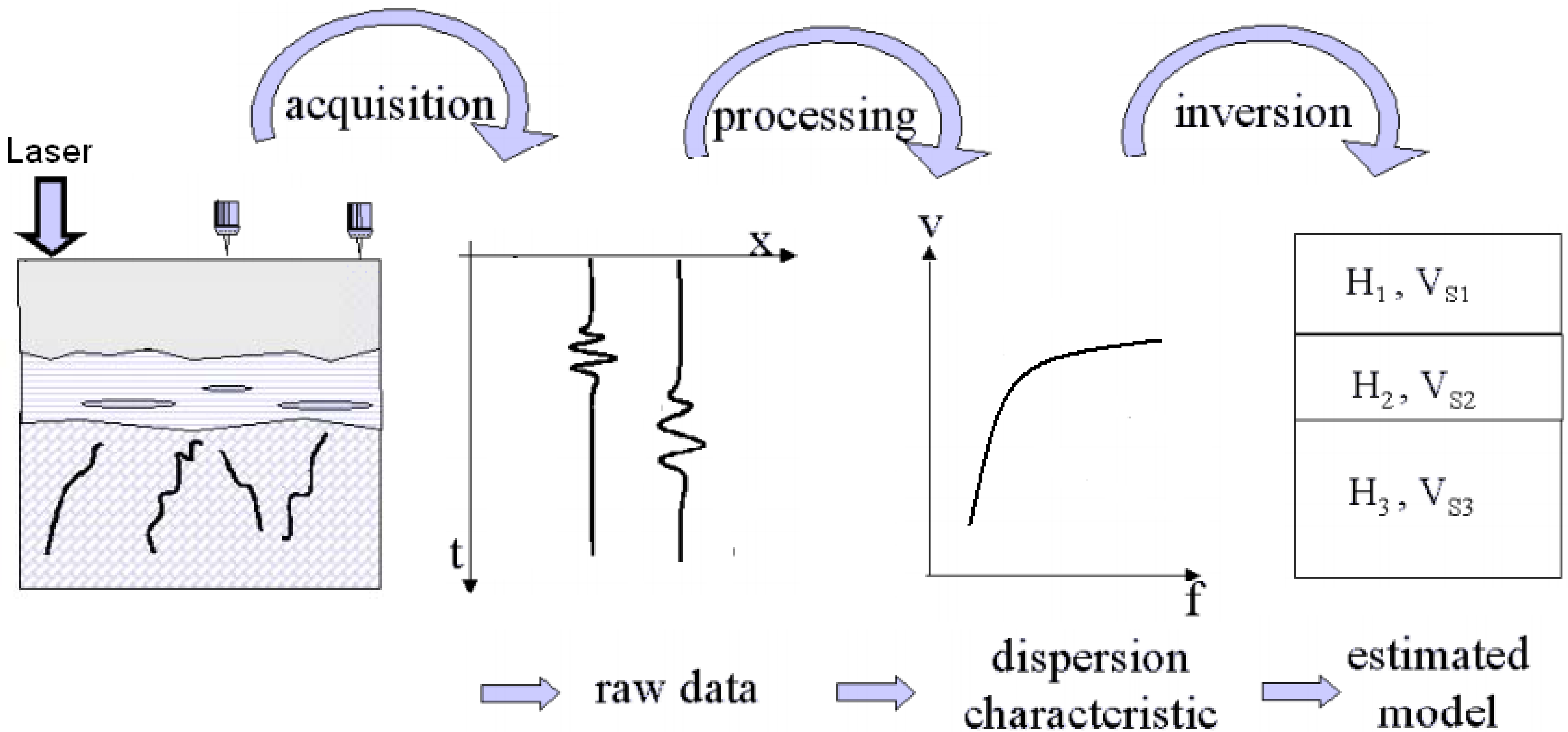
Where *E* is the Young's Modulus, *v* is the Poisson's Ratio, and ρ is density of material

Our novel approach

- Generate Rayleigh wave by laser pulse
  - Rich of frequency component, large frequency bandwidth;
  - Non-contact;
  - A line source to increase the sensitivity

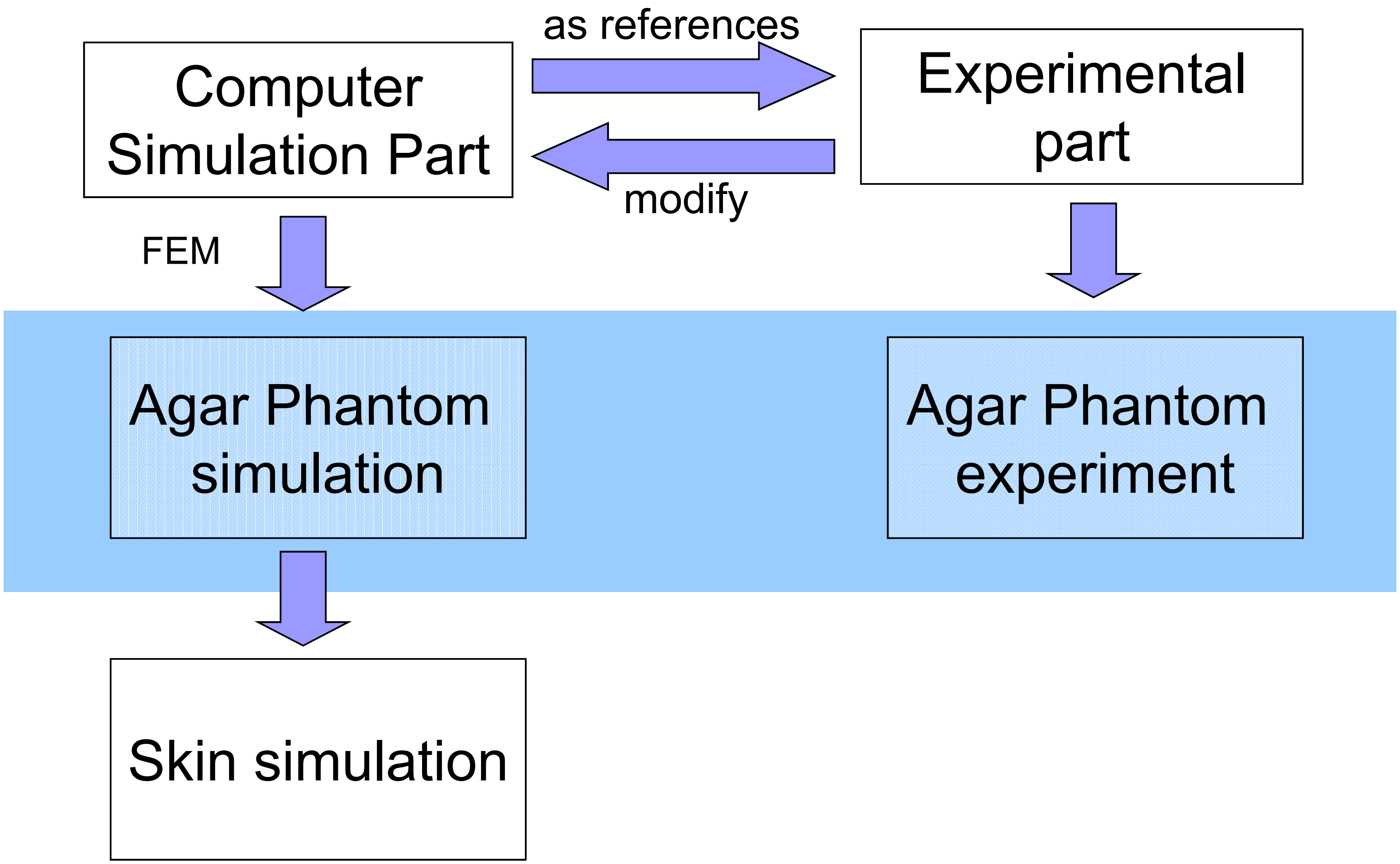
- Detect Rayleigh wave by low coherence interferometry
  - localize the targeted positions on the sample surface,
  - Good for skin study and avoid noise;
  - OCT imaging system to provide the geometrical structure of samples as well as elasticity;

procedures



Reference: ' Surface Wave Methods Acquisition, processing and inversion ', Claudio Strobbia, 2002

FE simulation as reference



FE Simulation

- Sequential Coupled Analysis (Thermal mapped to mechanic)
  - Thermal analysis
  - Mechanical analysis

- Advantages
  - predict feasibility;
  - provide guide and reference of experimental work;
  - produce detailed information;

Experimental setup

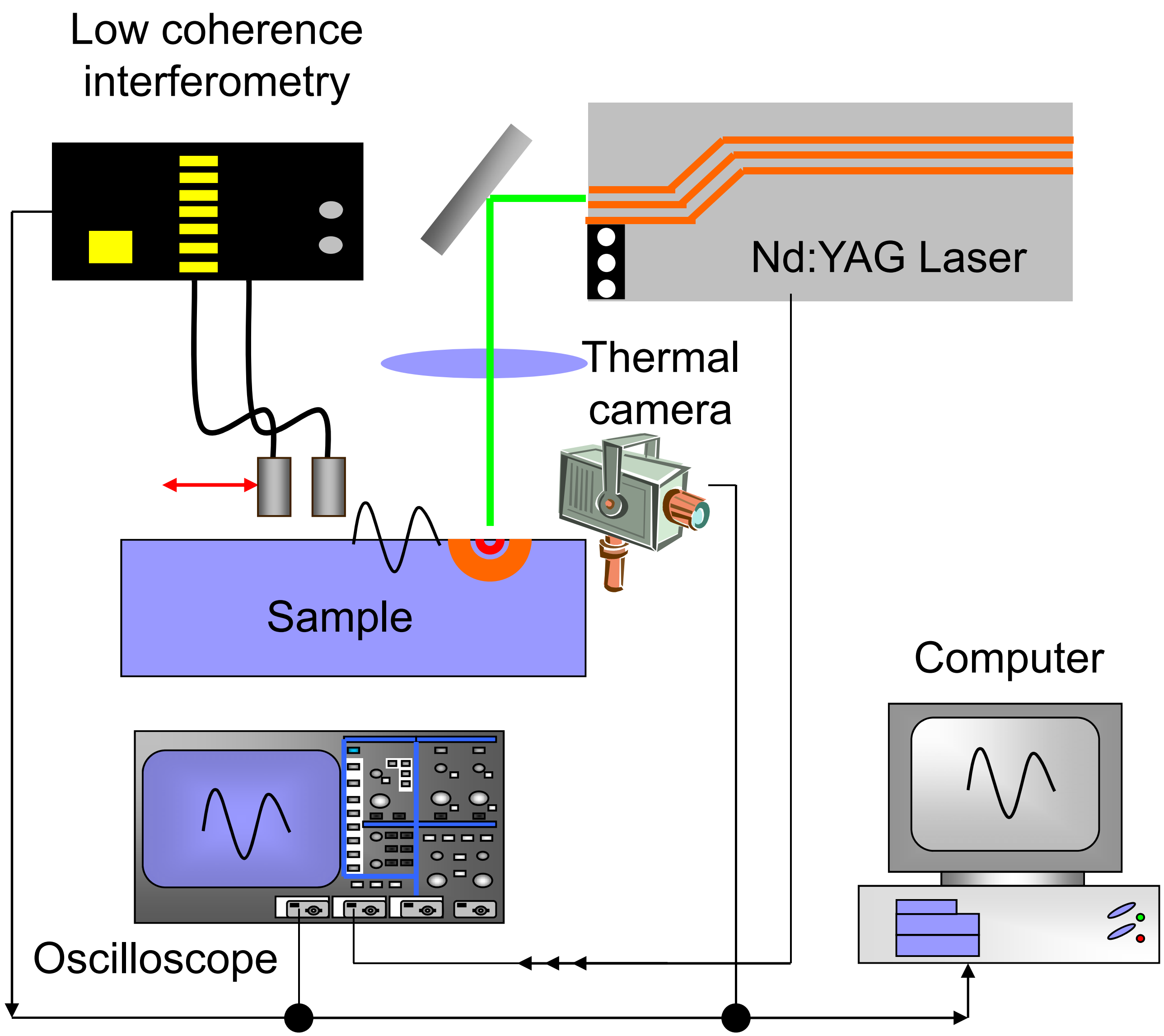
- High energy solid state ~532nm Nd:YAG laser source (Continuum Surelite Laser)

- Jade infrared thermal camera to detect thermal effect on sample surface to modified the temperature, avoid ablation;

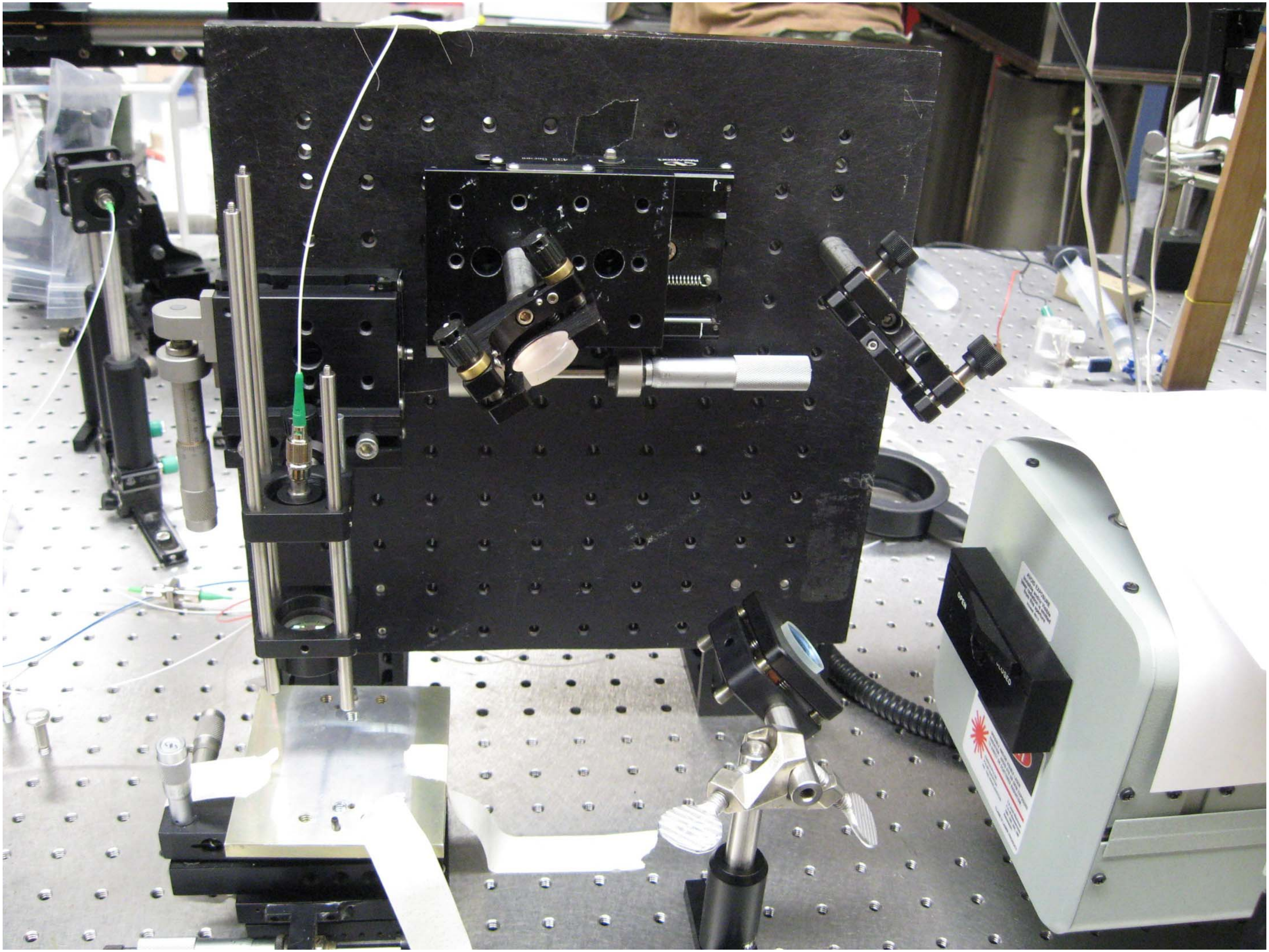
- Fiber Michelson interferometer to detect surface acoustic signals

  - Non contact detection
  - Broader frequency range
  - High spatial and temporal resolution

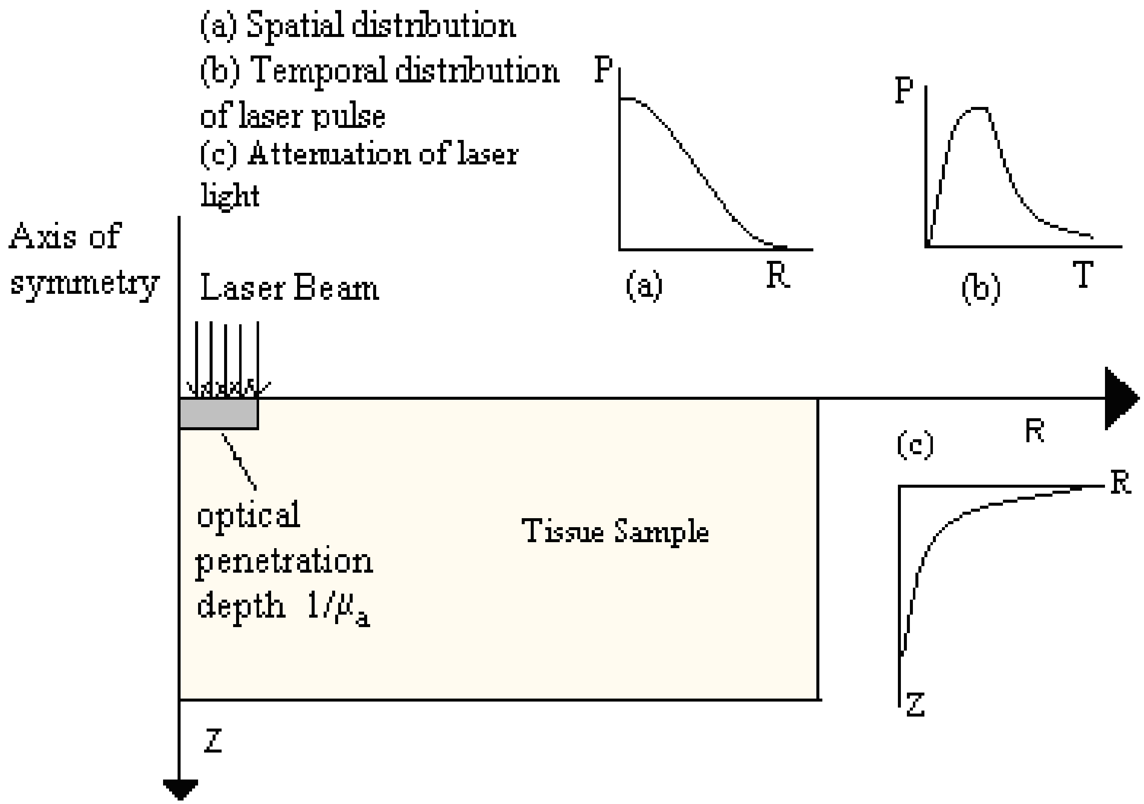
- Black agar phantom is used in the experiment, both one layer and two layers



Low coherence interferometry
Nd:YAG Laser
Thermal camera
Sample
Computer
Oscilloscope



Simulation of Single layer agar phantom

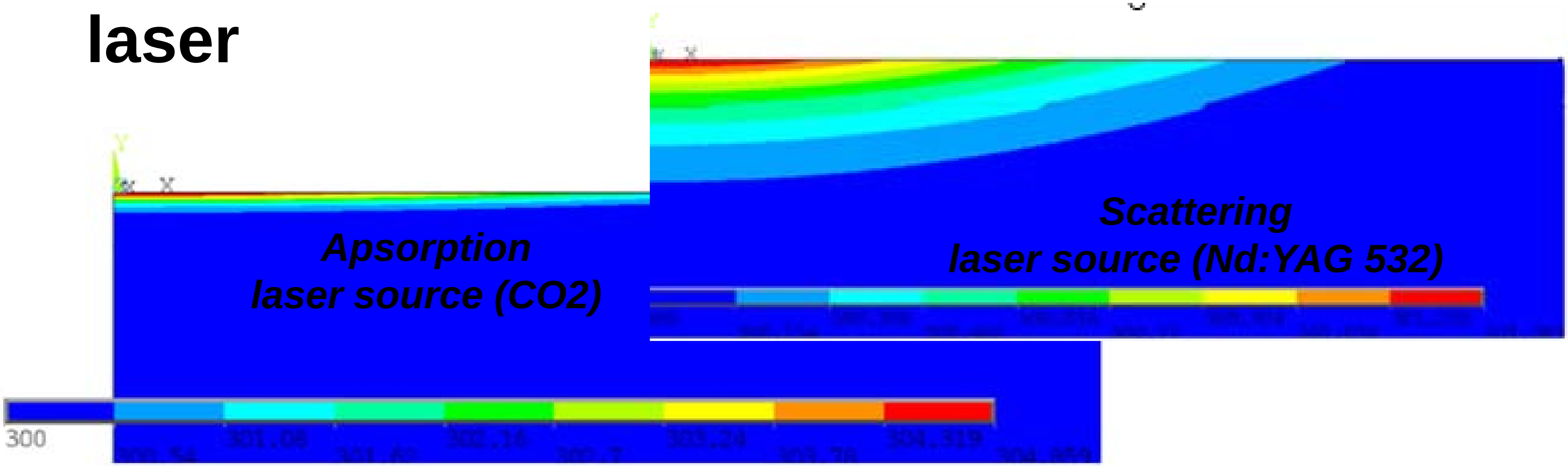


Same conditions as the experiments:

- The time steps is 0.1ns with total of 1ms;
- Laser pulse wavelength 532nm;
- The pulse energy is set at 2.6-3mJ per pulse with rise time 3ns;
- Laser beam radius of 0.5mm;

Thermal Characterisation

Analysis 1: Absorptive laser vs Scattering laser

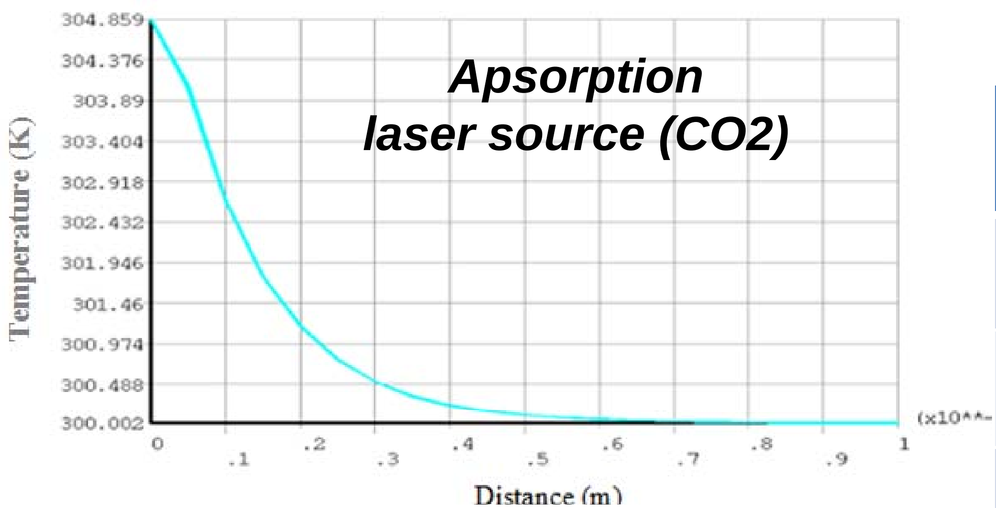


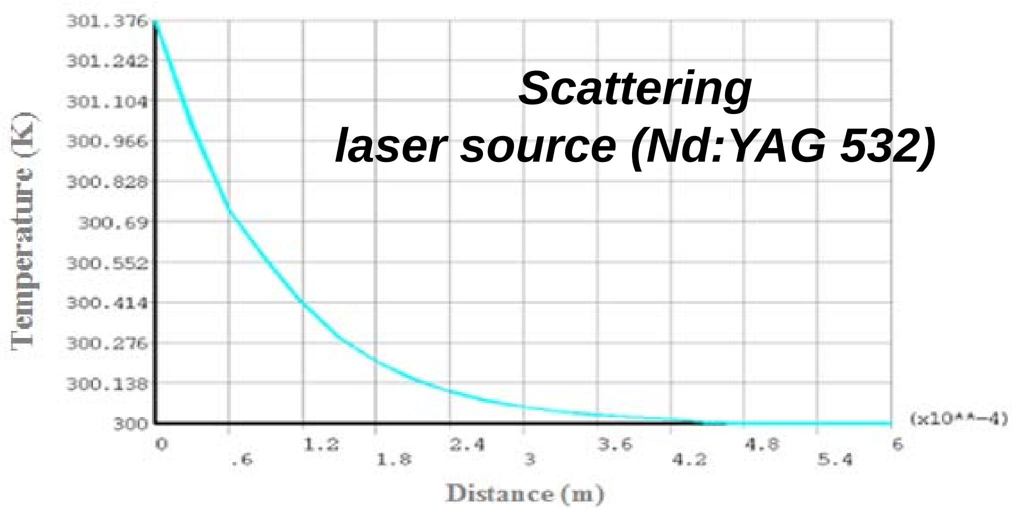
Contour plots of thermal distribution in the PVA model induced by different laser sources

Properties of different laser source

Laser	Wavelength	μ_a (mm^{-1})	μ_s (mm^{-1})	g	Penetration depth (mm)
CO_2	10600	82	-	0.9	0.012
Nd: YAG/KTP	532	0.2	2.5	0.9	0.45

Thermal Characterisation



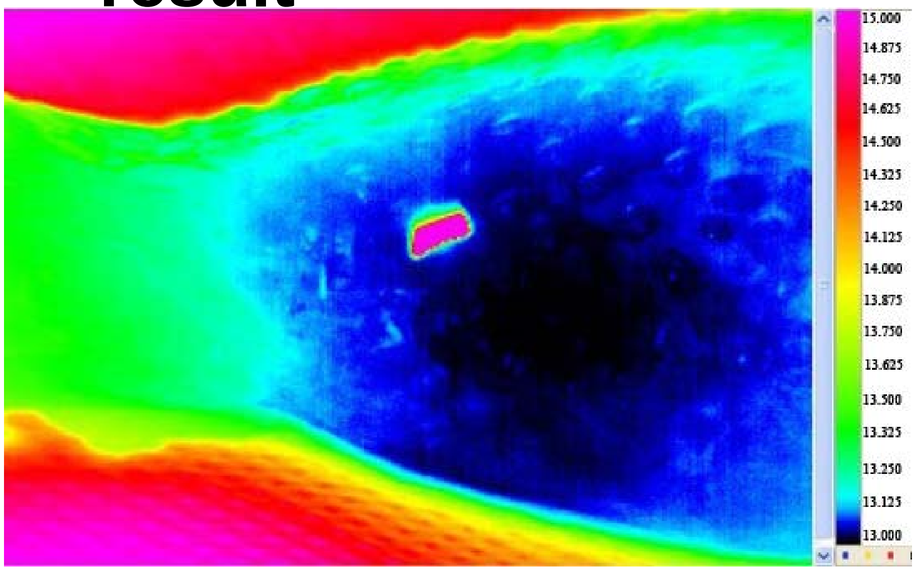


laser type	CO_2	ND:YAG532
Energy	1 mJ	5mJ
Pulse Radius	1mm	1mm
Pulse Rise Time	3ns	3ns
Temperature Rise	4.859 (K)	1.376(k)

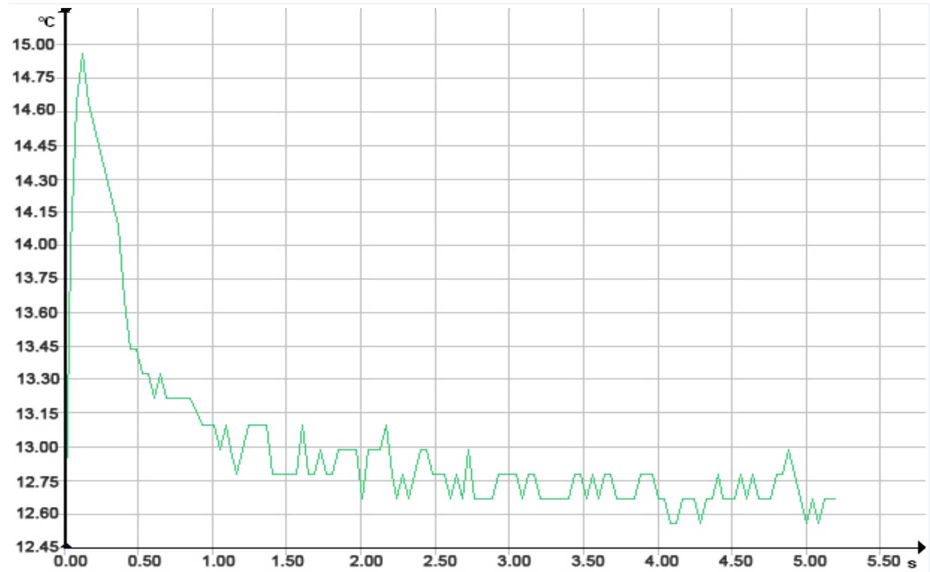
Scattering laser source penetrates more however generates lower heating

Thermal Characterisation

Analysis 2: Simulation compared with Experiment result



Thermal contour plots



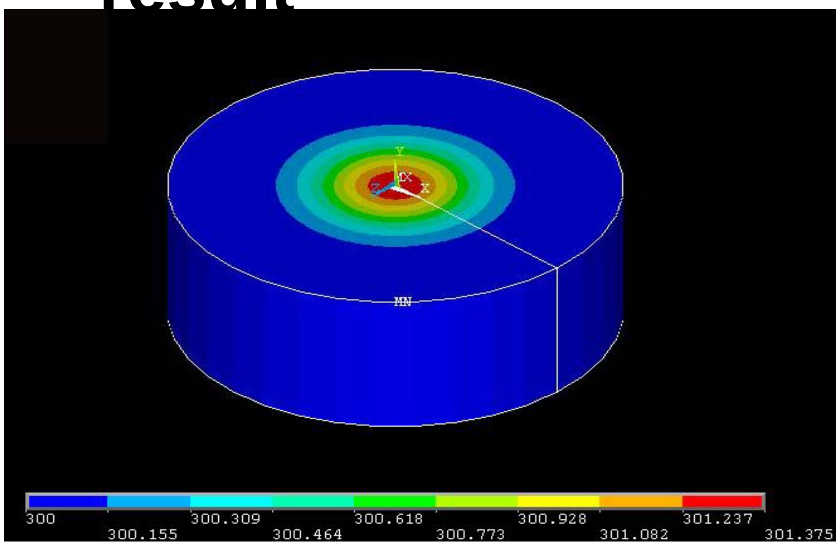
Thermal timing graph

Experiment set-up

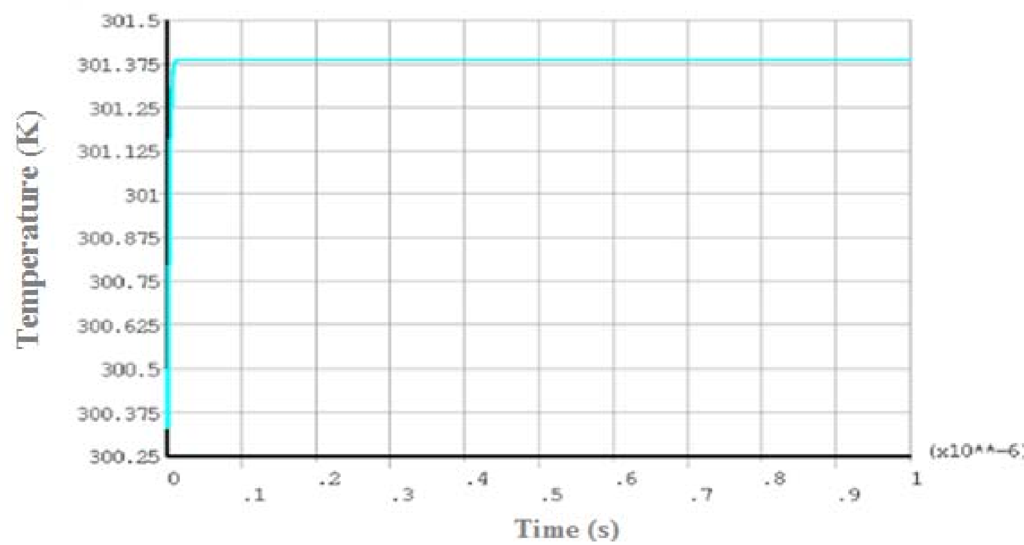
Laser Type	Energy	Pulse Risetime	Pulse Radius	Sample	Temperature Rise
Nd: YAG 532	5mJ	3ns	1mm	Chicken	1.921 (K)

Thermal Characterisation

Analysis 2: Simulation compared with Experiment result



Thermal contour plots

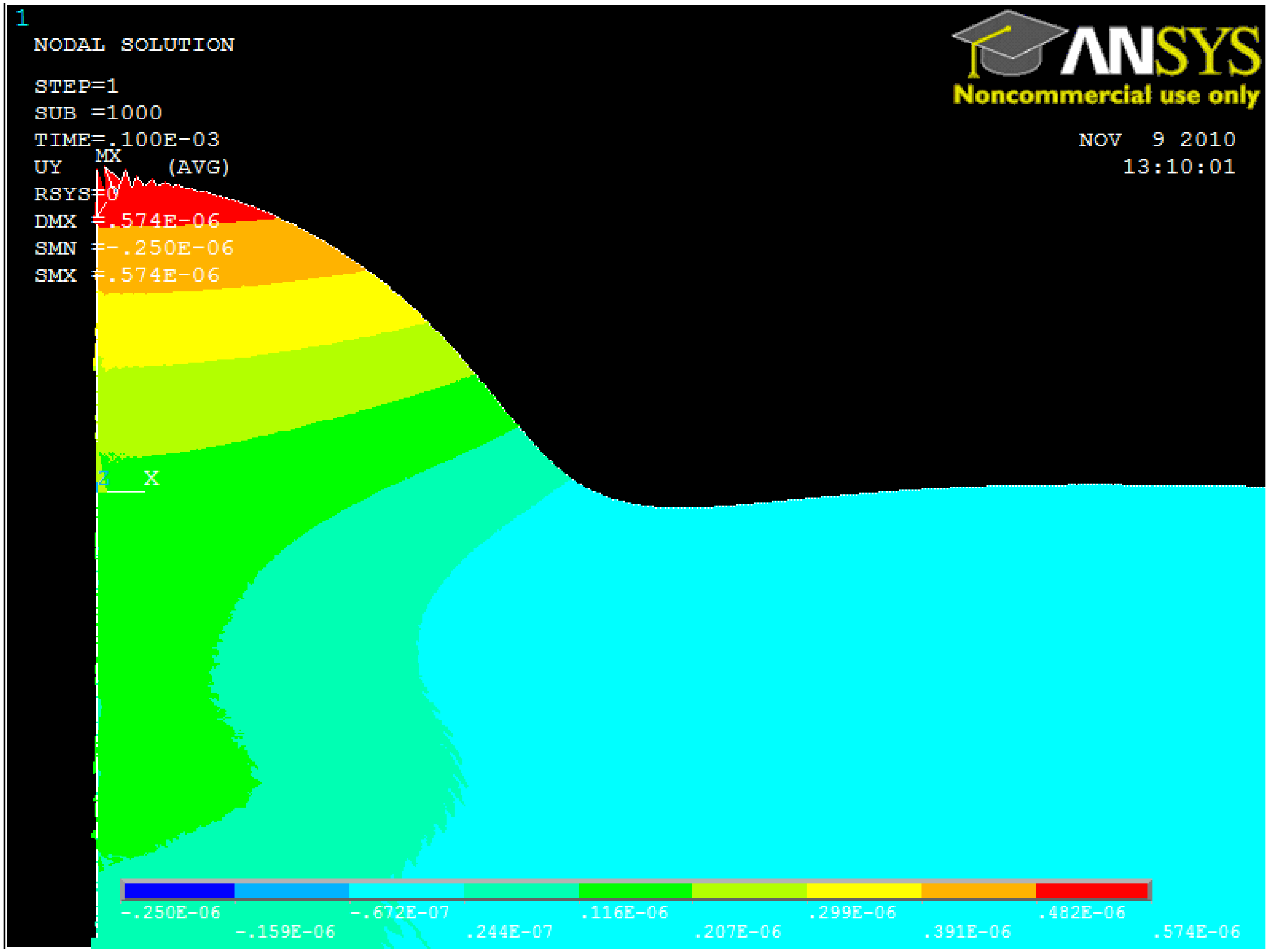


Thermal timing graph

Simulation set-up

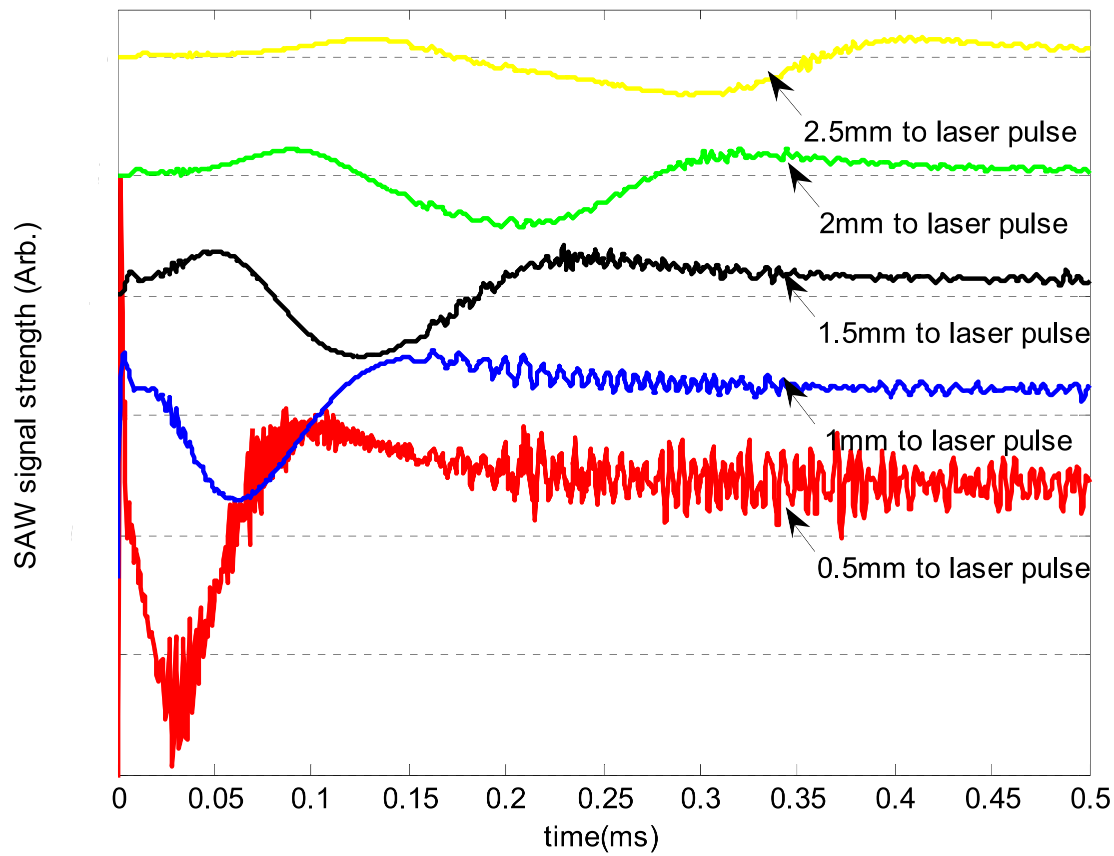
Laser Type	Energy	Pulse Rise Time	Pulse Radius	Sample	Temperature Rise
Nd: YAG 532	5mJ	3ns	1mm	PVA Phantom	1.375 (K)

FE results – wave propagation



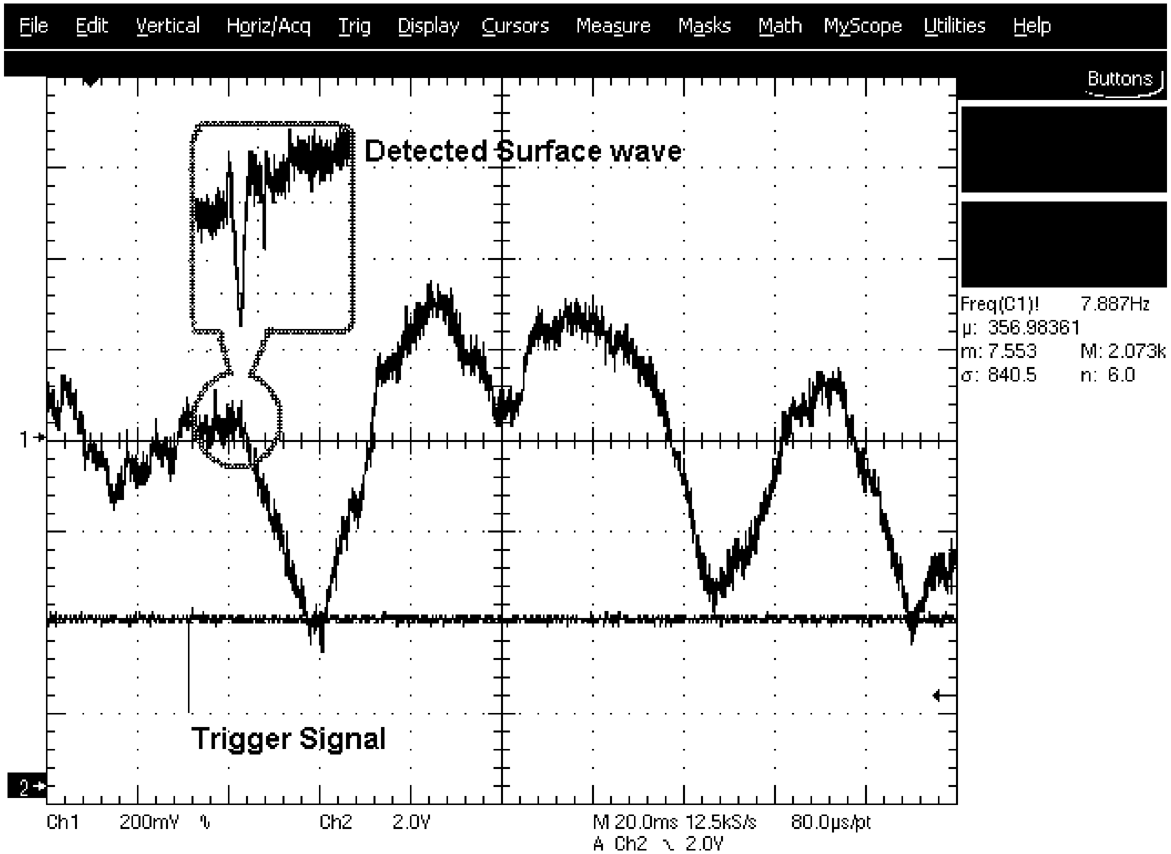
Structural contour plots

predicted displacement data of 3.5% agar phantom



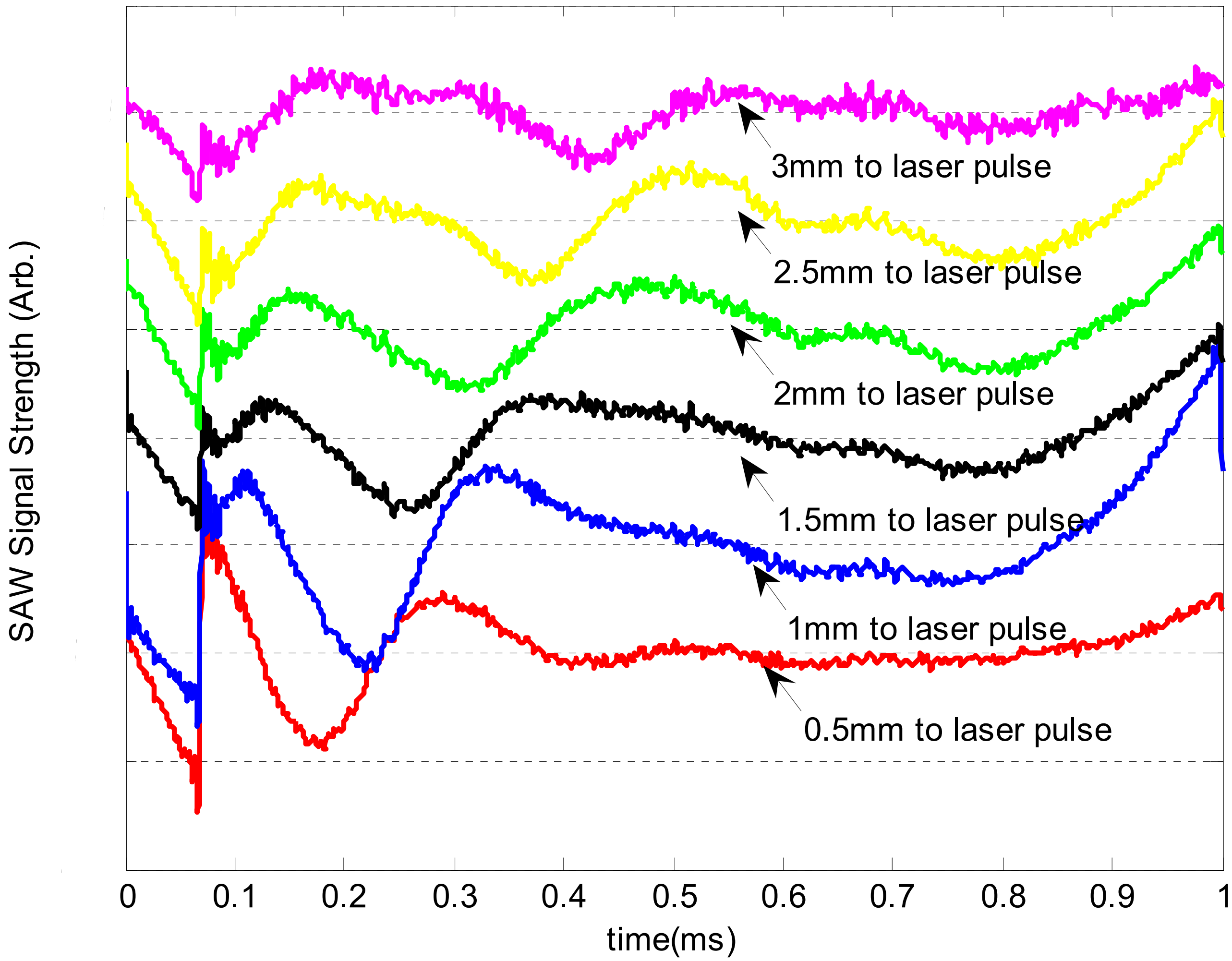
Laser Type	Energy	Pulse Rise Time	Pulse Radius	Step interval	Sample Rate
Nd: YAG 532	3mJ	3ns	0.5mm	50um	2MHz

Result of experiment

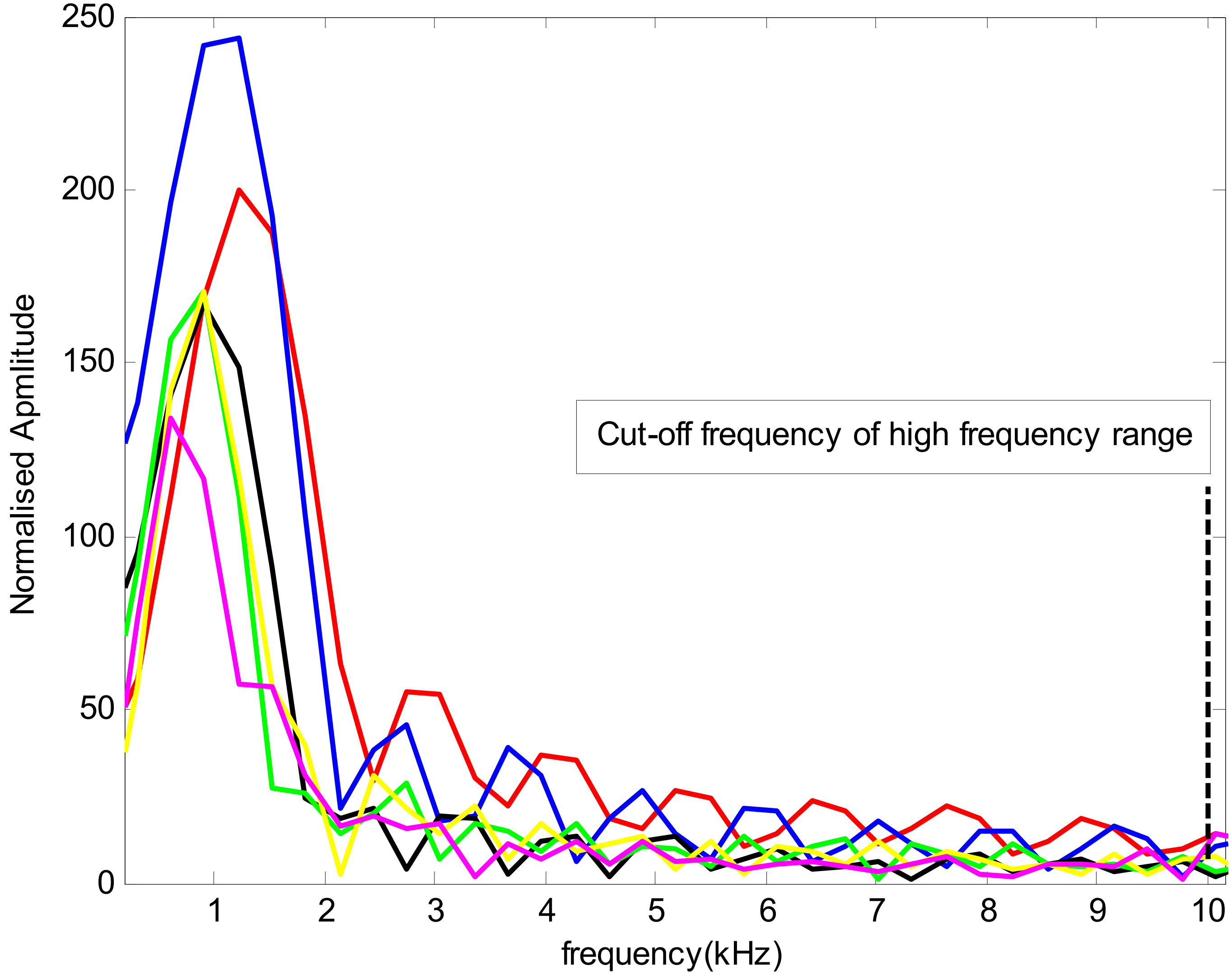


Surface wave signal is on environment vibration

Detected surface wave signal of signal layer agar phantom (concentration of 3.5%)

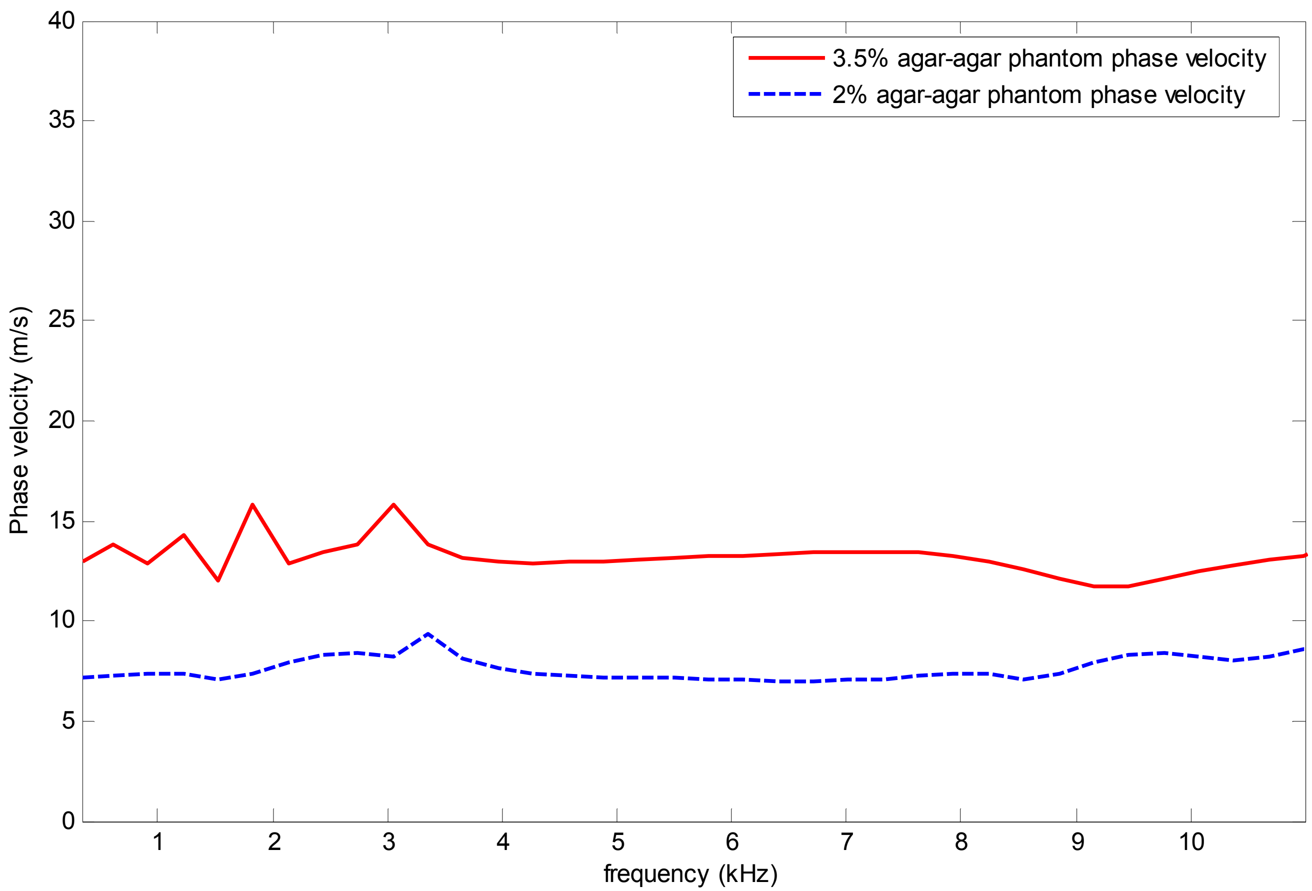


Signal processing – noise control



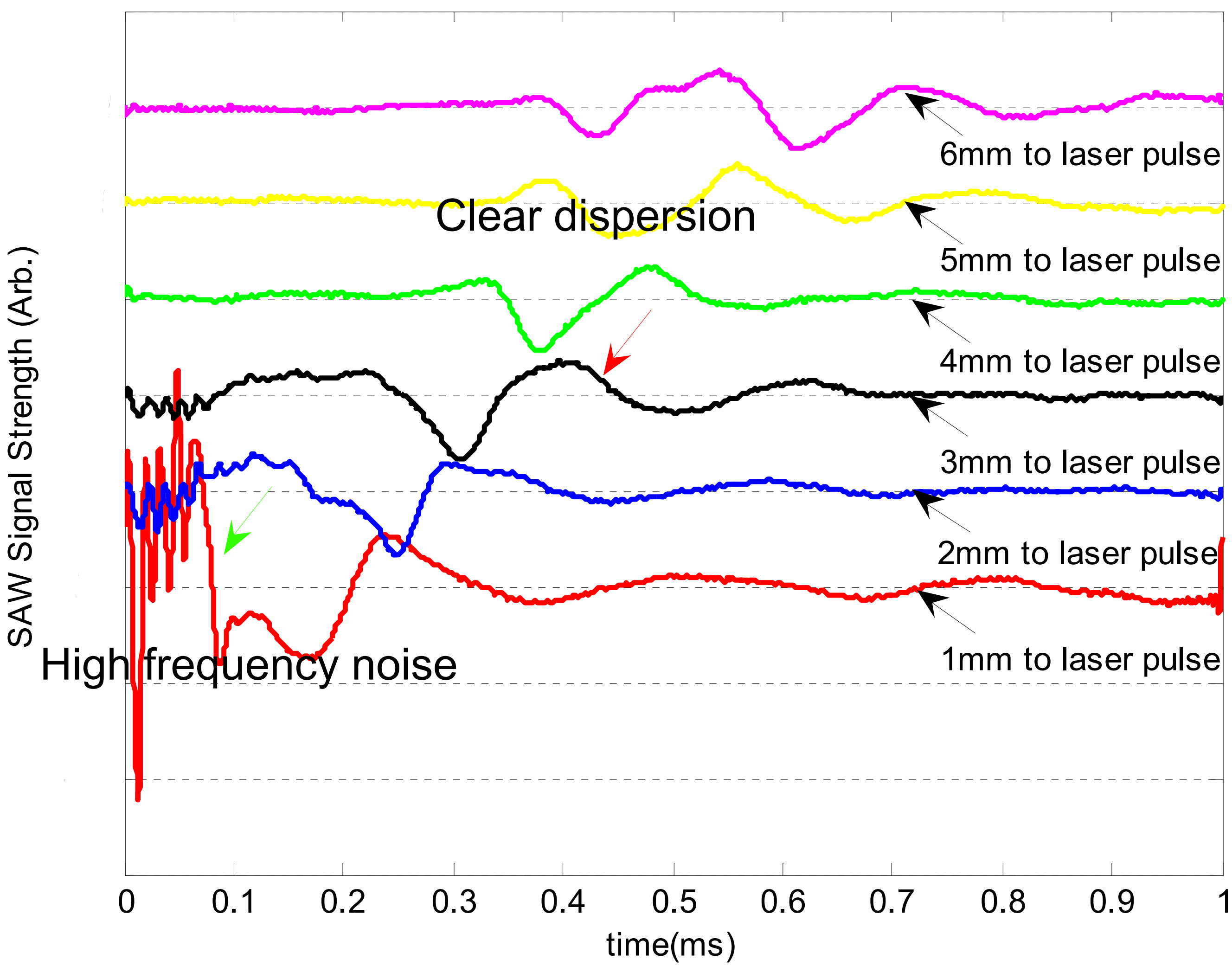
Available Frequency range of the signals

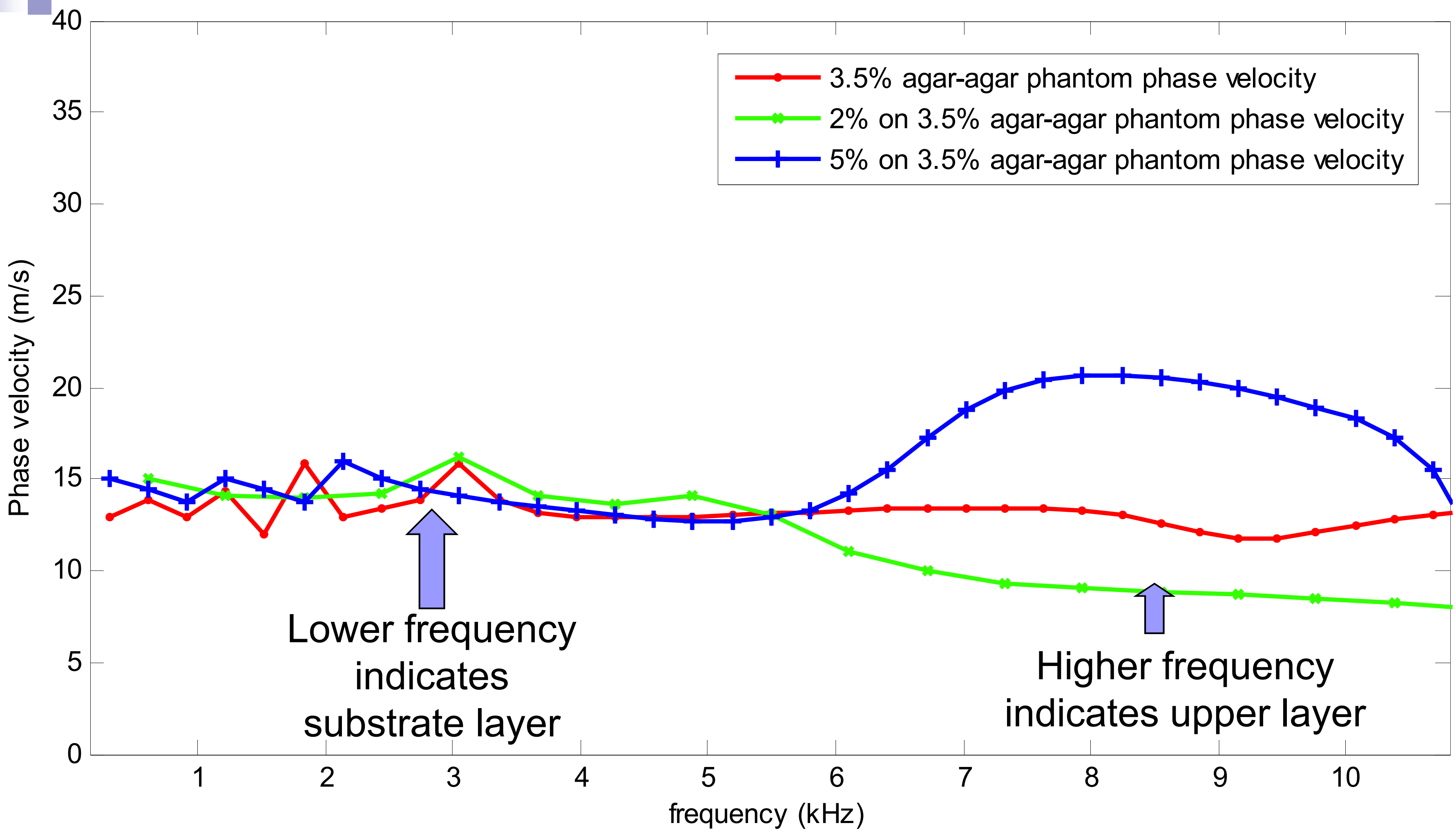
Phase velocity curve



- constant value presents homogeneous one layer sample.
- As the concentration of agar increasing, the Young's modulus of phantom will increasing
- the phase velocity also increases due to the impact of Young's modulus.

Detected surface wave signal of signal layer agar phantom (concentration of 2% agar on 3.5% agar)



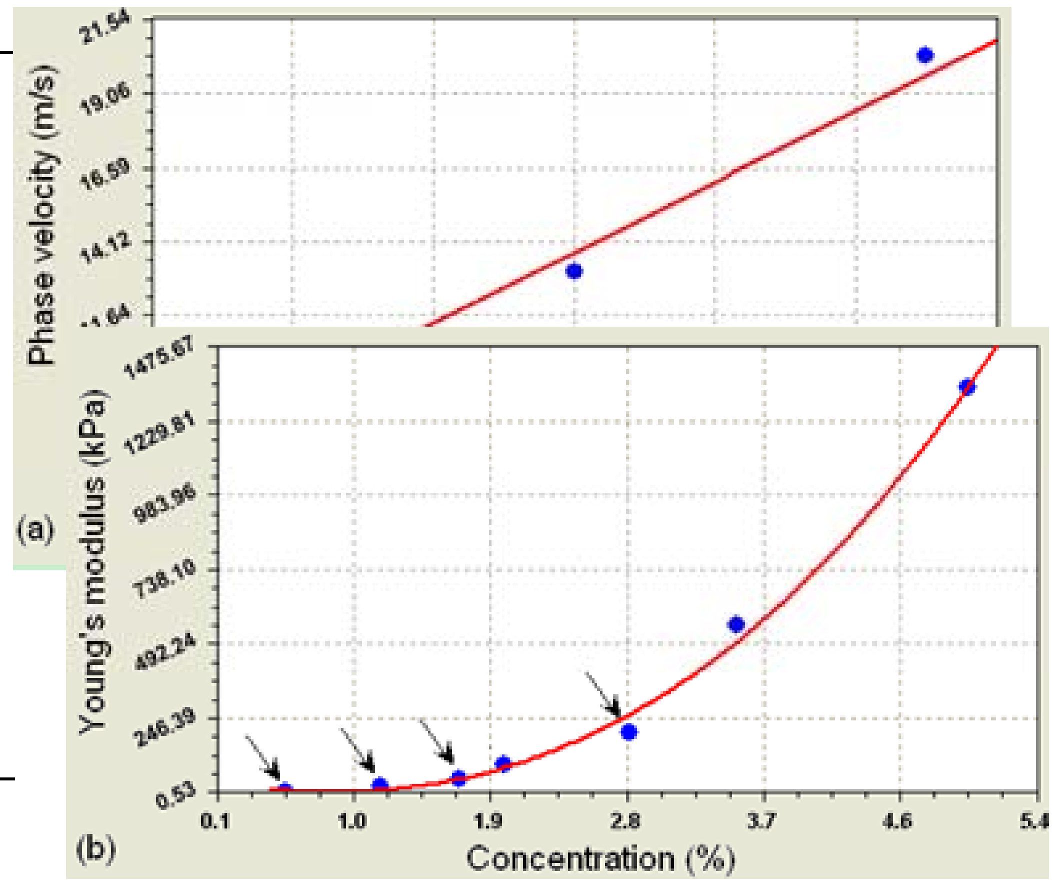


- Phase velocity curves are no longer a straight line, low frequency range indicates the substrate layer while upper layer indicates upper layer.

Inversion of experimental data

The relationships between the concentration of agar-agar phantom and the phase velocity are concluded in table. It indicates the linear relationship between different agar concentrations and their phase velocities.

Agar concentration	Phase velocity (m/s)	Young's modulus (kPa)
2%	7.93±1.56	93±8.24
3.5%	13.08±1.22	557±5.04
5%	20.3±1.25	1342±5.29



Discussion and Future work

- We used a laser line-source to generate SAW in different agar-agar phantoms with both one layer and two layers. The experiments provide very promising results.

- As there are no phase velocity dispersion in one layer sample, and clear phase velocity dispersion in two layers phantoms. Clear differences of phase velocity between different concentration of phantom samples, and with the increasing of concentration the phase velocity is increasing as well, with a linear relationship.

- The novel combination of Laser Ultrasonics and OCT system.