Distributed fiber sensing systems for 3D combustion temperature field monitoring in coal-fired boilers using optically generated acoustic waves (DE-FE0023031)

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Outline

- ❑ Brief overview of DOE project
- • Introduction
- ❑ Experimental results
- • Signal generator
- • Signal receiver
  - Fiber Bragg grating (FBG) fiber sensor
  - Fabry-Perot (F-P) fiber sensor
- • Temperature measurement
  - Water temperature measurement
  - Steel plate temperature measurement
  - Air temperature test and reconstruction
- • Distributed sensing capability test
- • GE pilot test
- • Furnace test
- • 2D/3D temperature distribution system
- ❑ Signal processing and temperature reconstruction
- ❑ Conclusions

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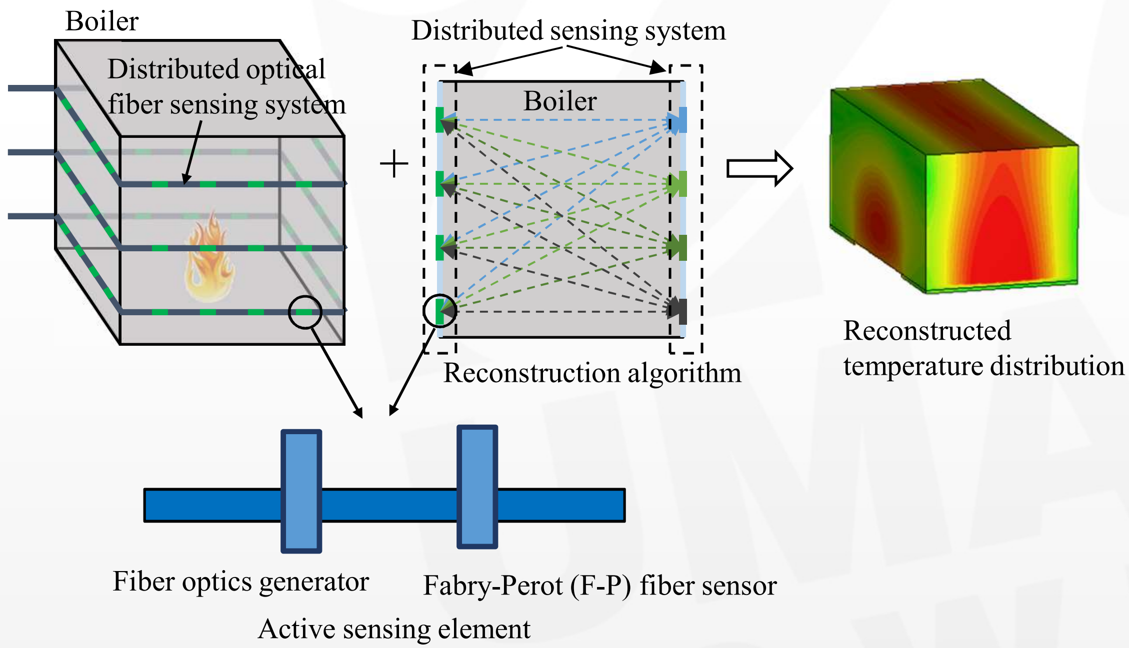
Introduction



Overview of DOE project.

- Reconstruct the 3D high temperature distribution within a boiler with a novel fiber optic distributed temperature sensing system that uses optically generated acoustic waves.

Introduction

- Speed of acoustic waves depend on the temperature of gaseous medium.

- The TOF (time-of-flight) of an acoustic signal over a propagation path can be calculated as:

$$TOF(l_j) = \int \frac{1}{C(x,y,z)} dl_j = \int \frac{1}{Z\sqrt{T(x,y,z)}} dl_j$$

$C(x,y,z)$ the velocity of sound at position (x,y,z)
z the ratio between the specific heats at constant pressure and volume of the gas
$d(x,y,z)$ the reciprocal of velocity
j the number of paths;

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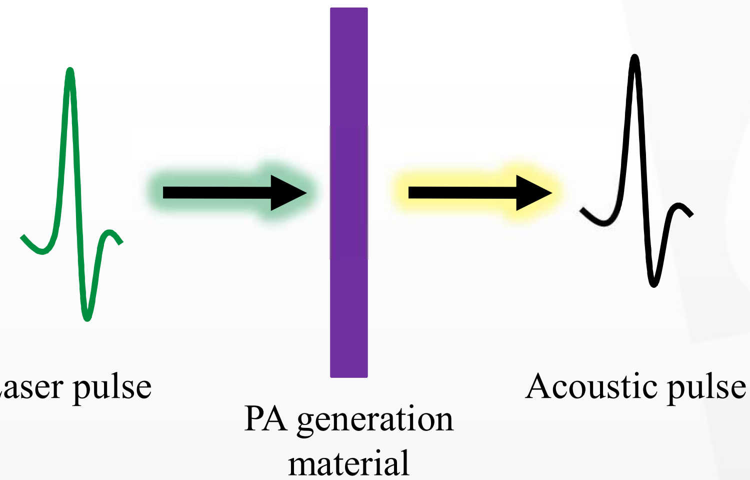
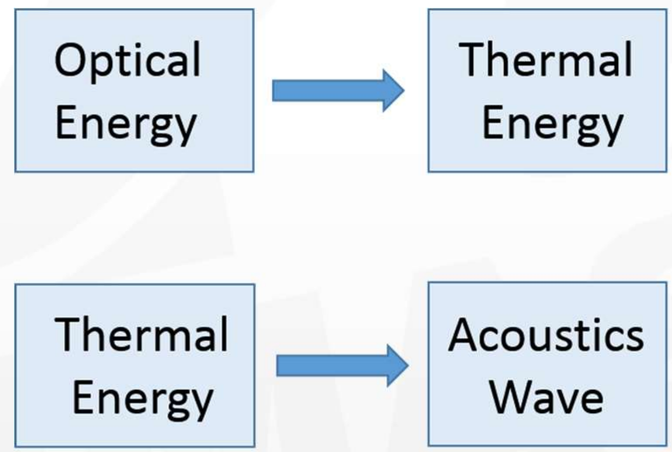
Photoacoustic



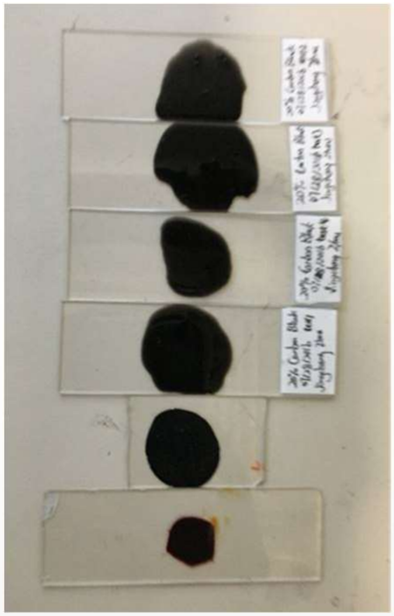
Photoacoustic definition



Photoacoustic principle

- Note: The PA principle is an optical approach to generate ultrasound signals. It involves a PA generation material which absorbs the optical energy from the laser and converts it into a rise in localized temperature.

Photoacoustic Materials



Carbon Black 1

Carbon Black 2

Carbon Black 3

Carbon Black 4

Carbon Black 5

Gold-nanocomposite

Ultrasound signal strength generated by different photoacoustic materials

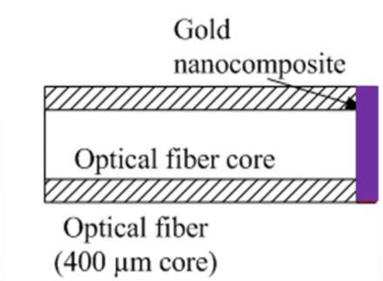
	First Test (mV)	Second Test (mV)	Third Test (mV)	Average (mV)
Carbon Black 1	3.0	3.0	2.8	2.93
Carbon Black 2	2.9	2.5	2.6	2.67
Carbon Black 3	2.2	2.2	2.4	2.27
Carbon Black 4	2.4	2.6	2.5	2.50
Carbon Black 5	2.1	2.1	2.2	2.13
Gold Nanocomposite	2.5	2.2	2.3	2.33

Different photoacoustic materials

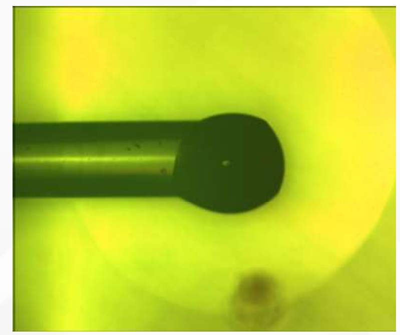
- Carbon Black 1-4 are 20% Carbon black (partial size 20 nm) + PDMS.
- Carbon Black 5 is 20% Carbon black (partial size 101 nm) + PDMS.
- Gold-nanocomposite is 12% Gold-nanoparticle + PDMS.
- Carbon Black 5 had the lowest ultrasound signal, due to it being used many times, which may have caused damage to it.
- Carbon Black 3 generated a low ultrasound signal because the thickness and the size of it was smaller than the others.

Tip generator

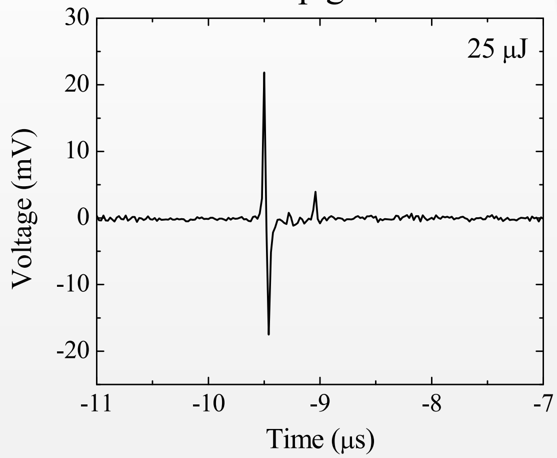
Photoacoustic materials coated on fiber tip



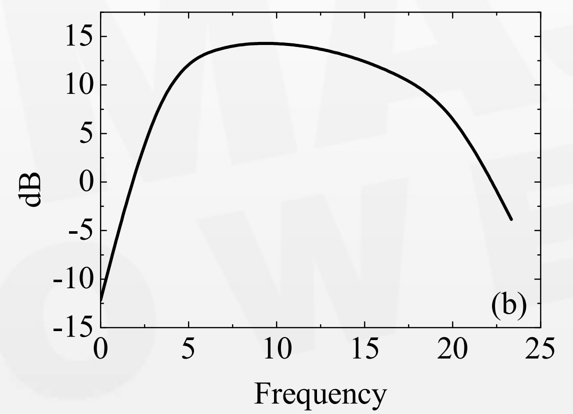
Structure of the tip generator



Microscope photo of the tip generator [1]



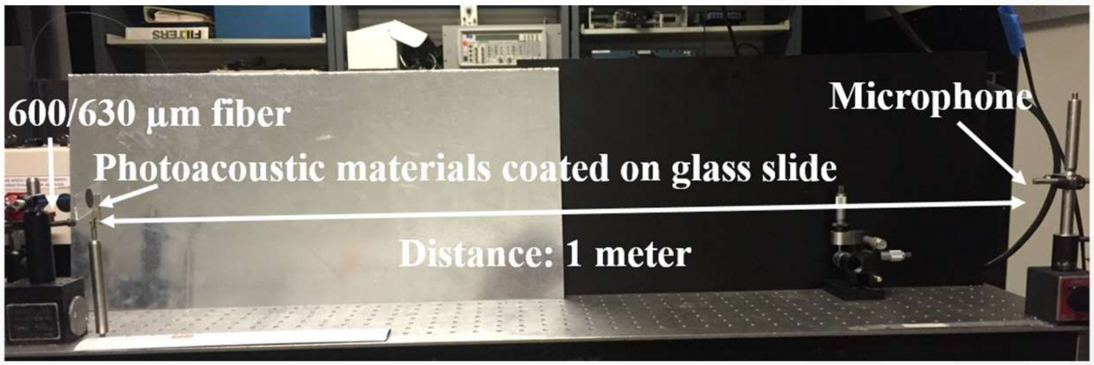
Profile of ultrasound signal [2]



Bandwidth is wider than 20 MHz

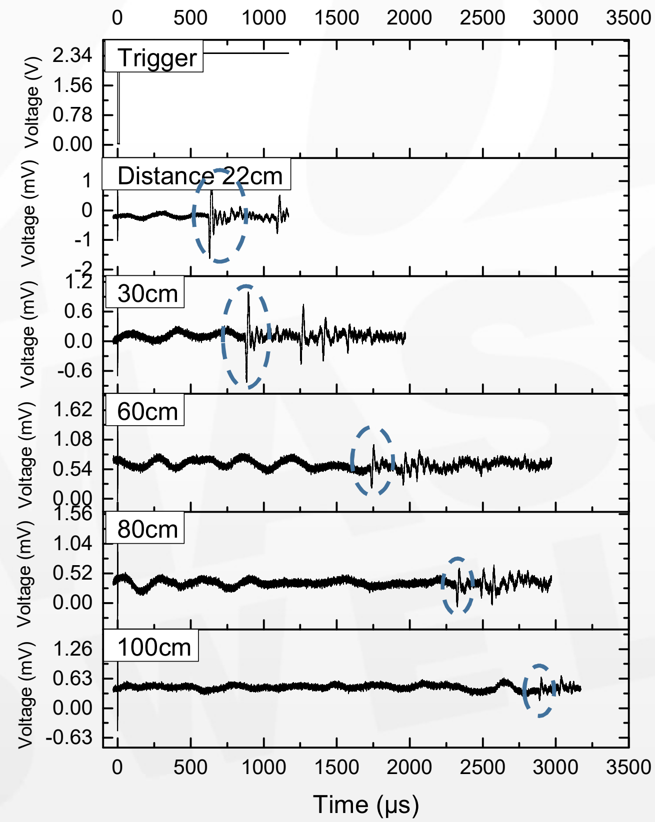
Tip generator

Photoacoustic materials coated on glass slide



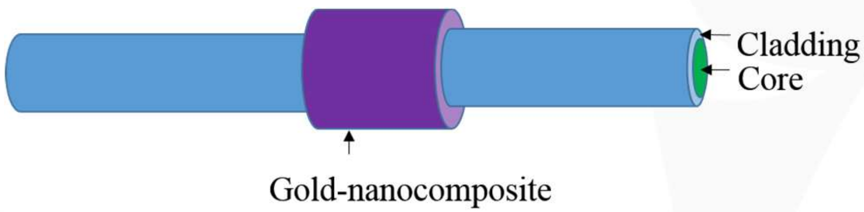
Experimental setup

◆ Note: This fiber optic ultrasound transducer system worked at a distance of 1 meter. 600/630 μm fiber and photoacoustic materials (Carbon black + PDMS) were used in this system. Photoacoustic materials were coated on glass slides.

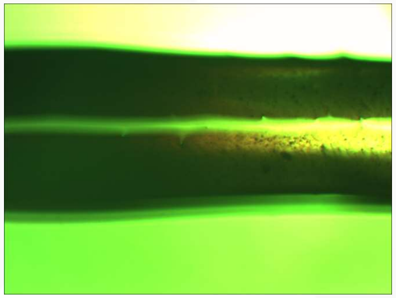


Ultrasound signals at different distances.

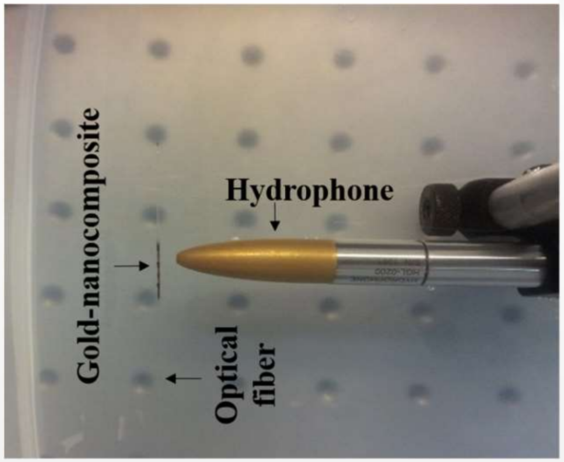
Sidewall generator 1



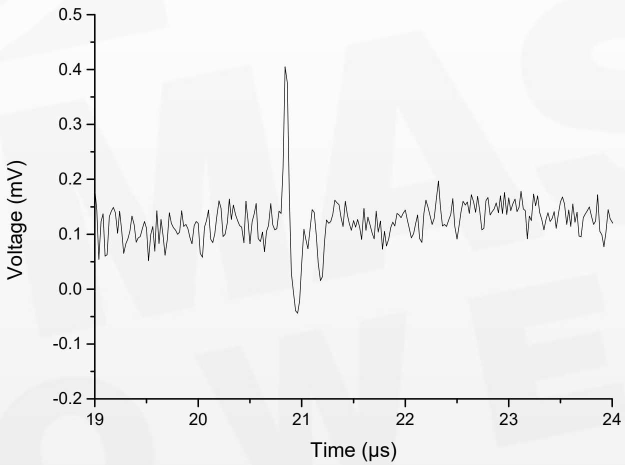
Coat gold nanocomposite on the sidewall of optical fibers [4].



Sidewall ultrasound generator configuration 1.



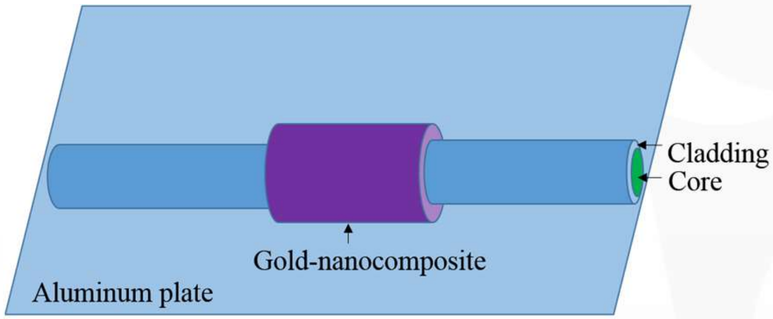
Experiment setup: test a sidewall generator.



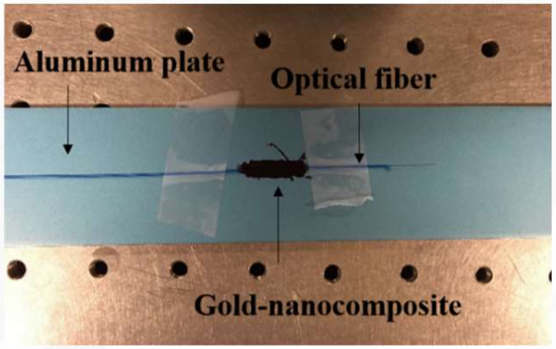
Acoustic signal generated from sidewall configuration 1.

- Note: Generated ultrasound signal was from the sidewall of a 400/425 μm fiber. A 532 nm Nd:YAG nanosecond laser (Surelite I-10, Continuum) was utilized as the optical radiation source. A hydrophone (HGL-0200, Onda) was used as a receiver to collect the ultrasound signals.

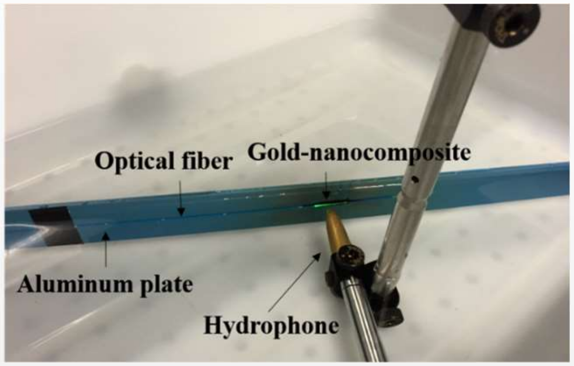
Sidewall generator 2



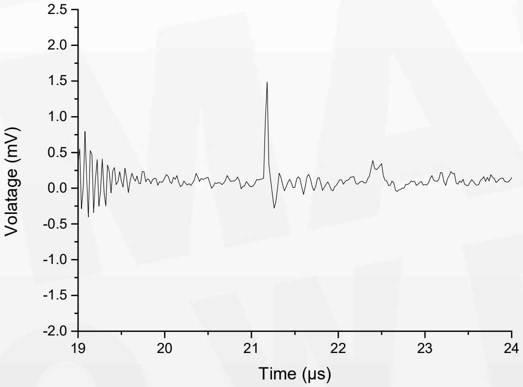
Sidewall fiber generator mounted on an aluminum plate [4].



Sidewall ultrasound generator configuration 2.



Experimental setup: test the sidewall ultrasound generator configuration 2.

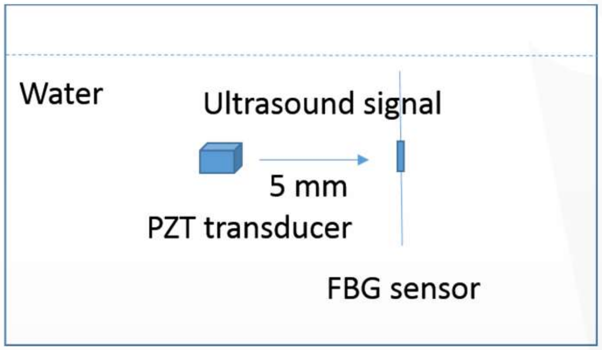


Acoustic signal generated from sidewall ultrasound generator configuration 2.

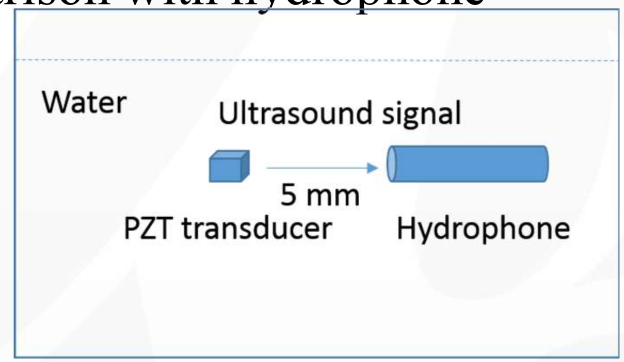
- Note: Ultrasound signal generated from this configuration on the aluminum plate was much higher than previous configuration when the laser power and detection distance is the same.

Fiber Bragg Grating (FBG) fiber sensor

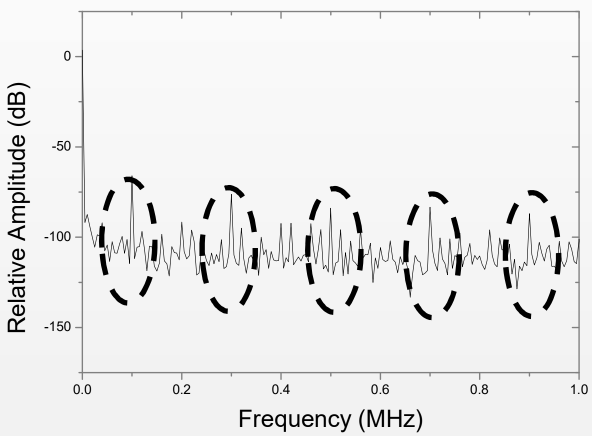
Fiber Bragg Grating performance comparison with hydrophone



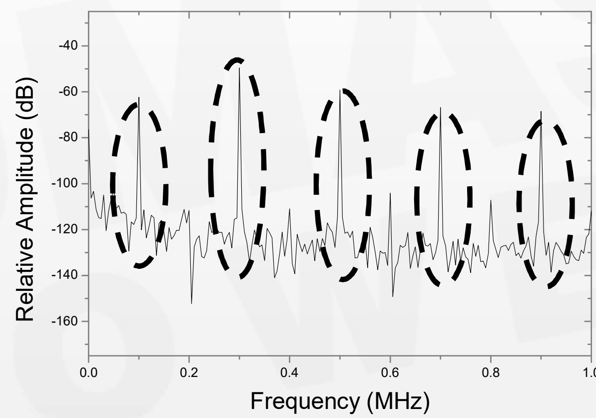
PZT as signal generator, FBG as signal receiver



PZT as signal generator, Hydrophone as signal receiver



Ultrasound signal received by FBG in frequency domain

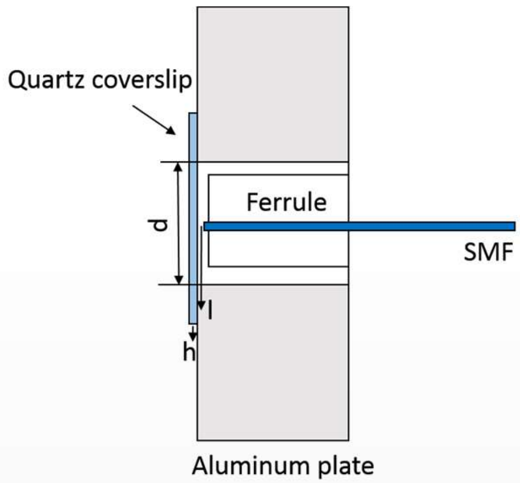


Ultrasound signal received by Hydrophone in frequency domain

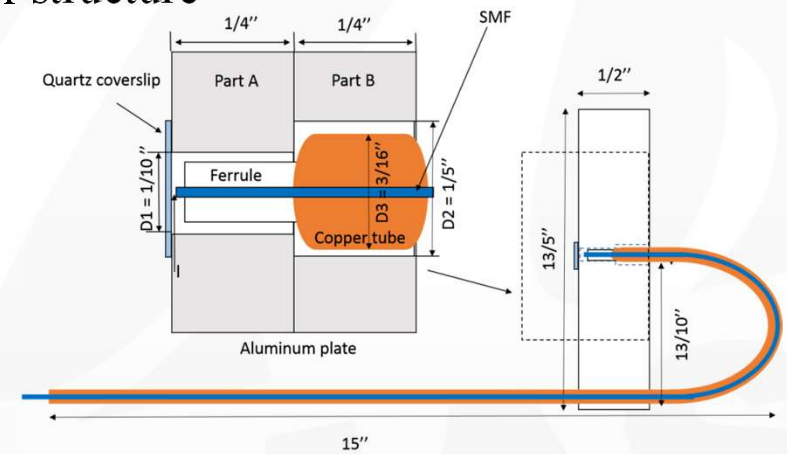
- Note: FBG fiber sensor got same results as hydrophone in the frequency domain. It showed that the FBG fiber sensor could be used to detect the ultrasound signal in water.

Fabry-Perot (F-P) fiber sensor

F-P fiber sensor structure



Structure of the F-P fiber sensor



Packaging of the F-P fiber sensor

Sensitivity (How much the center of the diaphragm will be deformed when a certain acoustic pressure applied on it):

$$Y_c = \frac{3(1-\mu^2)(d/2)^4}{16Eh^3} \cdot 10^9 \ (nm/Pa)$$

E is the quartz's Young's modulus, $E = 7.2*10^{10}$ Pa;
μ is the quartz Poisson ratio, $\mu = 0.17$;
h is the thickness of the quartz coverslip, $h = 0.10$ mm;
d is the diameter of the aluminum hole, $d = 2.54$ mm;
$Y_c = 0.0032$ nm/Pa.

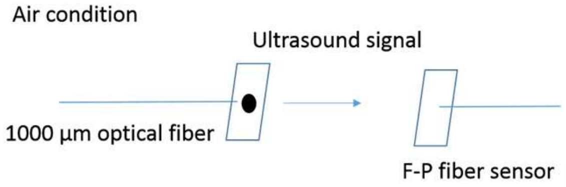
Resonant Frequency:

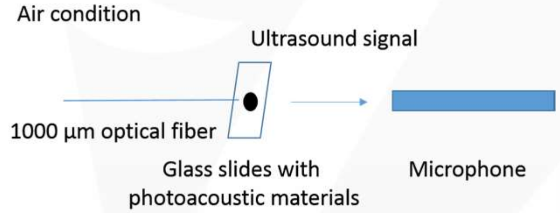
$$f_{00} = \frac{\alpha_{00}}{4\pi}\left[\frac{E}{3w(1-\mu^2)}\right]^{1/2}\left[\frac{h}{(d/2)^2}\right] \ Hz$$

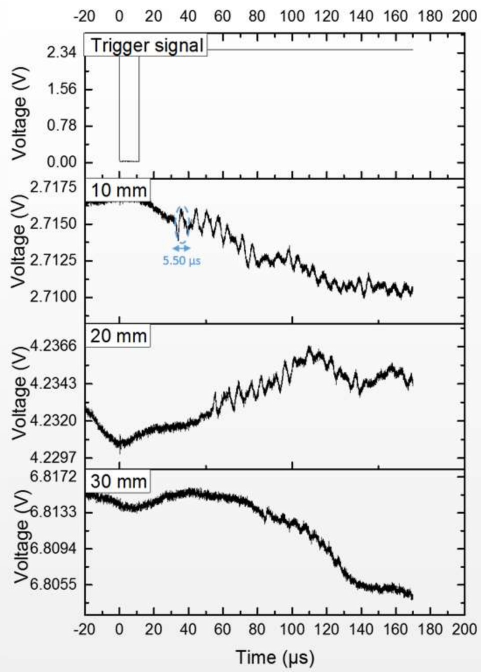
f_{00} is the lowest resonant frequency;
α_{00} is a constant related to the vibrating modes, $\alpha_{00} = 10.21$;
w is the mass density of the quartz, $w = 2.50$ g/cm^3.
E is Young's modulus of quartz coverslip, $E = 7.20*10^{10}$ Pa;
μ is the Poisson ratio of quartz, $\mu = 0.17$;
h is the thickness of the diaphragm, $h = 0.10$ mm;
d is the diameter of the diaphragm, $d = 2.54$ mm.
f_{00} could be calculated as 1.8805e+05 Hz which is 0.19 MHz.

Fabry-Perot (F-P) fiber sensor

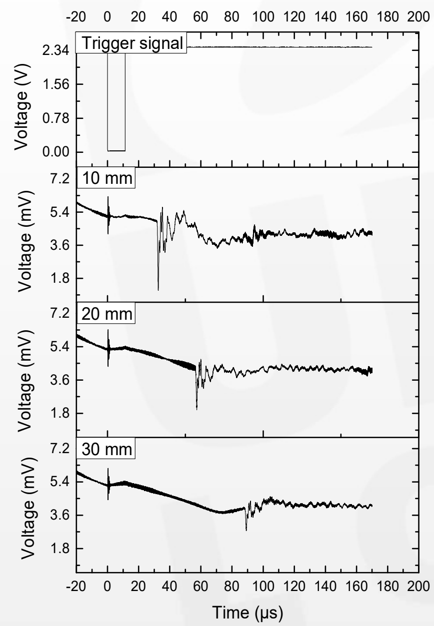
F-P fiber sensor performance comparison with microphone







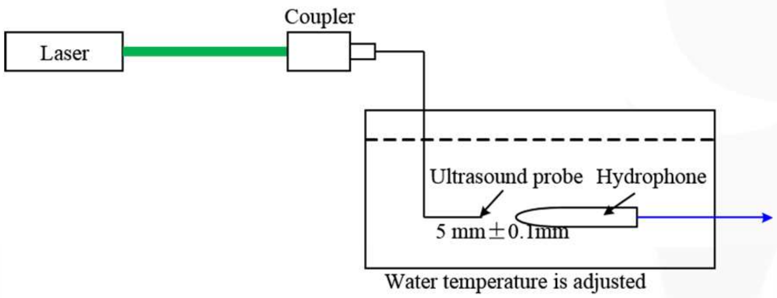
Ultrasound signal detected by
F-P fiber sensor (V20161202TEST2)



Ultrasound signal detected by
PCB microphone

- At the distance of 10 mm, the Vpp from the microphone and the FP sensor was 4.50 mV and 2.23 mV, respectively.
- The F-P fiber sensor (V20161202TEST2) has half the sensitivity of the microphone.
- The sensitivity of the microphone is 22.51 mV/Pa. Therefore, the F-P fiber sensor is 11.25 mV/Pa.
- The time cycle of the ultrasound signal detected by the F-P fiber sensor is shown on the left Fig which was 5.50 µs.
- The frequency was calculated as: $\frac{1}{5.50\ \mu s} = 0.18$ MHz.
- It was very close to 0.19 MHz, meaning it matched the resonant frequency calculation results.

Water temperature measurement



Schematic diagram of the water temperature measurement setup [1].

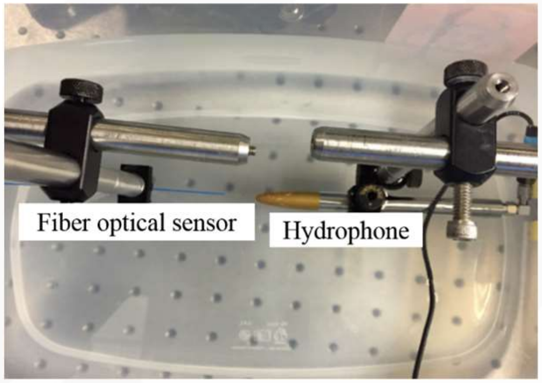
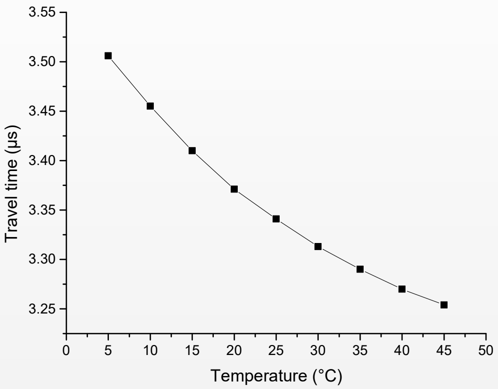
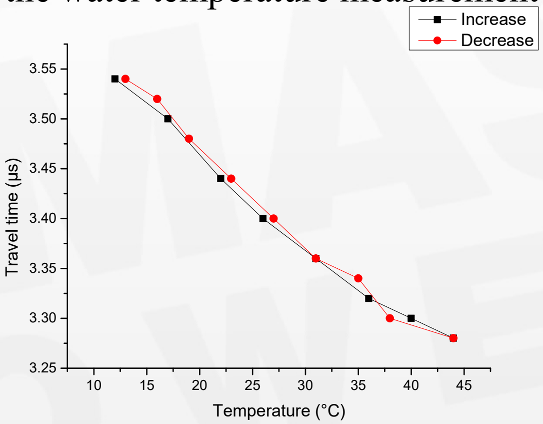


Photo of the water temperature measurement setup.



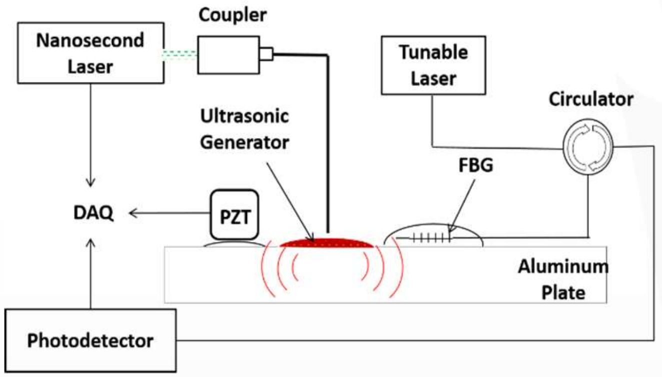
Travel time vs water temperature based on Marczak equation.



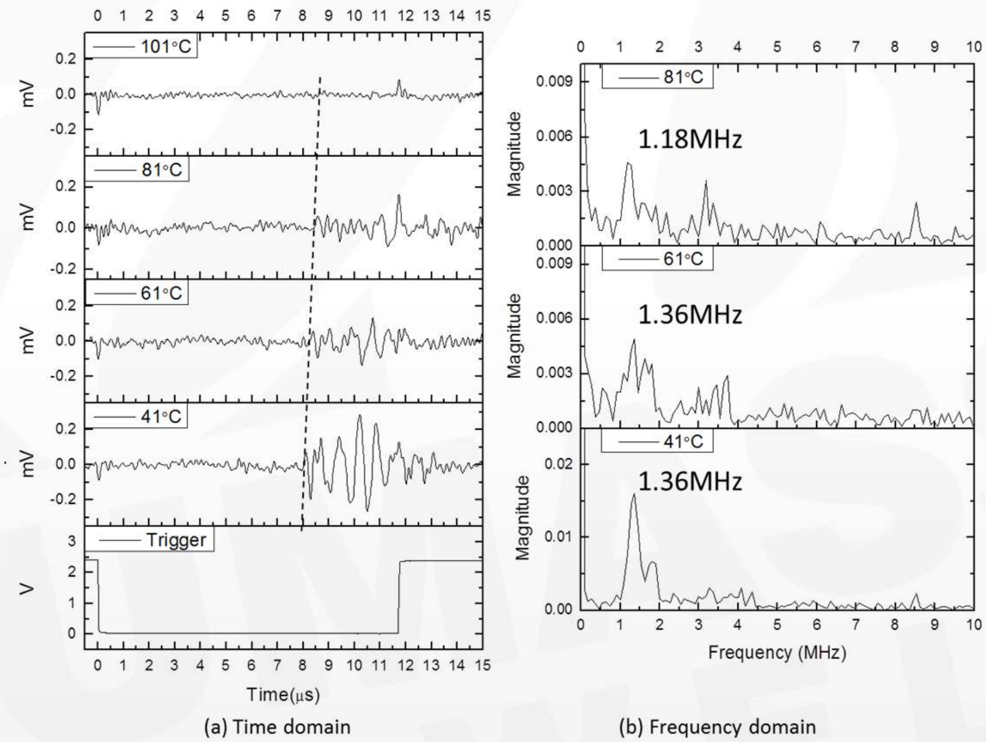
Experimental results: water temperature vs travel time

- Note: It demonstrated the temperature measurement capability of the fiber optic ultrasound transducer system in water.

Aluminum plate temperature measurement



Schematic diagram of steel plate temperature measurement [5].



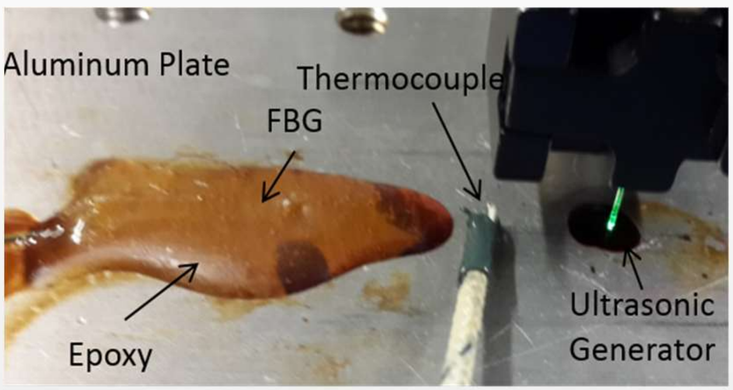


Photo of the Aluminum plate temperature measurement

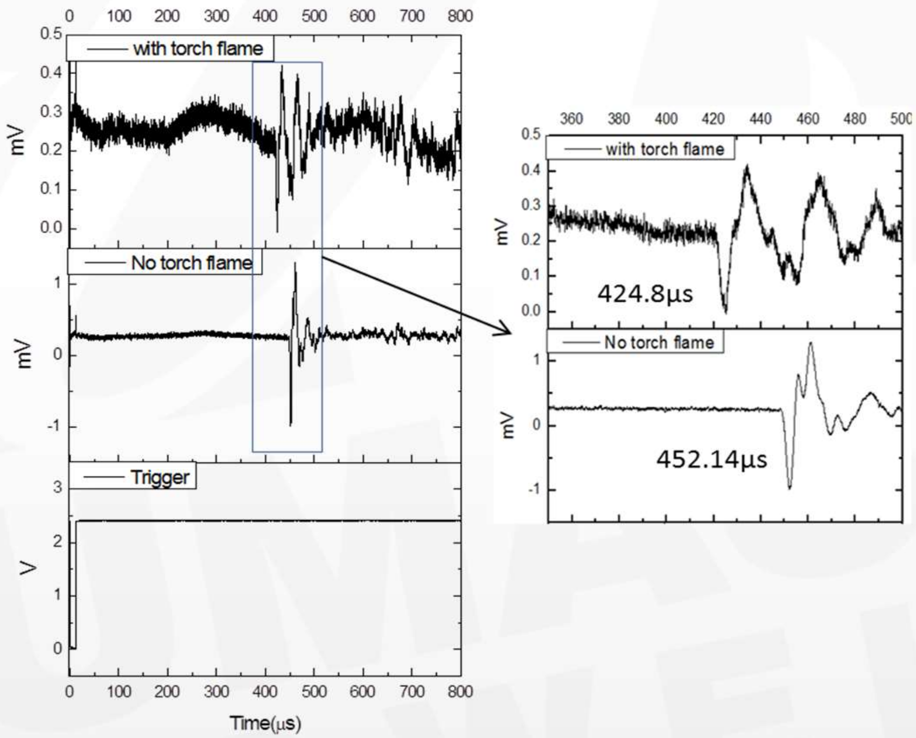
Experimental results of aluminum plate temperature test in (a) time domain and (b) frequency domain by FBG

- Note: FBG fiber sensor was used as the signal receiver in the solid condition. It proved the fiber optic ultrasound transducer system.

Air temperature test

Experimental setup: Measure the temperature of a torch flame.

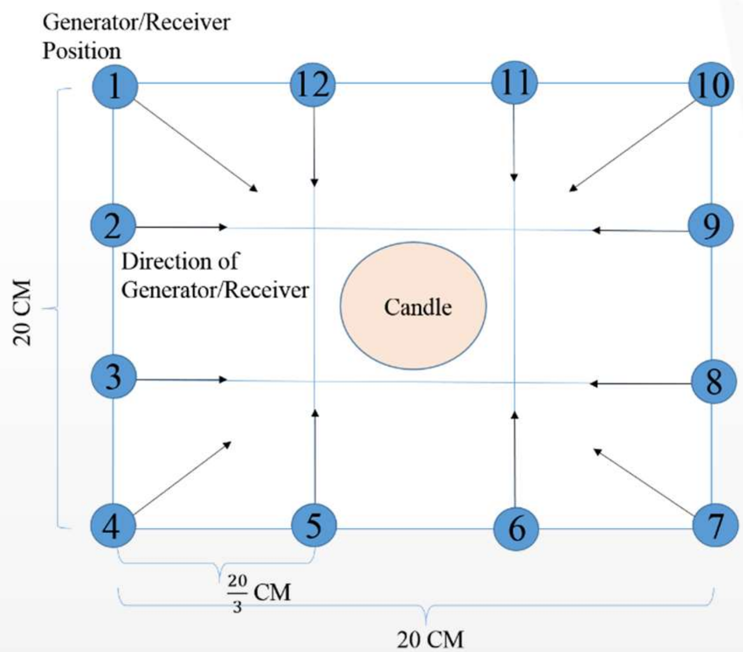
Experimental results of air temperature test in frequency domain.



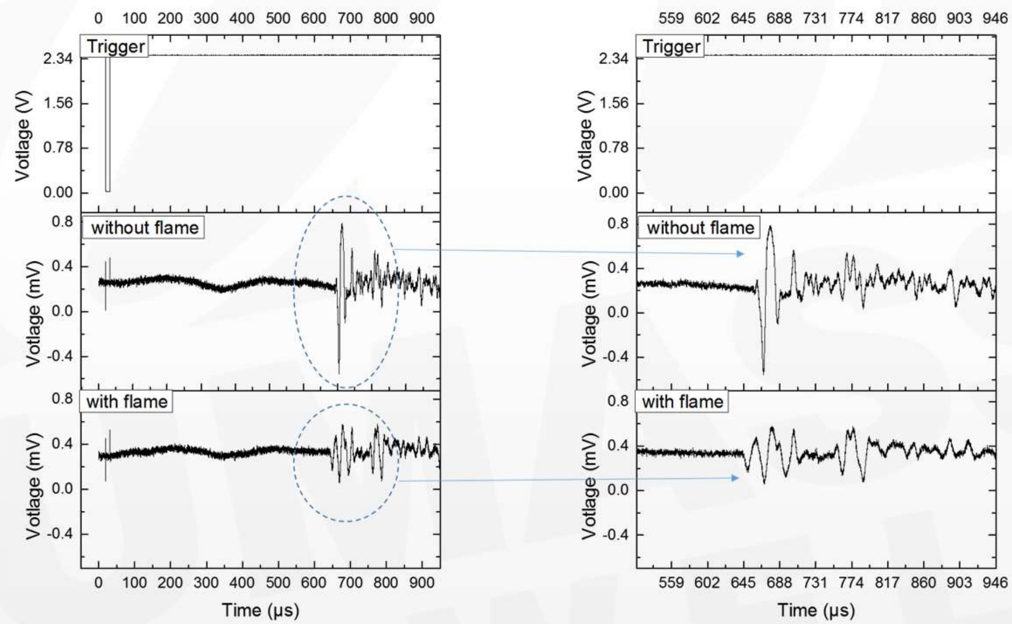
Experimental results of air temperature test in time domain.

- Note: It demonstrated that fiber optic ultrasound transducer system was able to measure the air temperature.

Air temperature reconstruction



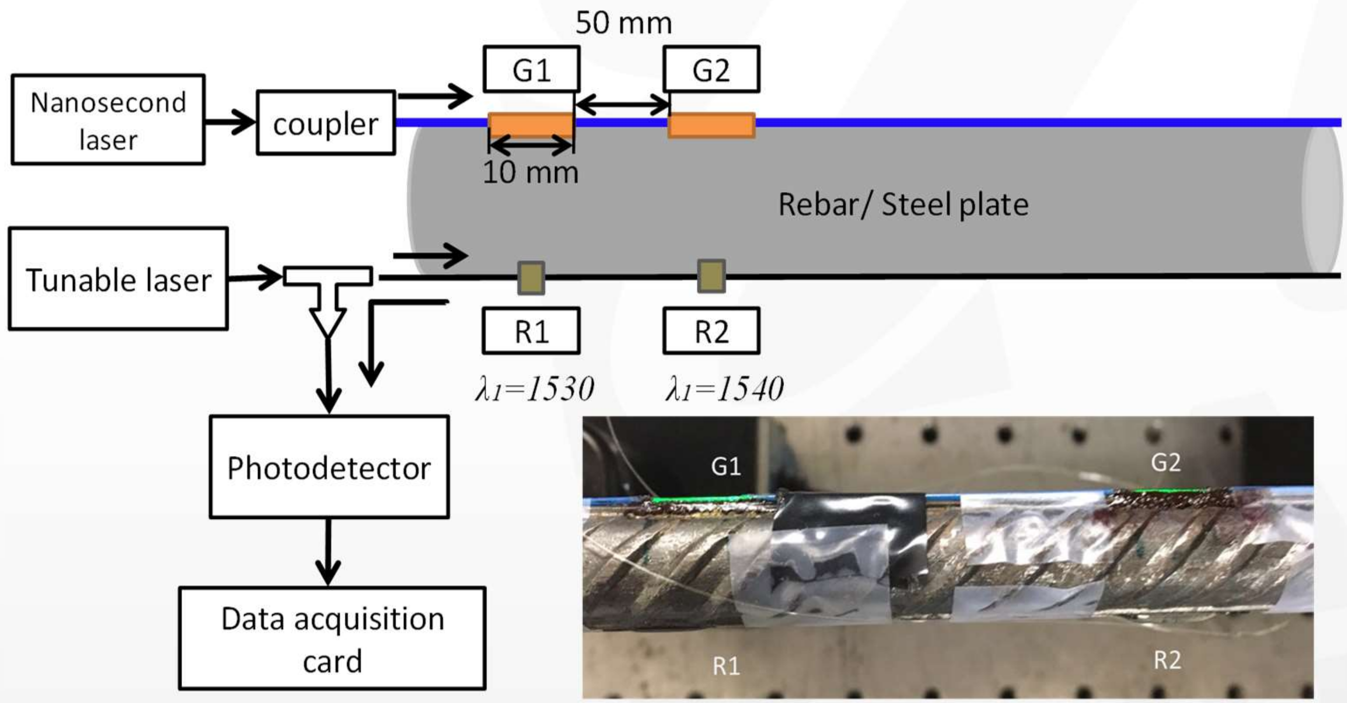
Air temperature test experimental setup [11].
(Top view)



Ultrasound signal between positions 2 and 8

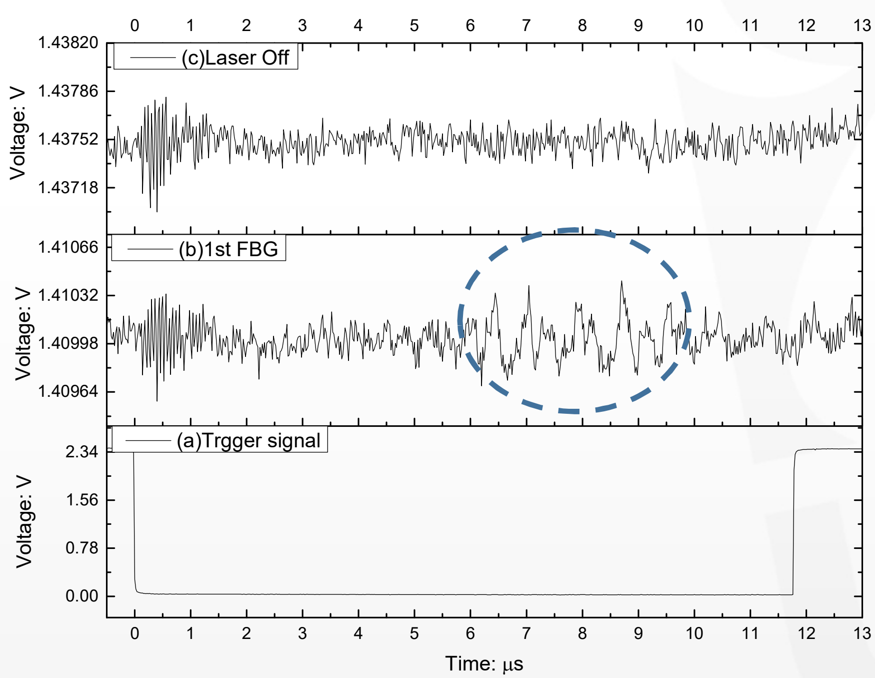
- Note: Air temperature reconstruction was done by using this fiber optic ultrasound transducer system [11].

Distributed sensing capability test

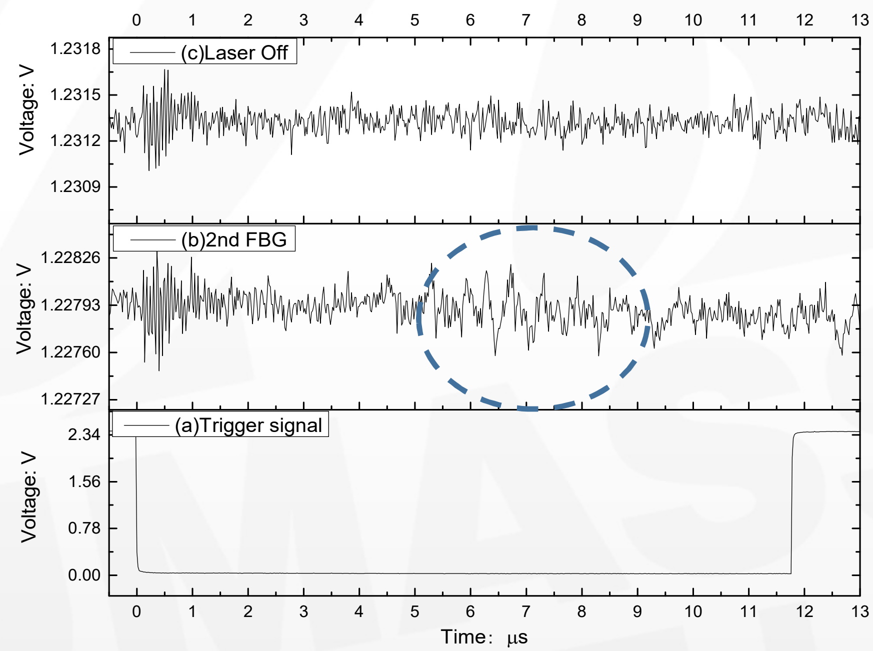


- Sidewall fiber generators (G1 and G2) and the FBG sensors (R1 and R2) were attached on the ridge of the rebar. The FBG sensors were attached along the ridge of rebar using epoxy.

Distributed sensing capability test



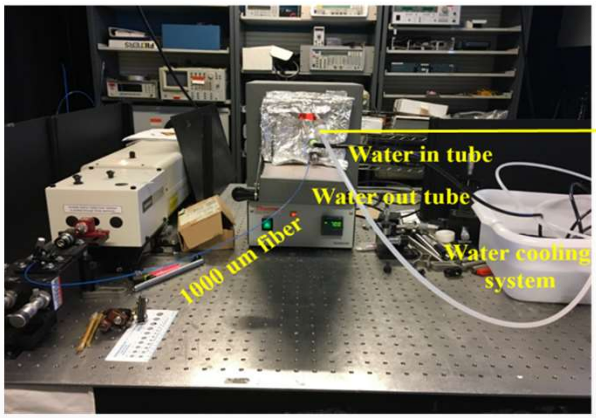
Ultrasound signal detected by R1

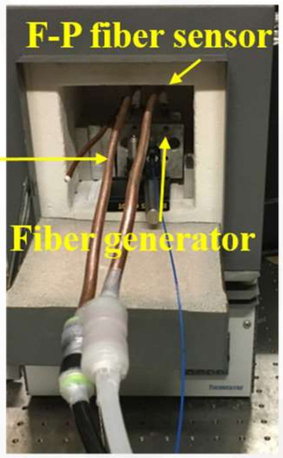


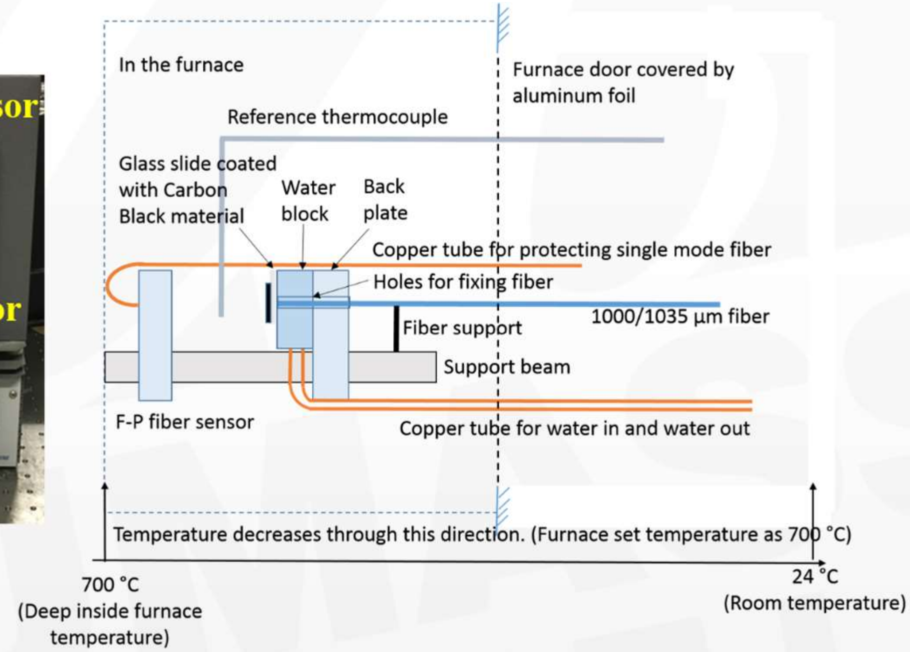
Ultrasound signal detected by R2

- Note: Ultrasound signal was detected in both receivers. This experimental demonstrated that the fiber optic ultrasound transducer system was able to use as multiple points at one time.

Furnace test

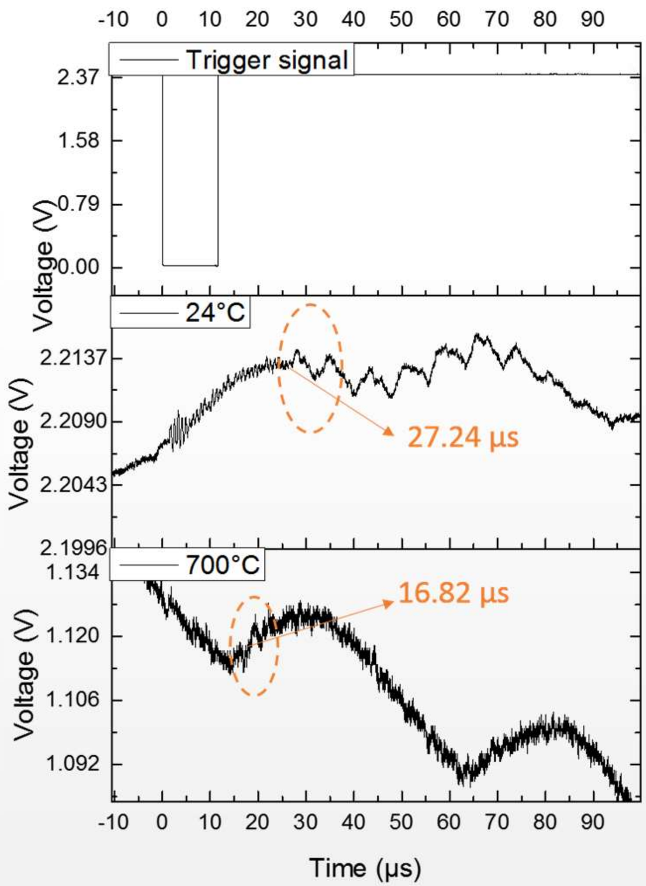




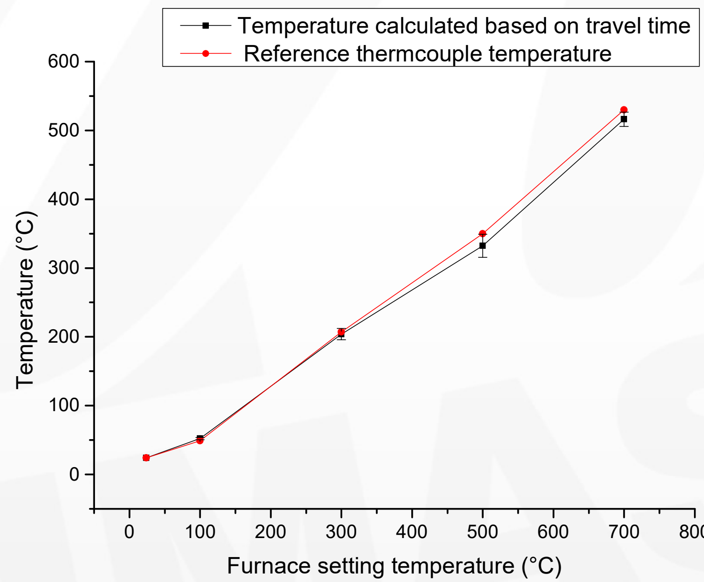


- Note: The F-P fiber sensor was used as the signal receiver. The Carbon Black shone by a 1000/1035 µm fiber was used as the acoustic signal generator. A water cooling system was used in this test. The distance between the generator and the receiver was fixed as 10 mm. The furnace temperature was set at room temperature (24ºC) to high temperature (700 ºC). The furnace door was covered by aluminum foil during the test.

Furnace test



Ultrasound signal when the furnace setting temperature at 24 ºC (room temperature) and 700 ºC, respectively.



Thermocouple reference temperature compared with temperature calculated based on travel time at the same furnace setting temperature

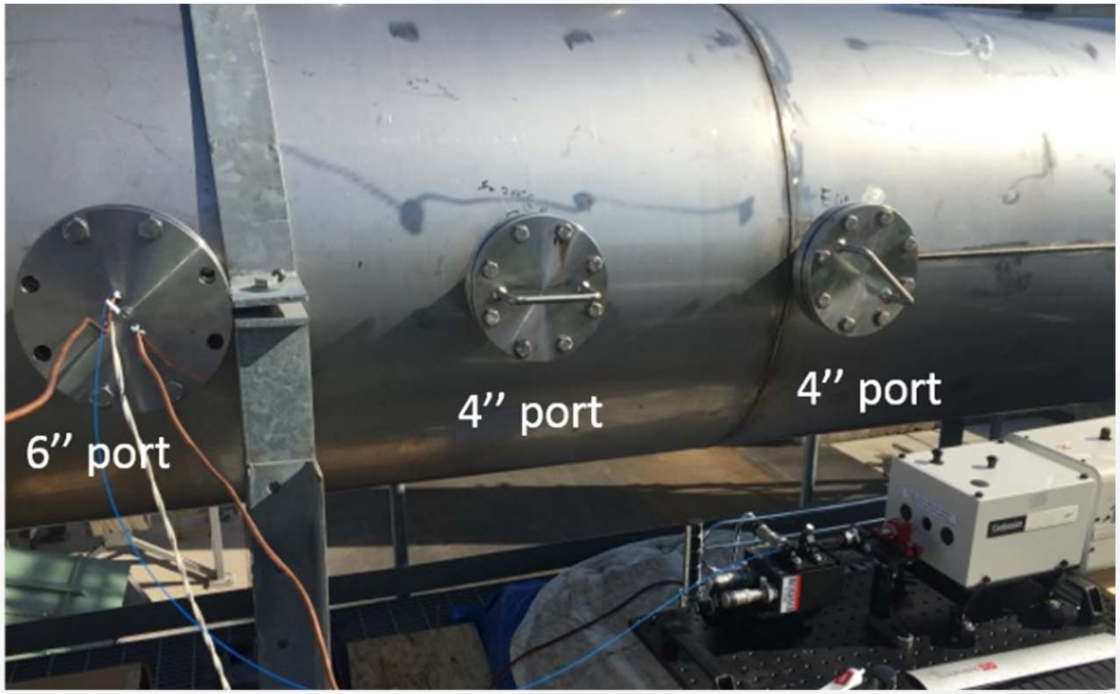
The sound speed was 345.549 m/s at 24 ºC (room temperature).

$$345.549\ \frac{m}{s} \times 27.24\ \mu s\ =\ 9.413\ \mathrm{mm}$$

$$\frac{9.413\ \mathrm{mm}}{16.82\ \mu\mathrm{s}}\ =\ 559.631\ \mathrm{m/s}$$

which was represented by 506.25 ºC according to the temperature and speed equation;

GE pilot test

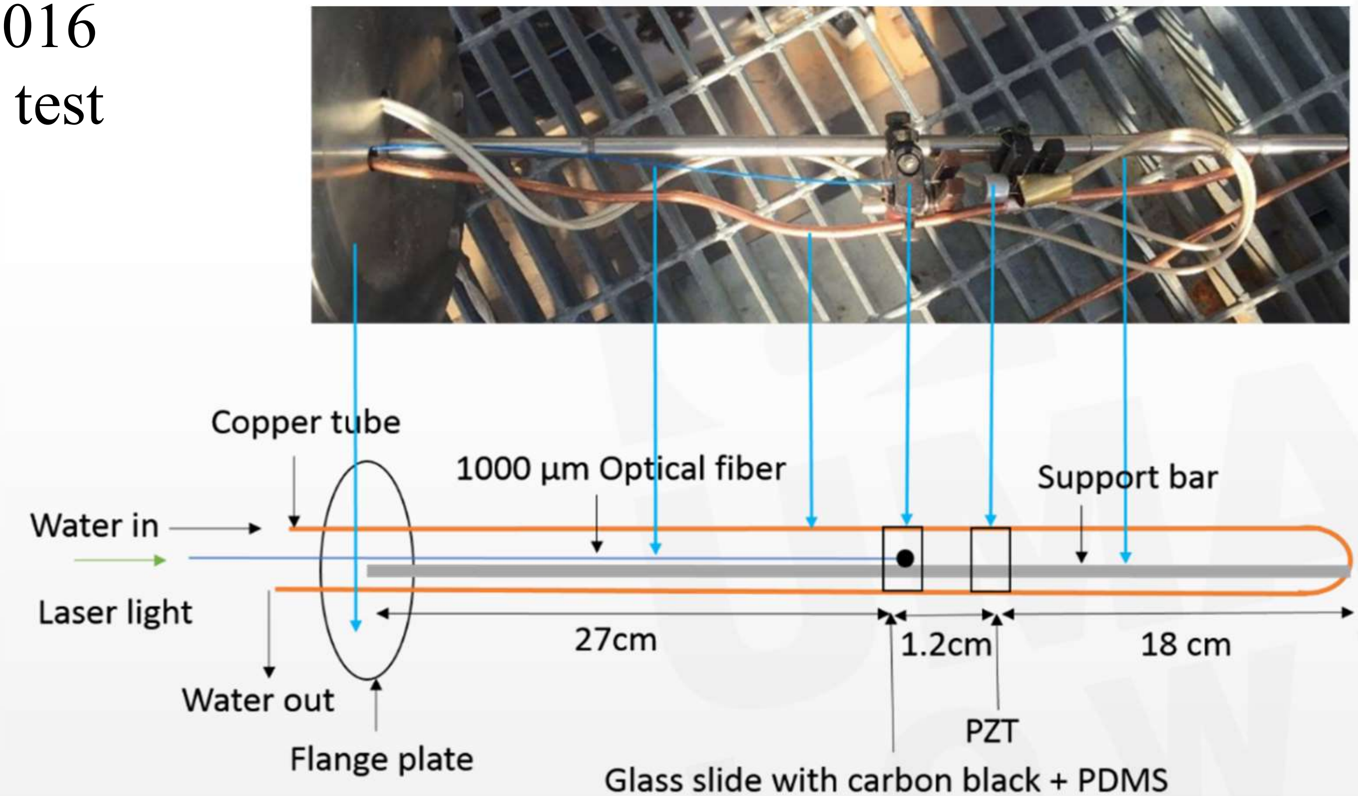


Testing port on exhausting pipe of the ISBF

◆ Note: The test location was chosen within an exhausting pipe of the ISBF. There are three standard ports along the pipe. The temperature within the pipe is around 480 ° F when the burner starts.

GE pilot test

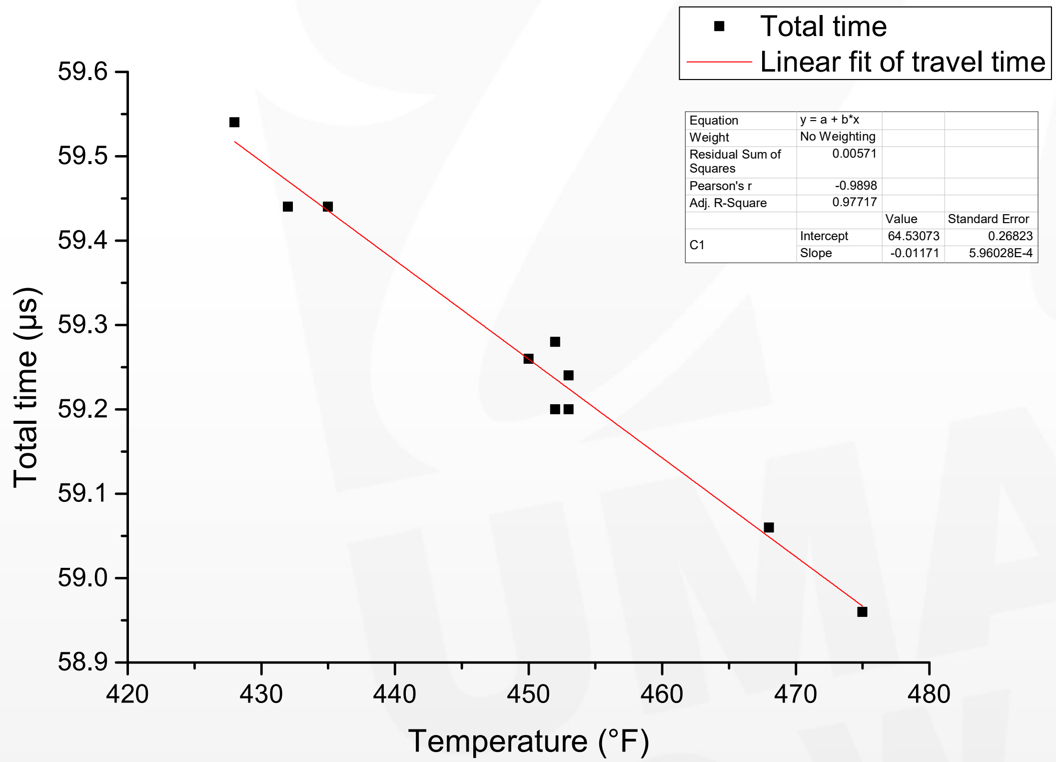
04-2016
Pilot test



Optical fiber sensor system 1, only the generator was made by fiber optics, the receiver was a PZT transducer.

GE pilot test

04-2016
Pilot test

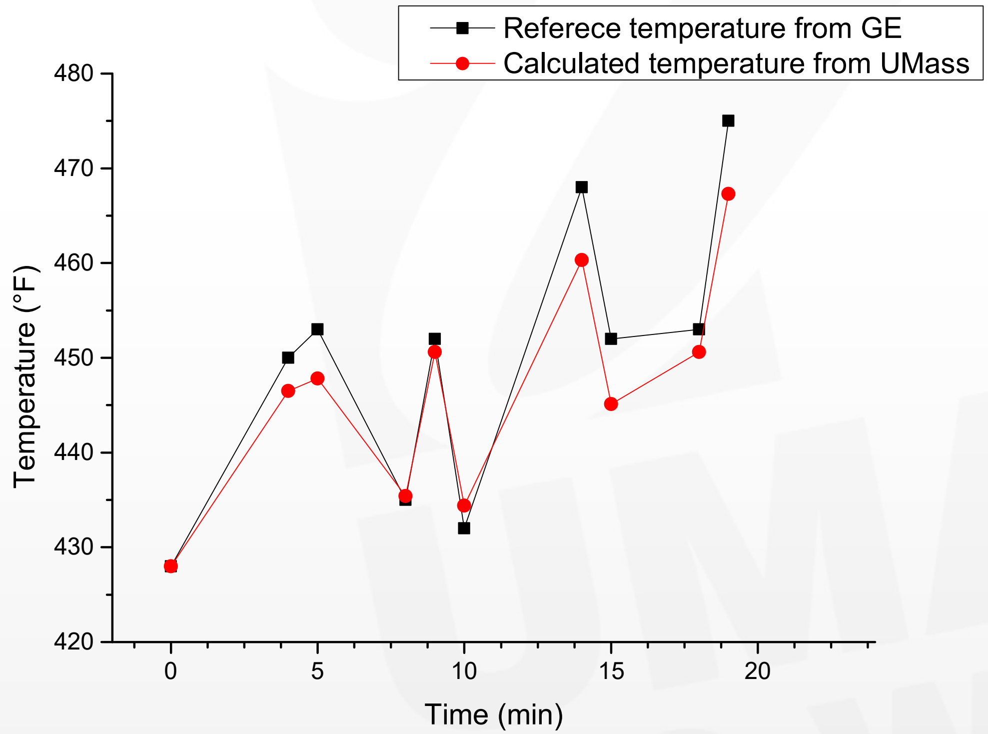


Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	0.00571		
Pearson's r	-0.9898		
Adj. R-Square	0.97717		
		Value	Standard Error
C1	Intercept	64.53073	0.26823
	Slope	-0.01171	5.96028E-4

- The above figure shows the 04-2016 pilot test data.
- The y value are the total time measured by UML sensor, the x value are the reference temperature provided by GE ref. sensor.
- The relationship between the reference temperature and the total time is linear which proves that the sound speed is directly proportional to the medium's temperature.

GE pilot test

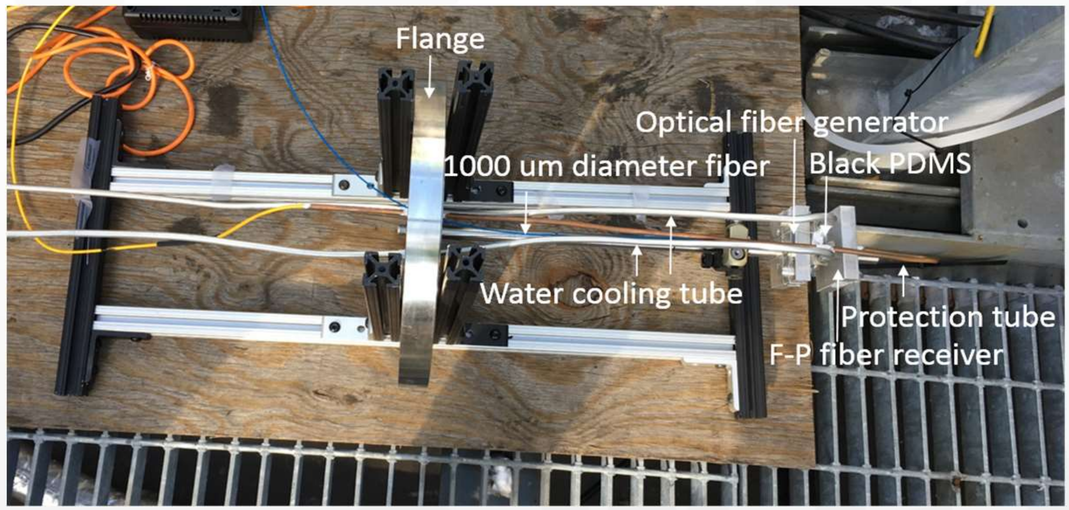
04-2016
Pilot test



- The above figure shows the 04-2016 pilot test data.
- The black points are the temperature information from GE Reference sensor.
- The red points are the temperature information calculated from UML test sensor.

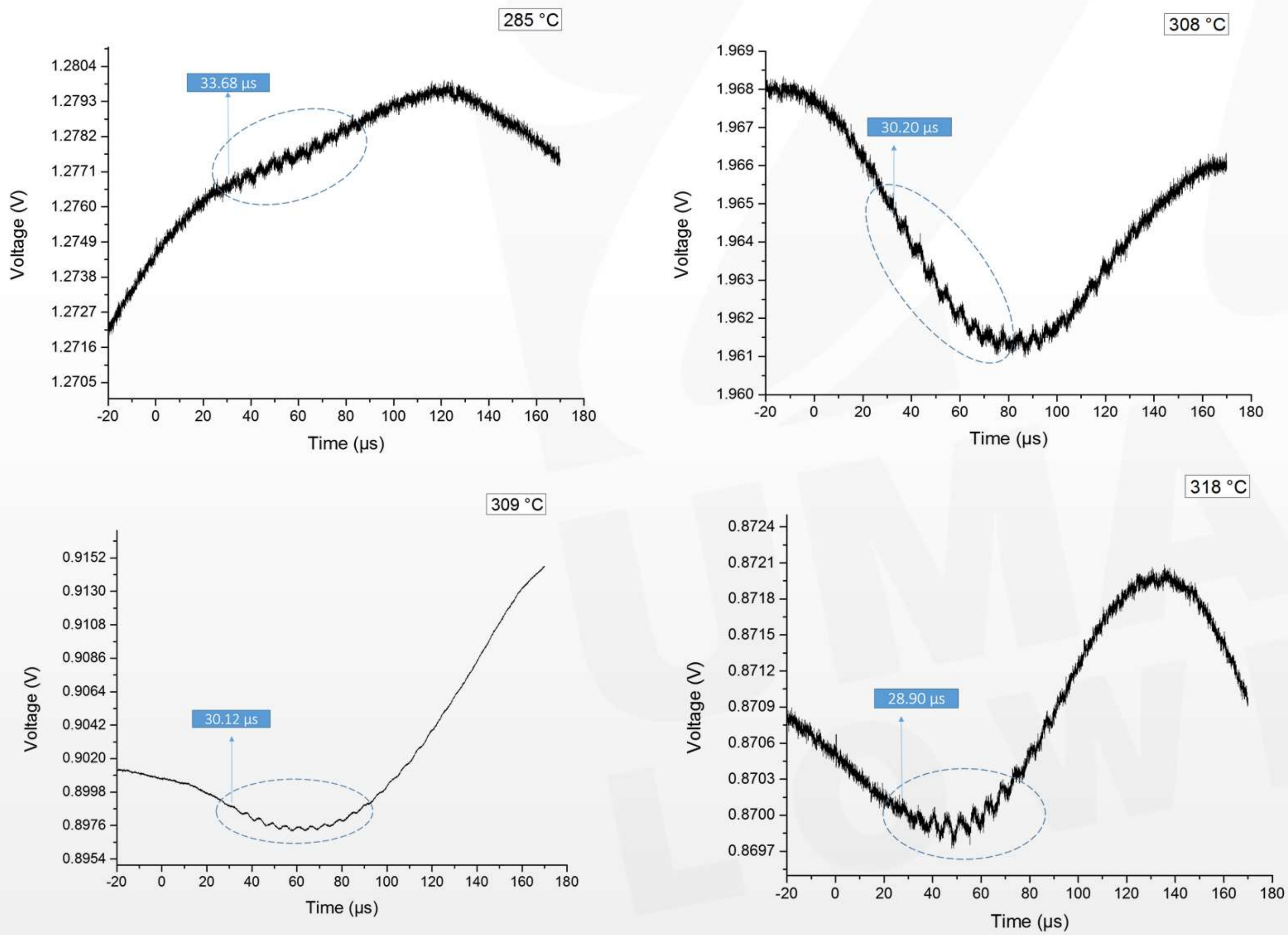
GE pilot test

08-2017
Pilot test



Optical fiber sensor system 2, the generator and receiver were both made by fiber optic systems.

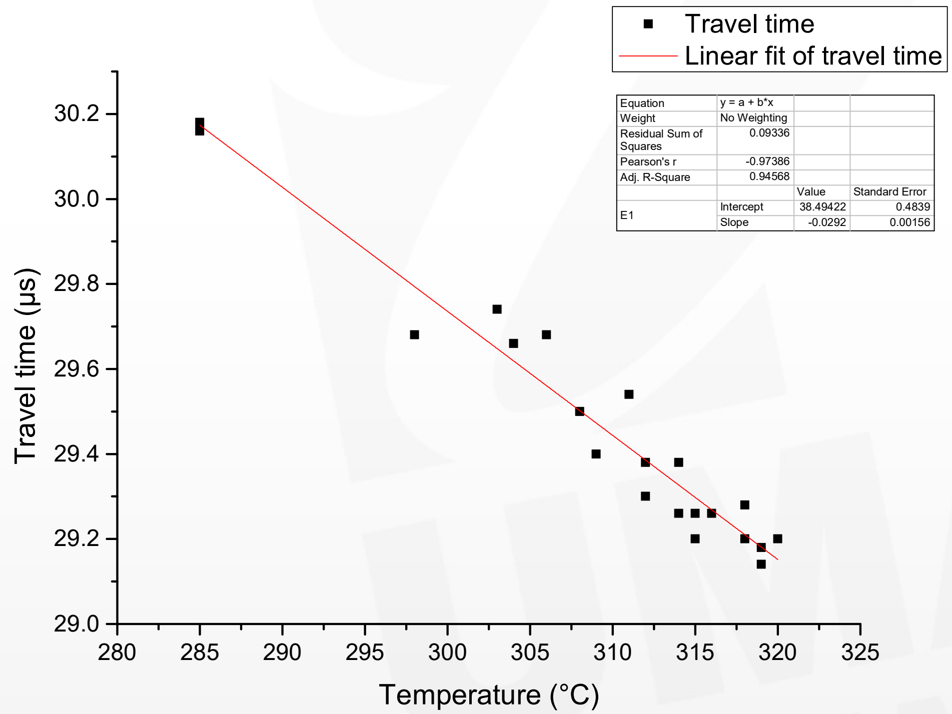
GE pilot test



- The above figure shows the 08-2017 pilot test data.
- The ultrasound signals at different temperature.

GE pilot test

08-2017
Pilot test

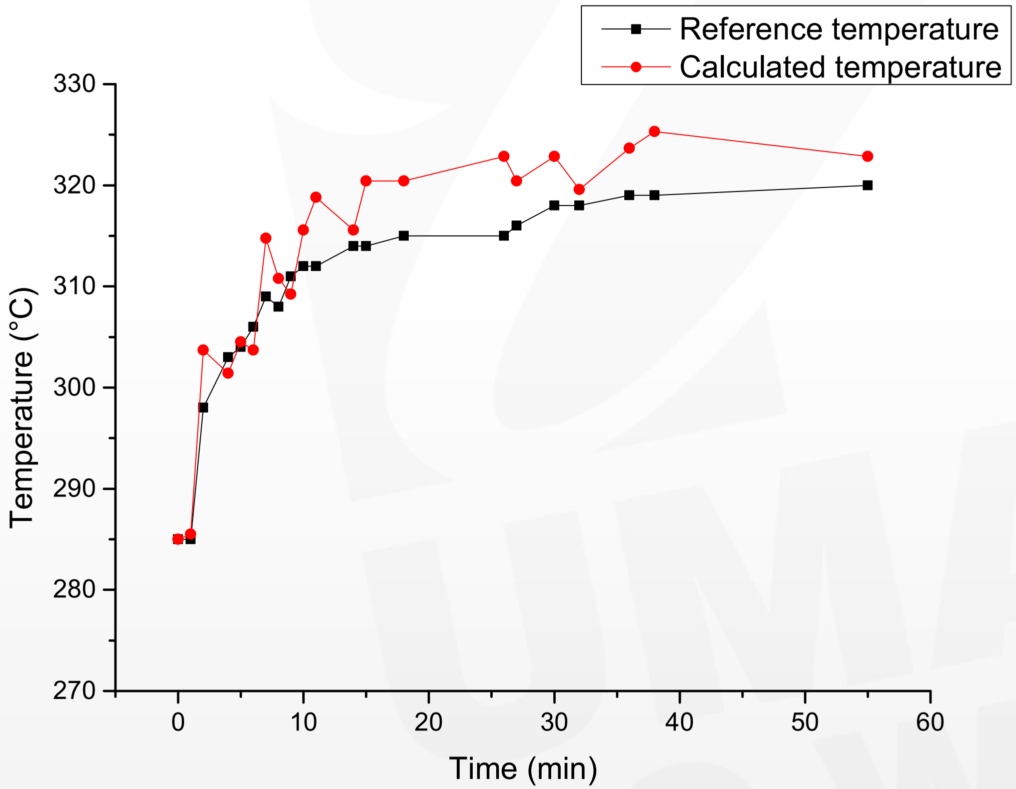


Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	0.09336		
Pearson's r	-0.97386		
Adj. R-Square	0.94568		
		Value	Standard Error
E1	Intercept	38.49422	0.4839
	Slope	-0.0292	0.00156

- The y value are the ultrasound travel time measured by the UML sensor, the x value shows the reference temperature data measured by the thermocouple.
- The relationship between the reference temperature and the total time is linear which proves that the sound speed is directly proportional to the medium's temperature.

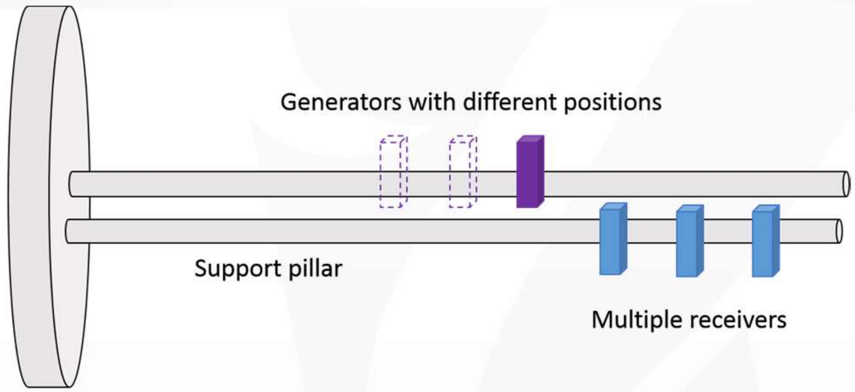
GE pilot test

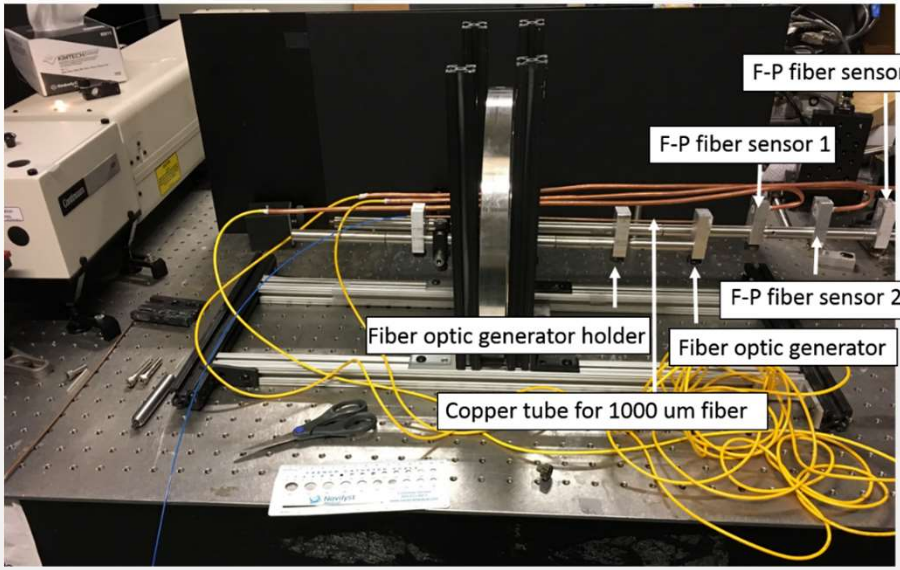
08-2017
Pilot test



- The black points are the temperature data from the reference sensor.
- The red points are the temperature information calculated by UML sensing system.
- The biggest variation was 7.86 °C, the biggest error over the full range was 2.49%.
- The difference between these two sets of data could be caused by different location of the sensors. The UML sensor provided the average temperature between the generator and the receiver. The reference temperature provided the point temperature near generator location.

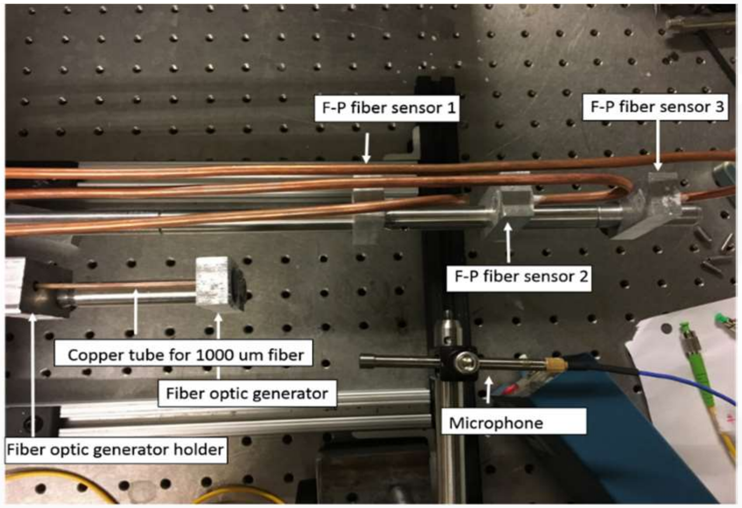
2D/3D temperature distribution system 1

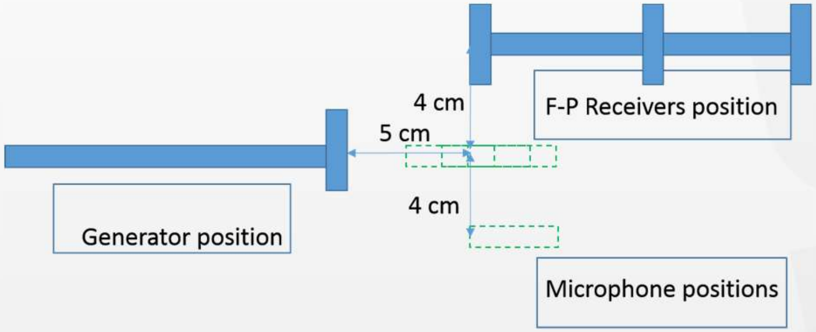


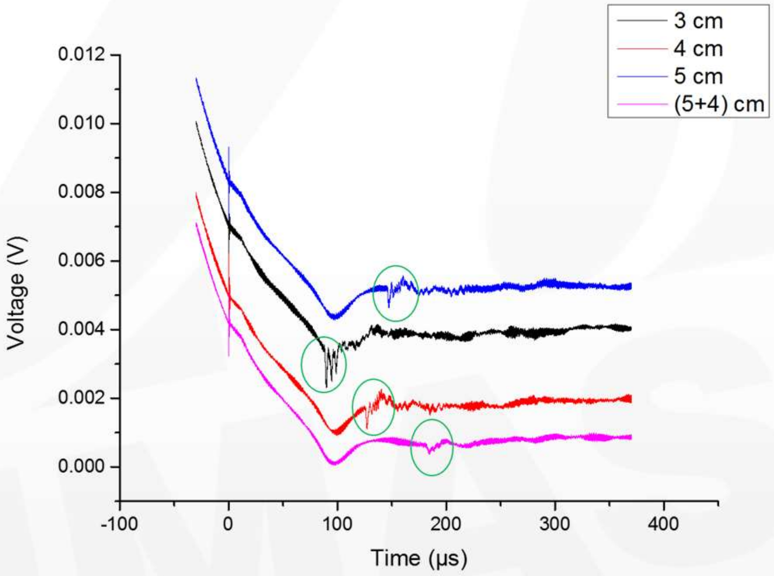


2D temperature distribution system 1

2D/3D temperature distribution system 1







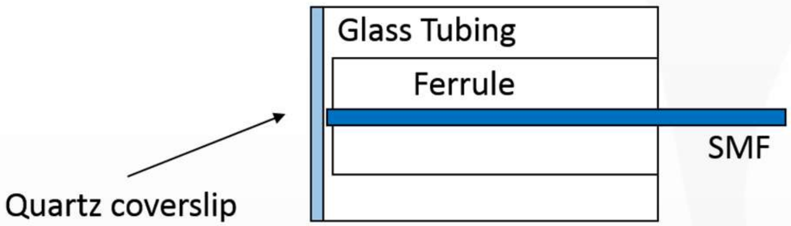
Ultrasound signal detected by the microphone

- Ultrasound signal cannot be detected by F-P fiber sensor on this setup.

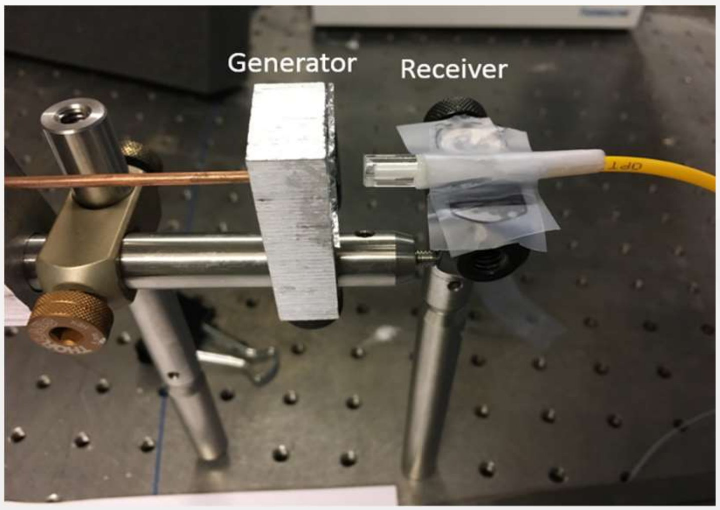
UMASS LOWELL

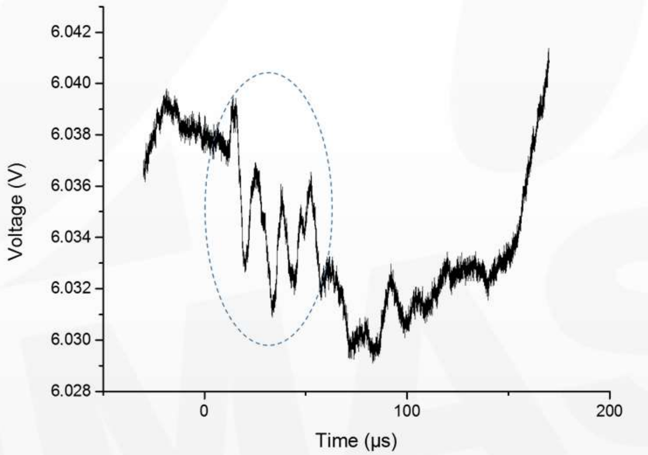
2D/3D temperature distribution system 2

New F-P fiber sensor



- A 2.7 mm inner dimension glass tubing was used to replace the aluminum disc to increase the sensitivity and reduce the size of the receiver.



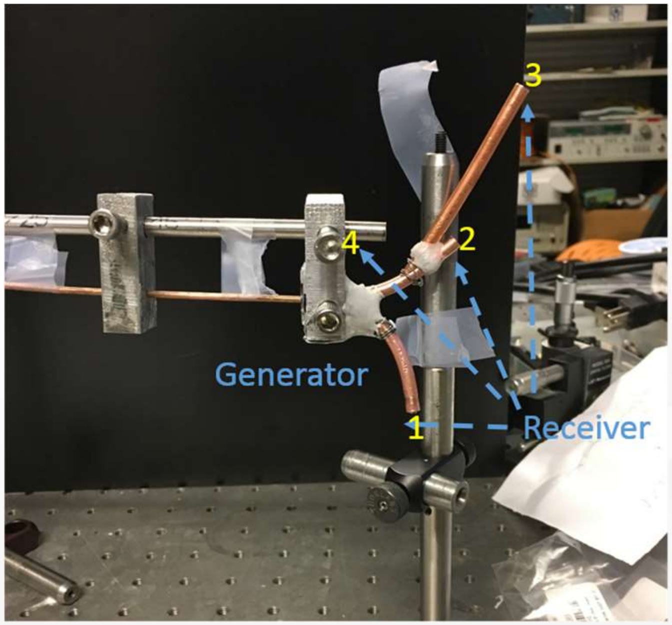


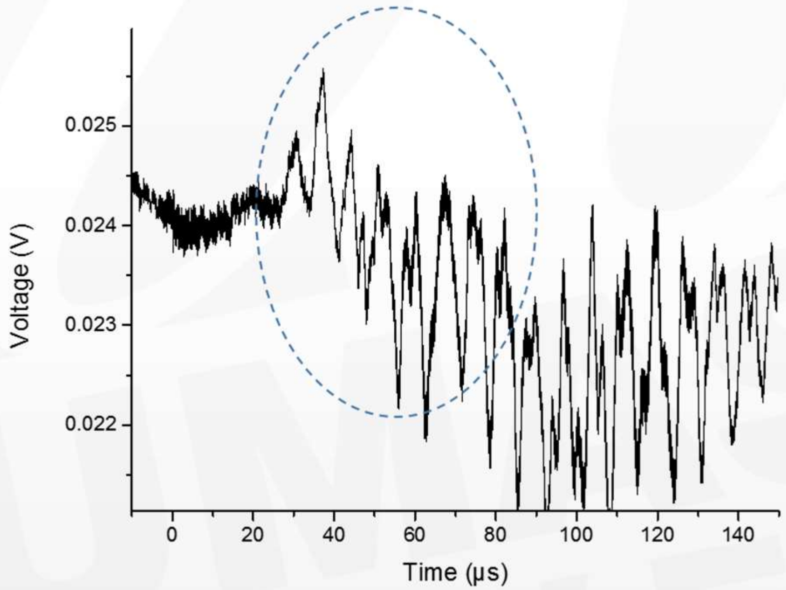
Ultrasound signal when distance set as 5 mm.

- The ultrasound travel time was 14 µs;
- The Vpp is 7 mV, which was 1.4 time to the previous F-P fiber sensor.
- Based on the sensitivity equation in page 14, the d increase from 2.54 to 2.7 mm, the sensitivity should increase to (2.7/2.54)4 =1.3 which matched the testing results.

2D/3D temperature distribution system 2

Temperature distribution system with copper tube



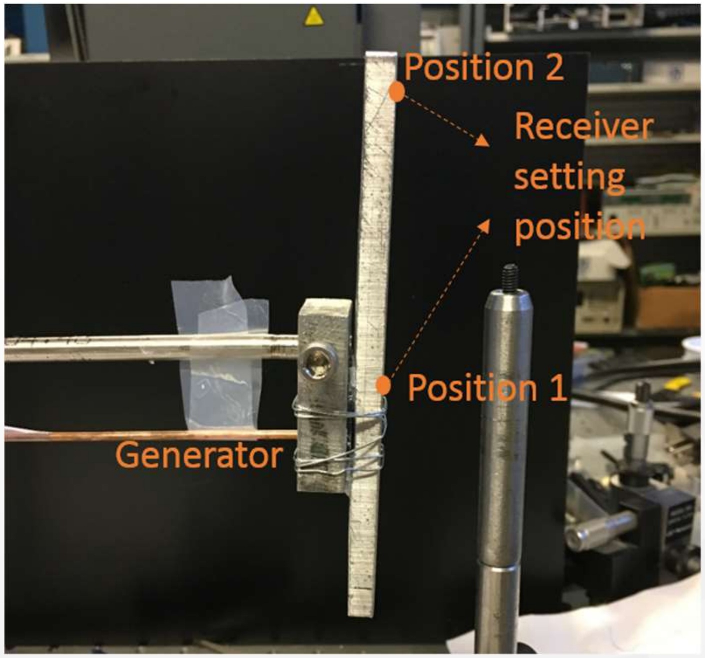


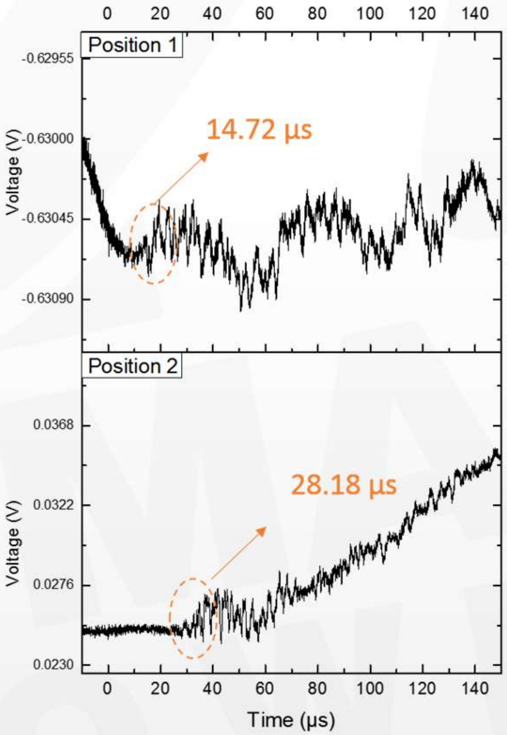
Ultrasound signal when receiver set at position 1.

- The ultrasound travel time was 25 μs, when the receiver was set at position 1.
- The distance between the generator and the receiver was 6 cm.
- 4 mm/ 340 m/s = 12 μs (Travel time in the air); 6 cm/ 4600 m/s = 13 μs (Travel time in copper tube); 12+13 = 25 μs (Total time)
- The Vpp of the ultrasound signal was 2.6 mV; much stronger that that in the previous all-optical fiber sensor design.

2D/3D temperature distribution system 3

Temperature distribution system with aluminum plate

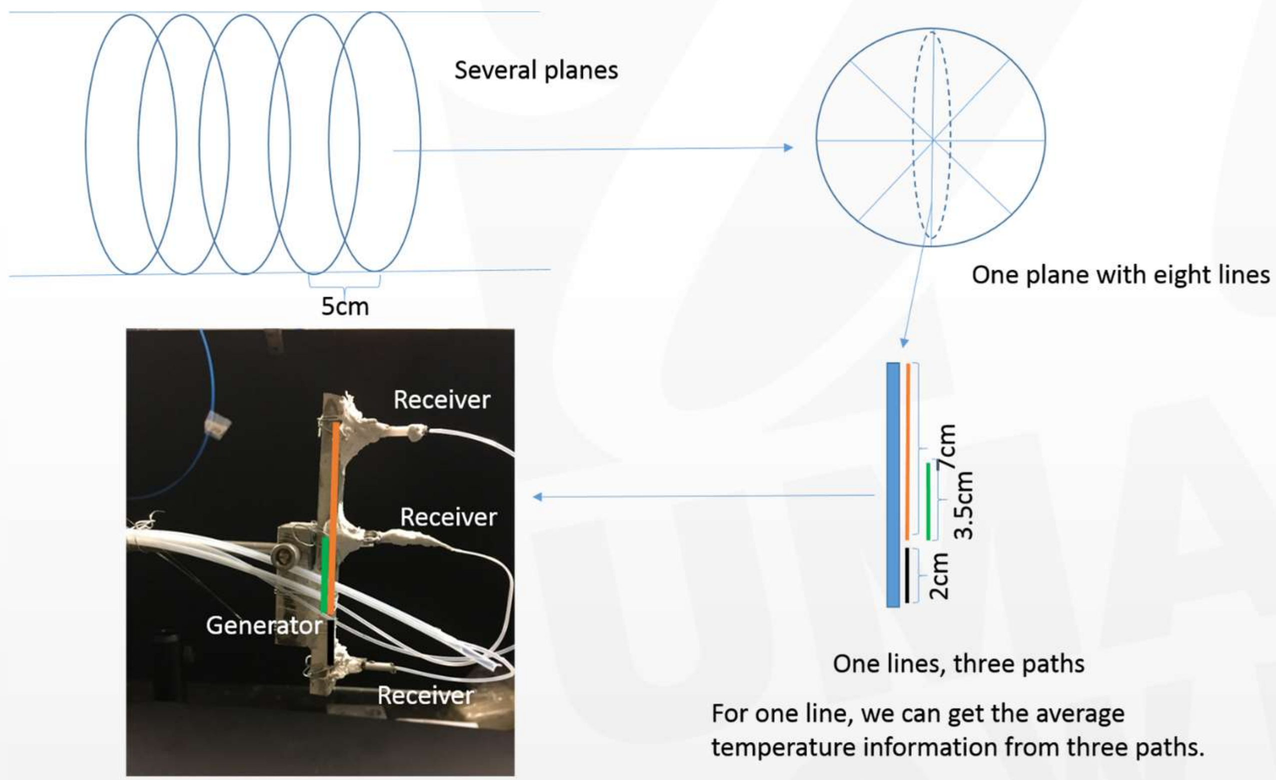




The ultrasound signal at position 1 and 2.

- The ultrasonic travel time to position 1 and position 2 are 14.72 µs and 28.18 µs, respectively.
- The distance between the position 1 and position 2 is 9 cm.
- Speed of sound travel in aluminum is 6320 m/s.
- The time difference is calculated as 9 cm/ 6320 m/s = 14.24 µs.
- And 28.18 µs - 14.72 µs = 13.46 µs.

2D/3D temperature distribution system 3

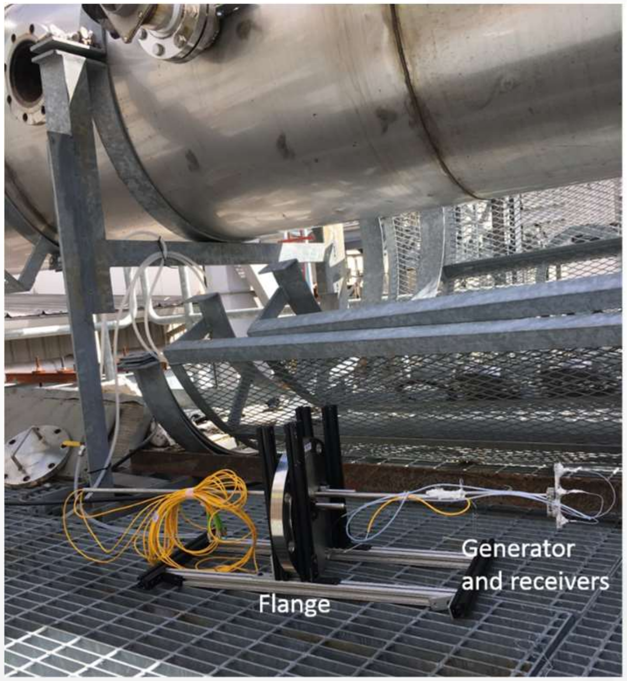


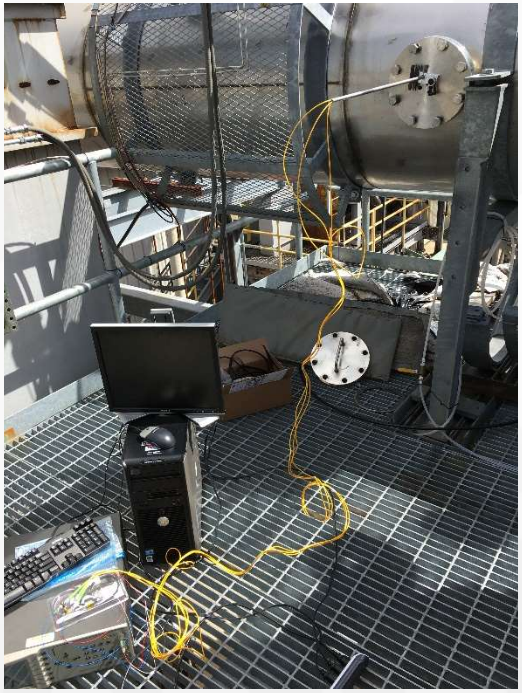
Temperature distribution system with aluminum plate

- Several planes. (At least 4 planes.)
- Each plane will have 8 lines.
- Each line will have 3 paths.
- For each plane we will get 3*8= 24 average temperature path data.

2D/3D temperature distribution system 3

Pre-pilot test on system 3 on 04-2018

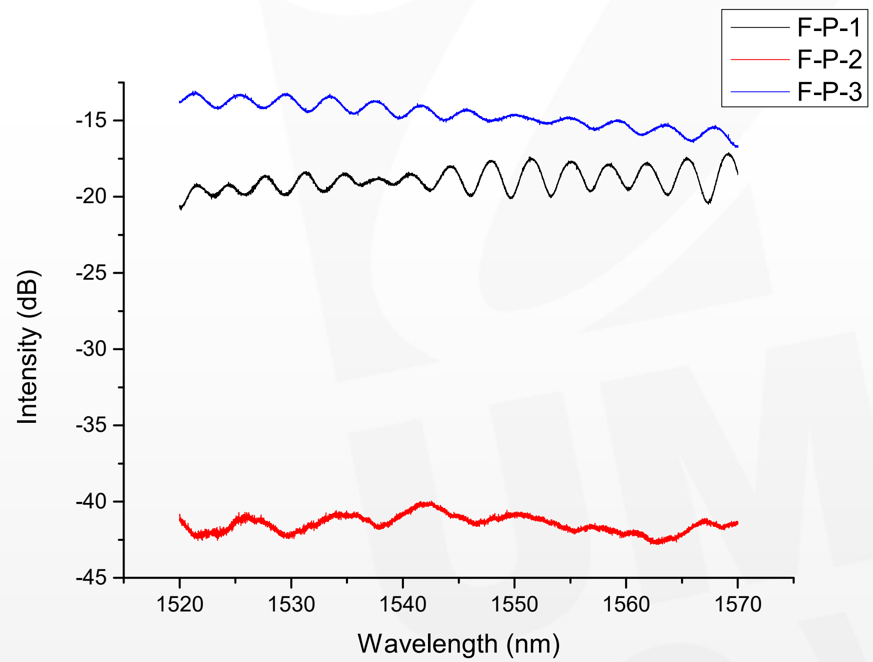




- Pre-pilot test: Put the system into the testing area to check three F-P fiber receivers.

2D/3D temperature distribution system 3

Pre-pilot test on system 3 on 04-2018



Spectrum of three F-P fiber sensors in the testing area.

- Two sensors were good based on their spectrum. (Intensity great than -20 dB)
- One sensor was broken during the installation process since it collided to the mesh wires in the testing area.

Outline

- ❑ Brief overview of DOE project
- • Introduction
- ❑ Experimental results
- • Signal generator
- • Signal receiver
  - - Fiber Bragg grating (FBG) fiber sensor
  - - Fabry-Perot (F-P) fiber sensor
- • Temperature measurement
  - - Water temperature measurement
  - - Steel plate temperature measurement
  - - Air temperature test and reconstruction
- • Distributed sensing capability test
- • GE pilot test
- • Furnace test
- • 2D/3D temperature distribution system
- ❑ Signal processing and temperature reconstruction
- ❑ Conclusions

Signal Processing

Acoustic Fiber Signal Detection (Field Test)

- Sampling rate: 50MHz
- No address code coding or modulation
- Emitter: Acoustic fiber -- pulse acoustic signal
- Signal detection: sliding correlation

The field test conducted in GE had set fire to boiler 6 times. During each time of combustion, they took measurements 3 times. Between each combustion, there is one measurement.

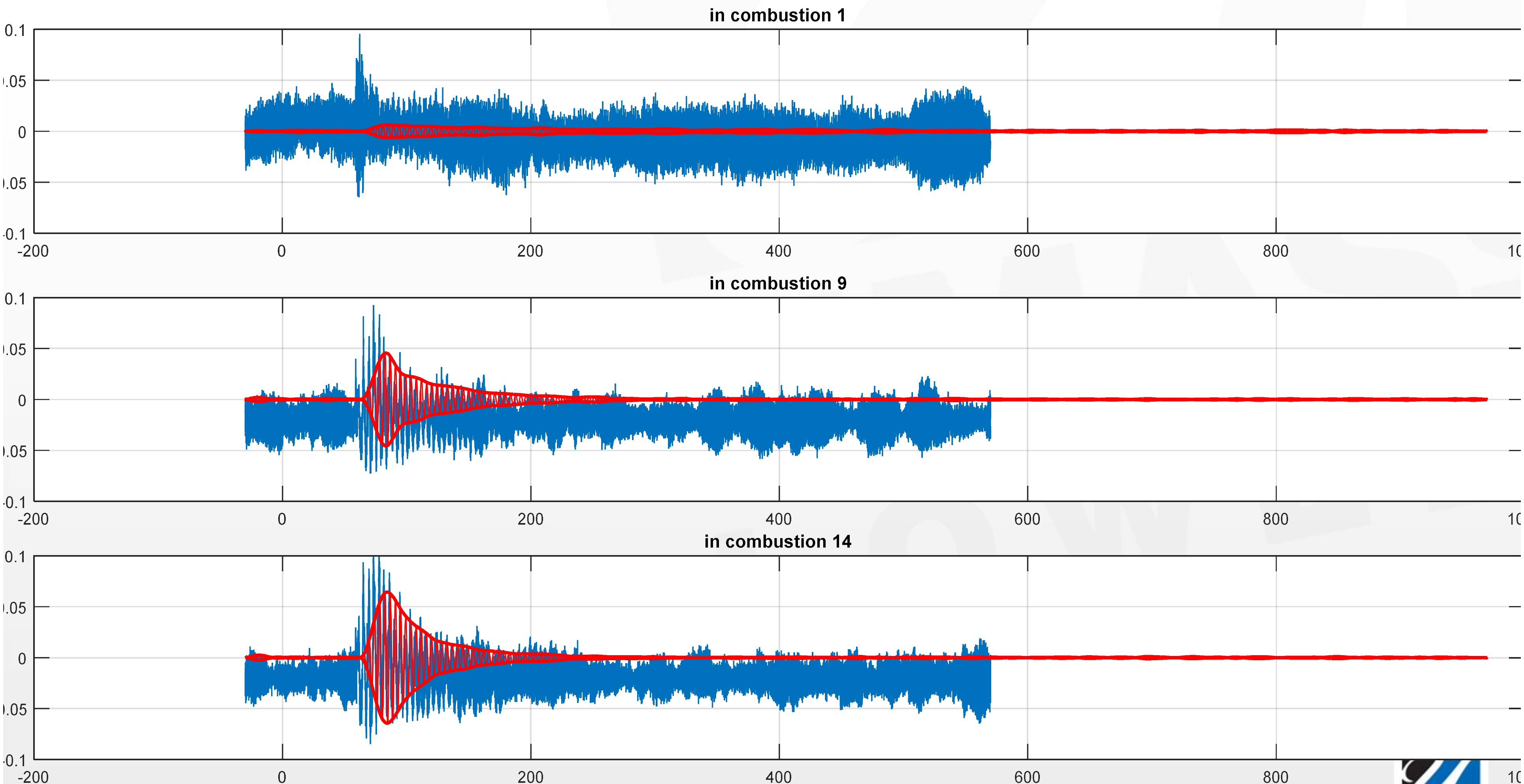
The ***idea*** of signal processing: based on the sliding correlation, the time-index with maximum value will be the arrive point for interesting signal.

The ***procedure*** of signal processing is shown as follow:

- Filtered signal with band-pass filter : 200kHz – 250kHz
- Sliding correlation : two methods

Acoustic Fiber Signal Detection (Field Test)

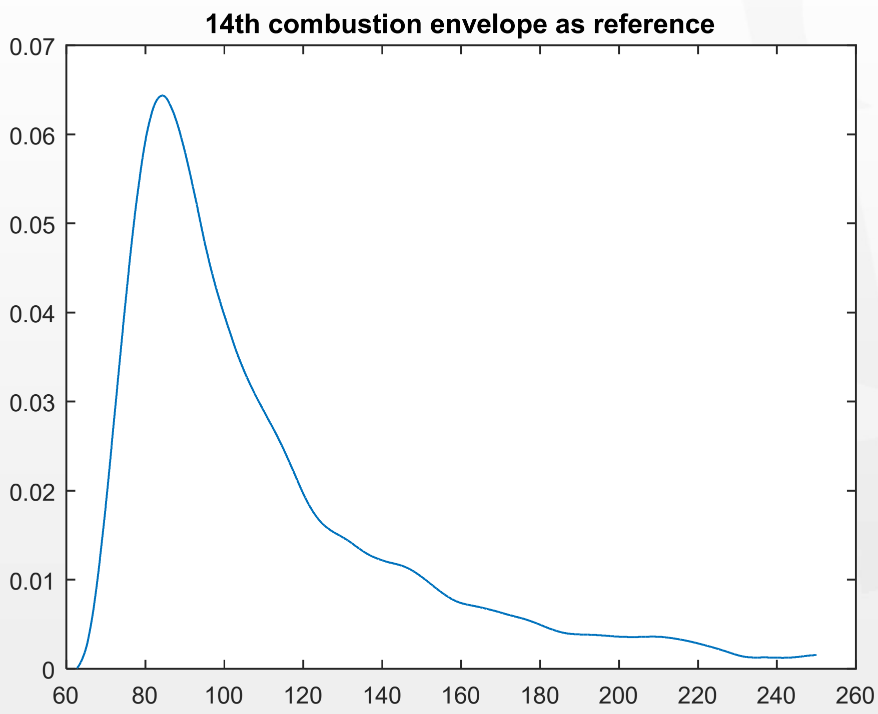
Using Chebyshev filter with pass-band: 200kHz to 250kHz

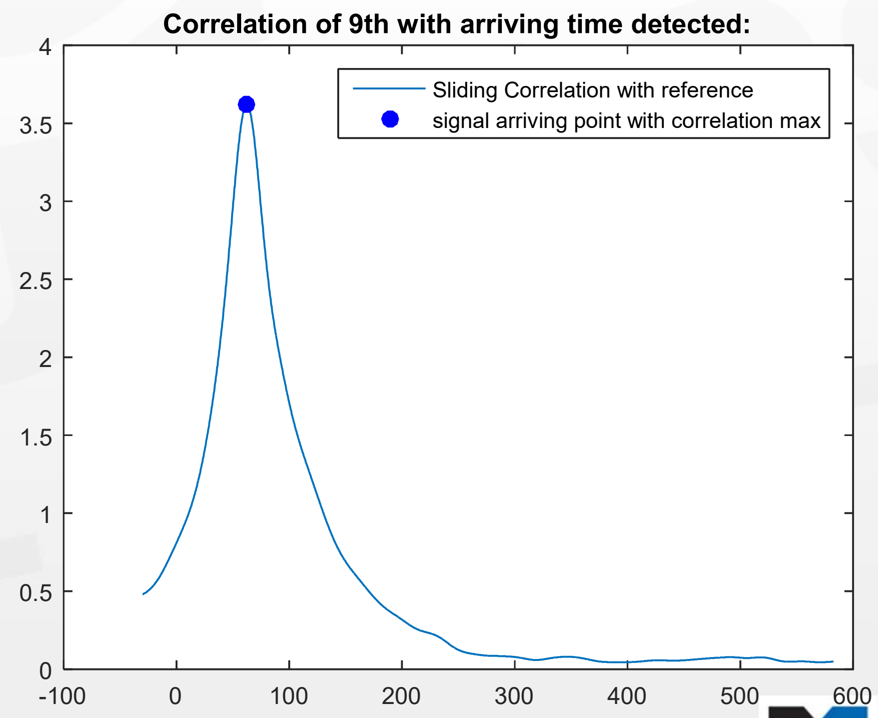


Acoustic Fiber Signal Detection (Field Test)

Sliding correlation :

- ***Method 1***: get envelope lines of each filtered signal, then pick one envelope as reference chip to do correlation sliding along each signal's envelope line.



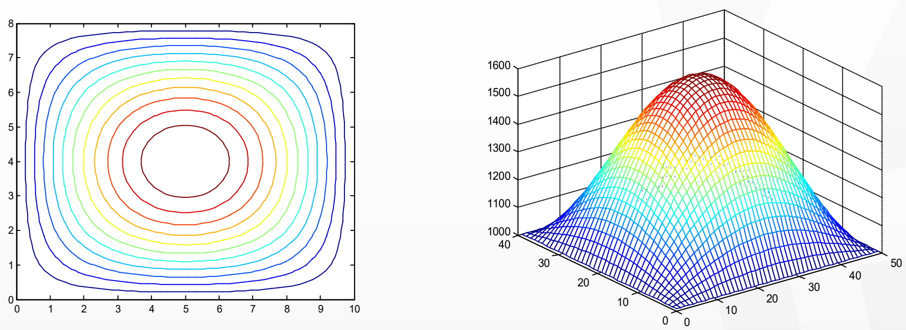


Temperature Reconstruction Algorithm with GRBF

- 2D temperature field case I:

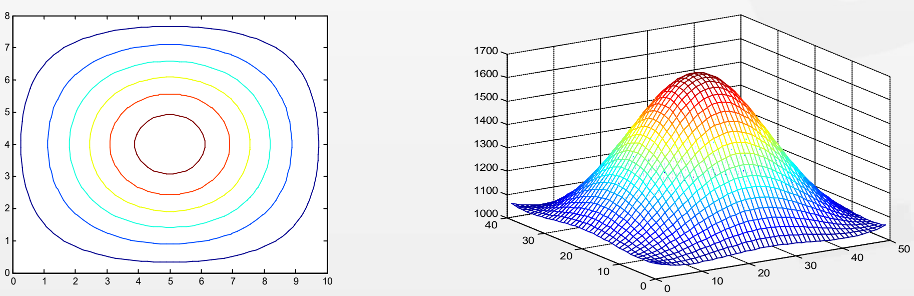
Unimodal symmetric

$$T(x,y) = 1000 + 600\sin(\pi x / length)\sin(\pi y / height)$$



Real Temperature Field

Notes: In the simulation, 10 sensors were evenly distributed, 10 basis functions were used and 24 paths are chosen.



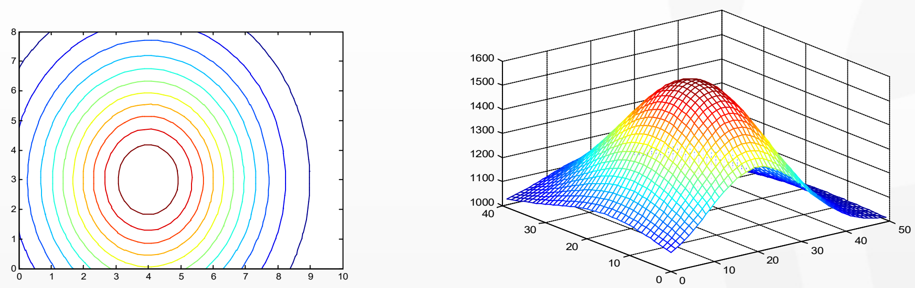
Reconstructed Temperature Field

Temperature Reconstruction Algorithm with GRBF

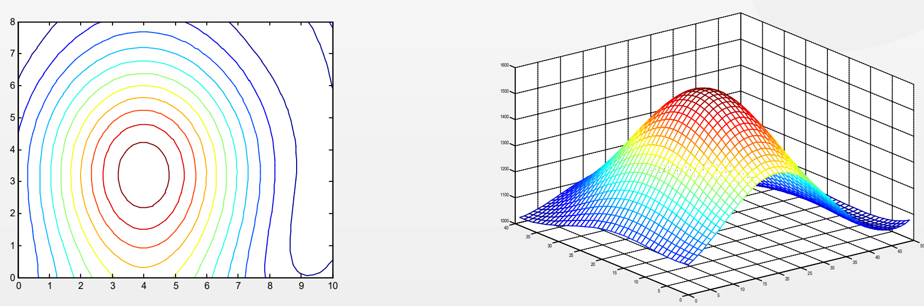
- 2D temperature field case II:

Unimodal deflection

$$T(x, y) = 600\exp((-(x-4)^2)/length - ((y-3)^2)/(2*height)) + 1000$$



Real Temperature Field



Reconstructed Temperature Field

Notes: In the simulation, 10 sensors were evenly distributed, 10 basis functions were used and 24 paths were chosen.

Experimental Results (Microphone)

- Sensor location: sensors are distributed as below (**Fig.1**)
- Reconstruction results of temperature field in 2D (**Fig.2**)

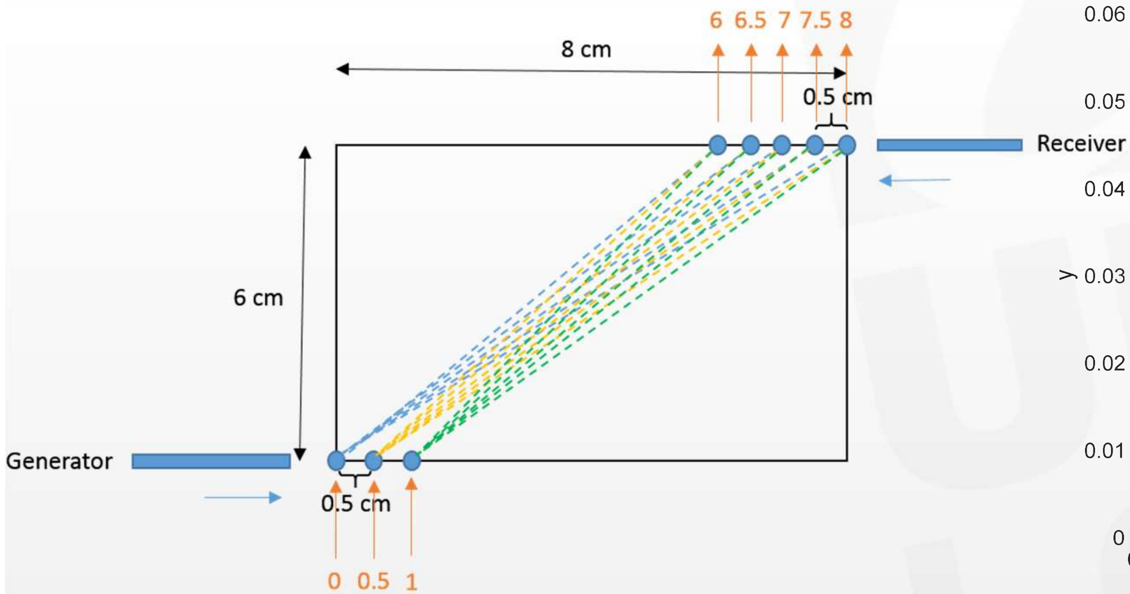


Fig.1. Sensor distribution

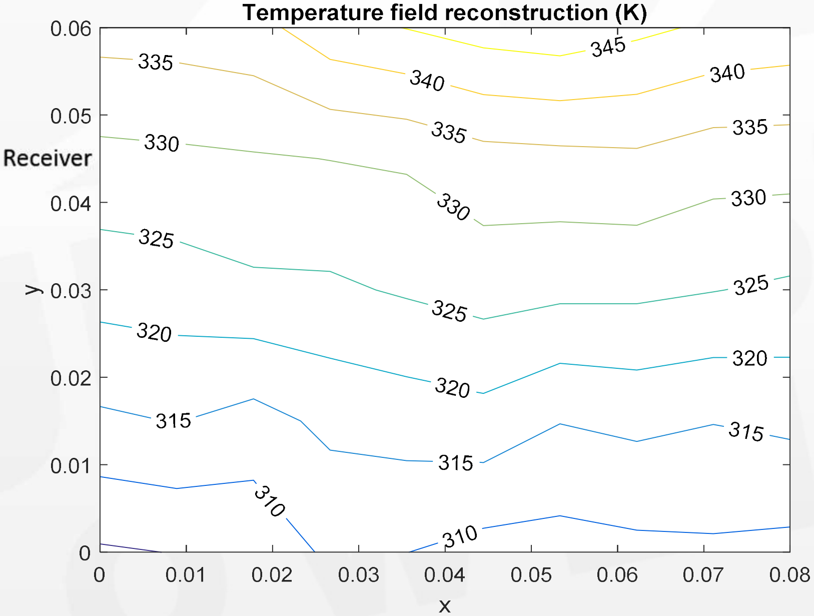


Fig.2. Temperature field

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- ❑ Conclusions

Conclusions

➢ What we have achieved.

1. Temperature test in water condition has been conducted.
2. Temperature test in a aluminum plate has been conducted.
3. Temperature test in air condition (furnace) has been conducted.
4. The temperature range for our all-optical fiber system in air condition (furnace) is 19 ºC - 700 ºC.
5. The pilot test conducted in GE has proved our system is workable.
6. The 2D/3D temperature distribution system has been conducted.
7. This Project has partially supported 1 postdoctoral researcher, 3 Ph.D. students, 1 master student and 2 undergraduate students.
8. We have published 13 papers related to this work, including conference papers (submitted, accepted, published).

Conclusions

Future work

1. All-optical fiber system will be tested in the GE facility in a higher temperature zone.
2. 2D and 3D temperature distribution system will be tested in GE pilot test facility.

Acknowledgement

1. We would like to thank the Department of Energy and our project managers for sponsoring this work (FE0023031).
2. We would like to thank Dr. Xinsheng Lou and Mr. Carl Edberg at General Electric for supporting the pilot test.
3. We would like to thank Mr. Junwei Su for assisting in machining the cooling system.

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- [3] Jingcheng Zhou, Nan Wu, Siwen Bi and Xingwei Wang, ”Ultrasound generation from an optical fiber sidewall” SPIE Smart Structures/NDE 2016
- [4] Siwen Bi, Nan Wu, Jingcheng Zhou, Xingwei Wang, Tong Ma, Yuqian Liu and Chengyu Cao, “Ultrasonic temperature measurements with fiber optic system” SPIE Smart Structures/NDE 2016
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- [9] Xiaotian Zou, Nan Wu, Ye Tian, Yang Zhang and Xingwei Wang, "Polydimethylsiloxane thin film characterization using all-optical photoacoustic mechanism", Applied Optics, 52(25), 6239-6244, 2013
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- [12] Yuqian Liu, Tong Ma, Chengyu Cao, Xingwei Wang, "3D temperature field reconstruction using ultrasound sensing system", SPIE Smart Structures/NDE
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- [16] Jingcheng Zhou, Xu Guo, Cong Du, Nan Wu, Xingwei Wang, "High temperature monitoring using a novel fiber optic ultrasonic sensing system" SPIE Defense + Commercial sensing, Orlando, Florida, United States, 15-19, April 2018 (Accepted)
- [17] Jingcheng Zhou, Xu Guo, Cong Du, Nan Wu and Xingwei Wang, "Characterization of ultrasonic generation from a fiber-optic sidewall" SPIE Defense + Commercial sensing, Orlando, Florida, United States, 15-19, April 2018 (Accepted)
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- [1] Jingcheng Zhou, Nan Wu, Xingwei Wang, Yuqian Liu, Tong Ma, Daniel Coxe, Chengyu Cao, “Water temperature measurement using a novel fiber optic ultrasound transducer system”, IEEE International Conference on Information and Automation, Lijiang, China, August 8-10, 2015
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Thanks