Forum on Tracking Detector Mechanics 2023

Estimation of Interfacial Strain Response for a Bi-material Strip in Tensile and Shear Loading Using THz-TDS

Sushrut Karmarkar, Vikas Tomar, Andy Jung

2 June 2023

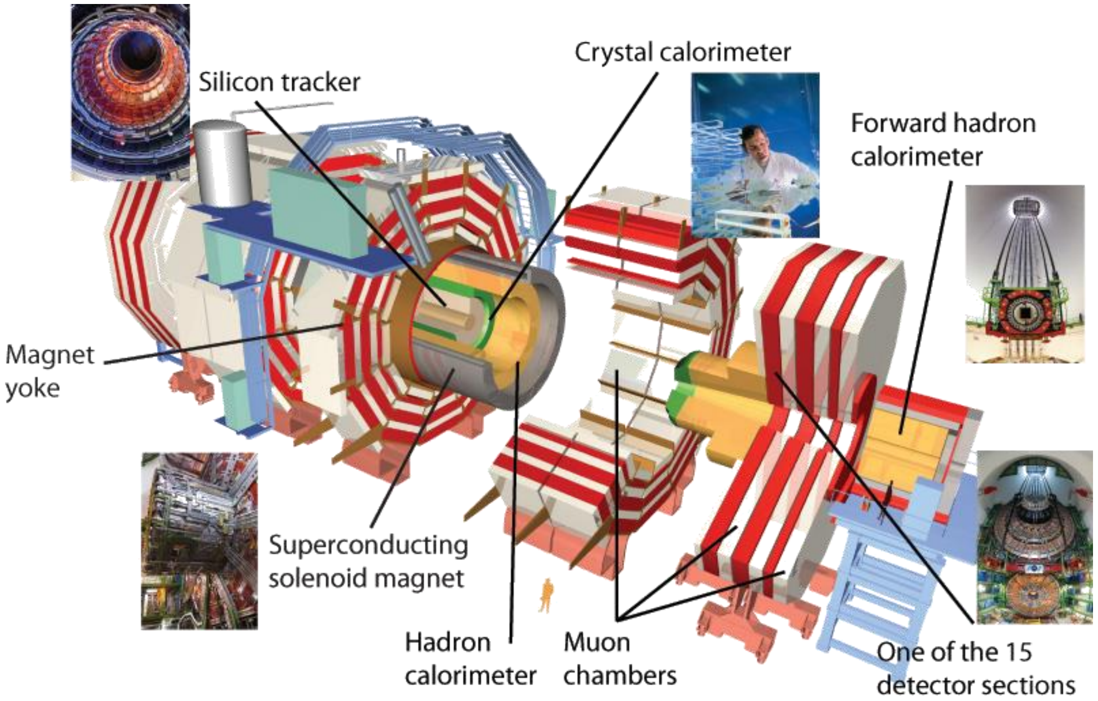
PURDUE UNIVERSITY®

School of Aeronautics and Astronautics

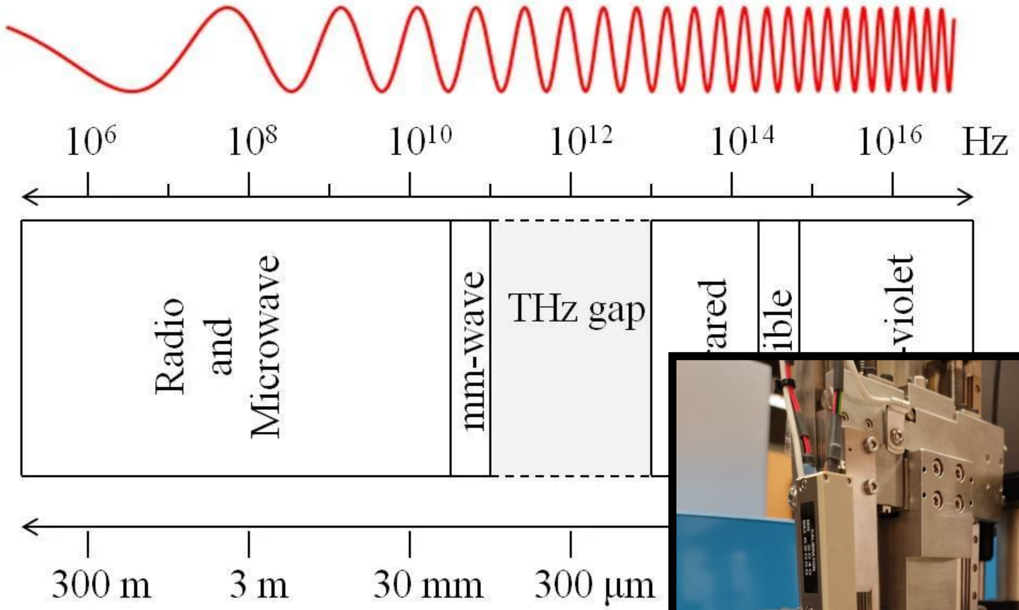
Presentation flow

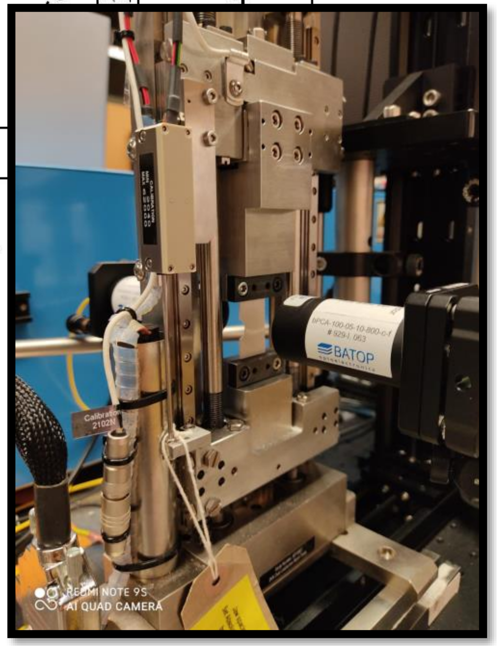
Presentation flow

1. Introduction



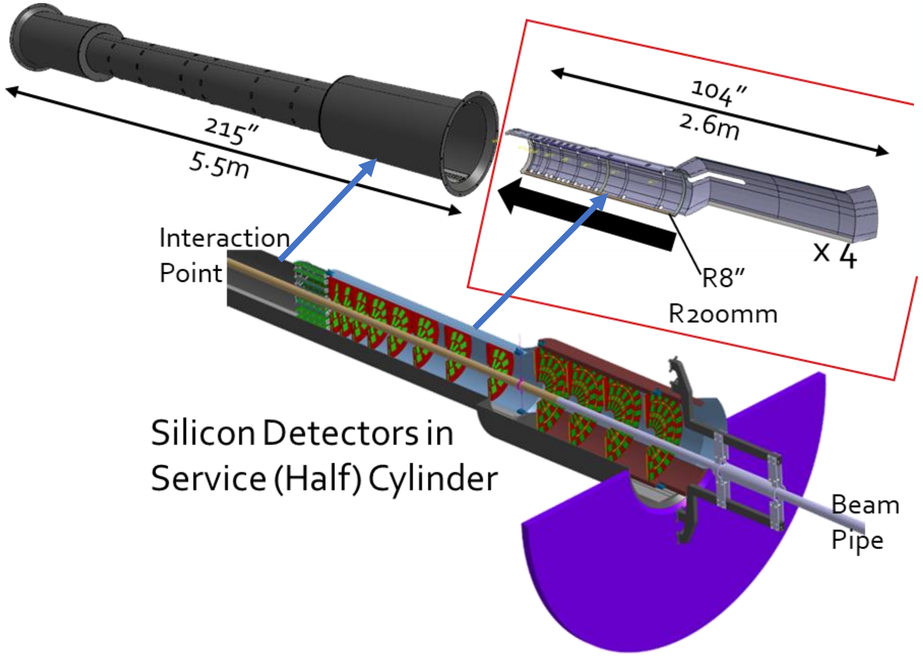
Compact Muon Solenoid detector at LHC-CERN

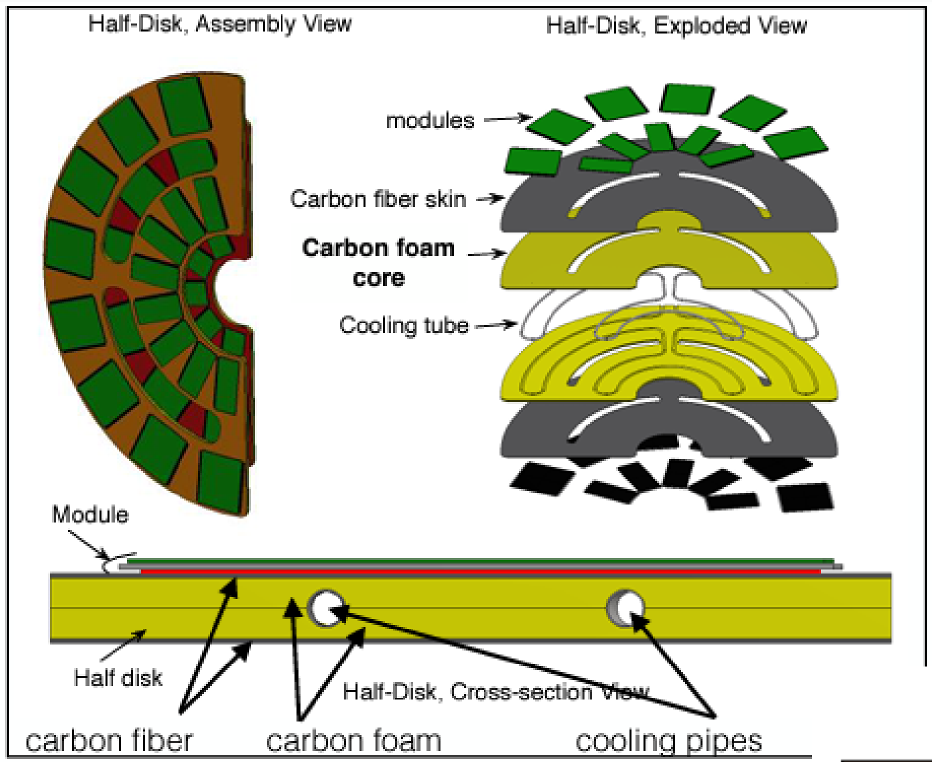




Terahertz Time Domain Spectroscopy – strain mapping

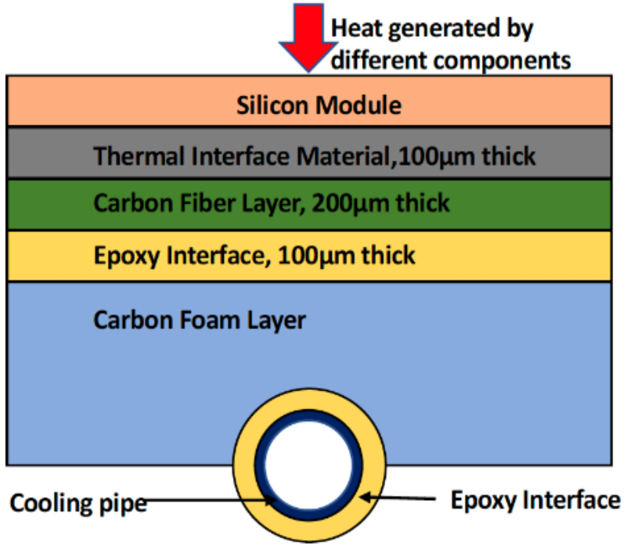
- Measurement of thermal and mechanical strains non-destructively in a composite Dee detector





Schematic of Dee cross section

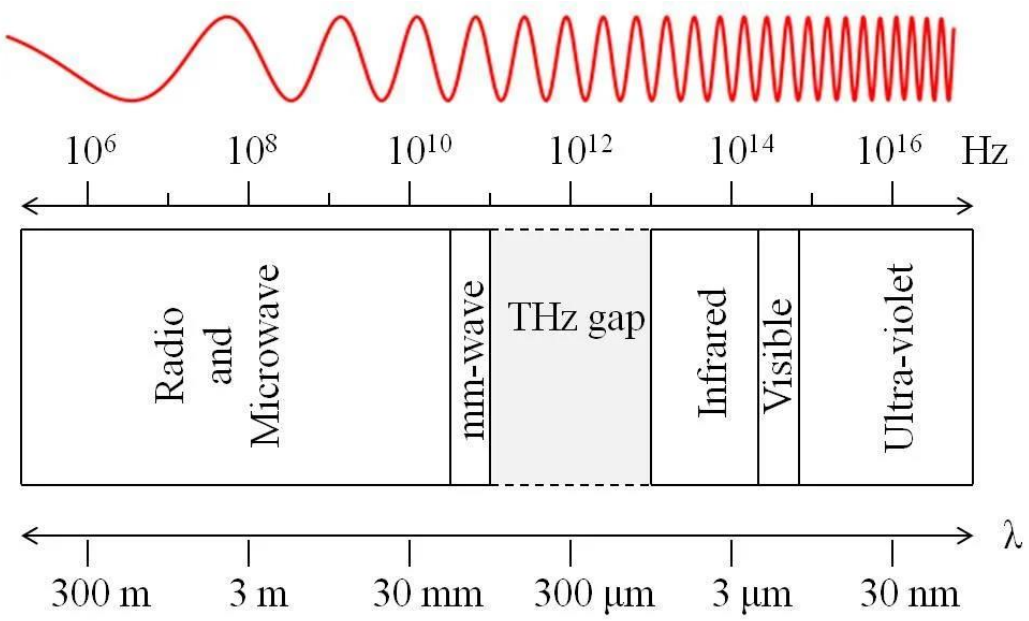
- Mechanical loads due to module weights
- Thermal loads due to CTE mismatch when Dee cooled to $-35°C$ using CO_2cooling

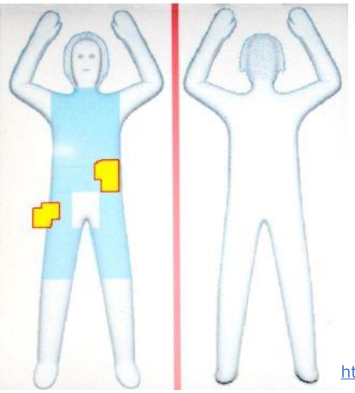


1. Introduction

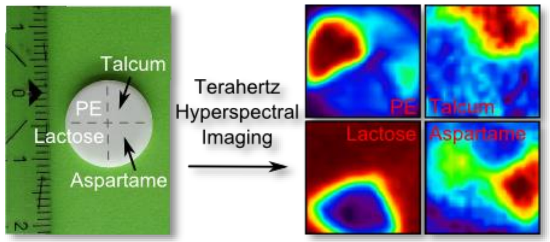
Ref: https://www.allaboutcircuits.com/technical-articles/introduction-to-terahertz/

- Tera Hertz Time Domain Spectroscopy allows
  - High transmission through visibly opaque materials
  - High resolution while avoiding scattering
  - High dynamic range, magnitude and phase recording with broad bandwidth
  - Quantifying small changes in dielectric properties of media
- Applications in security, chemistry, electronics, and now mechanics!



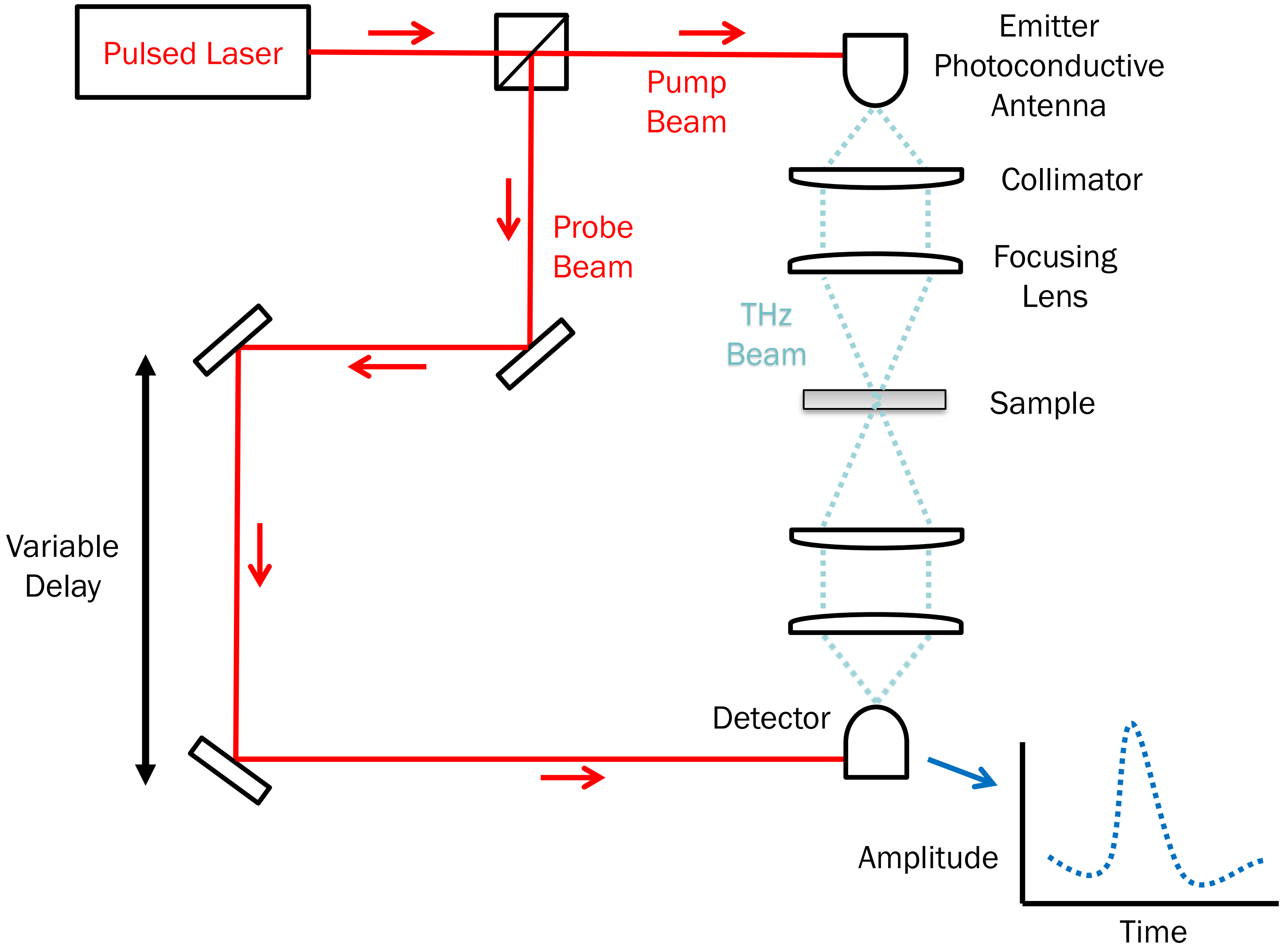


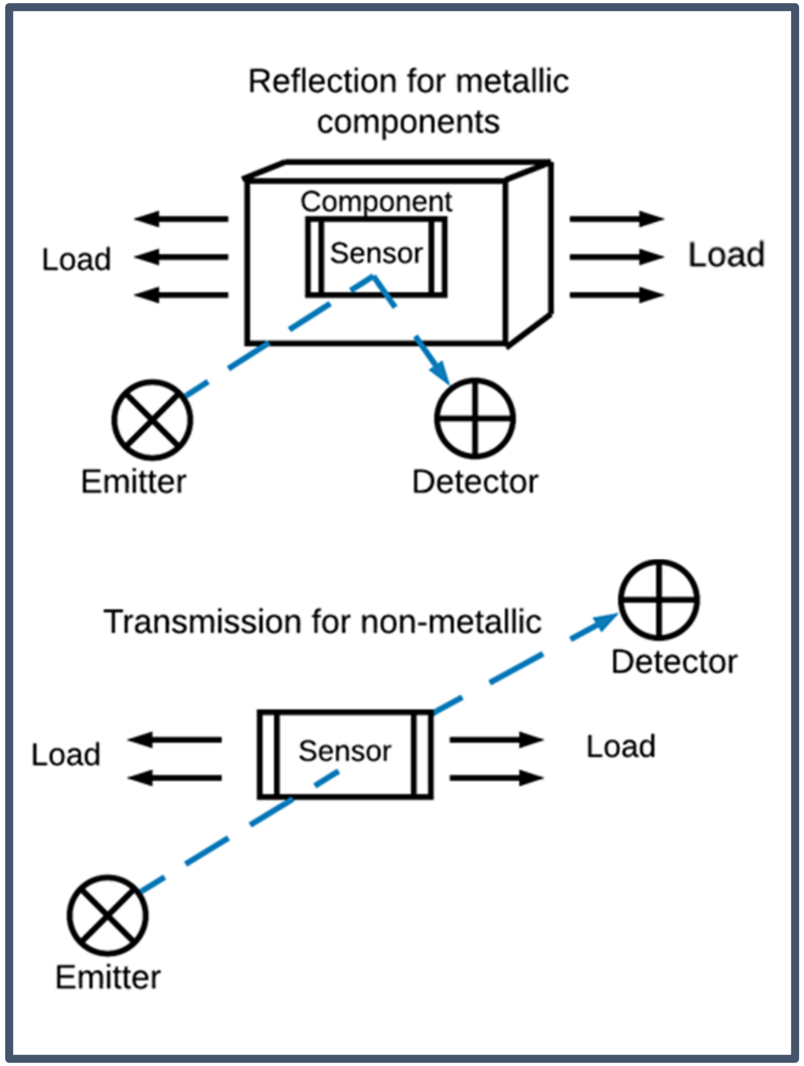
https://physics.aps.org/articles/v13/15



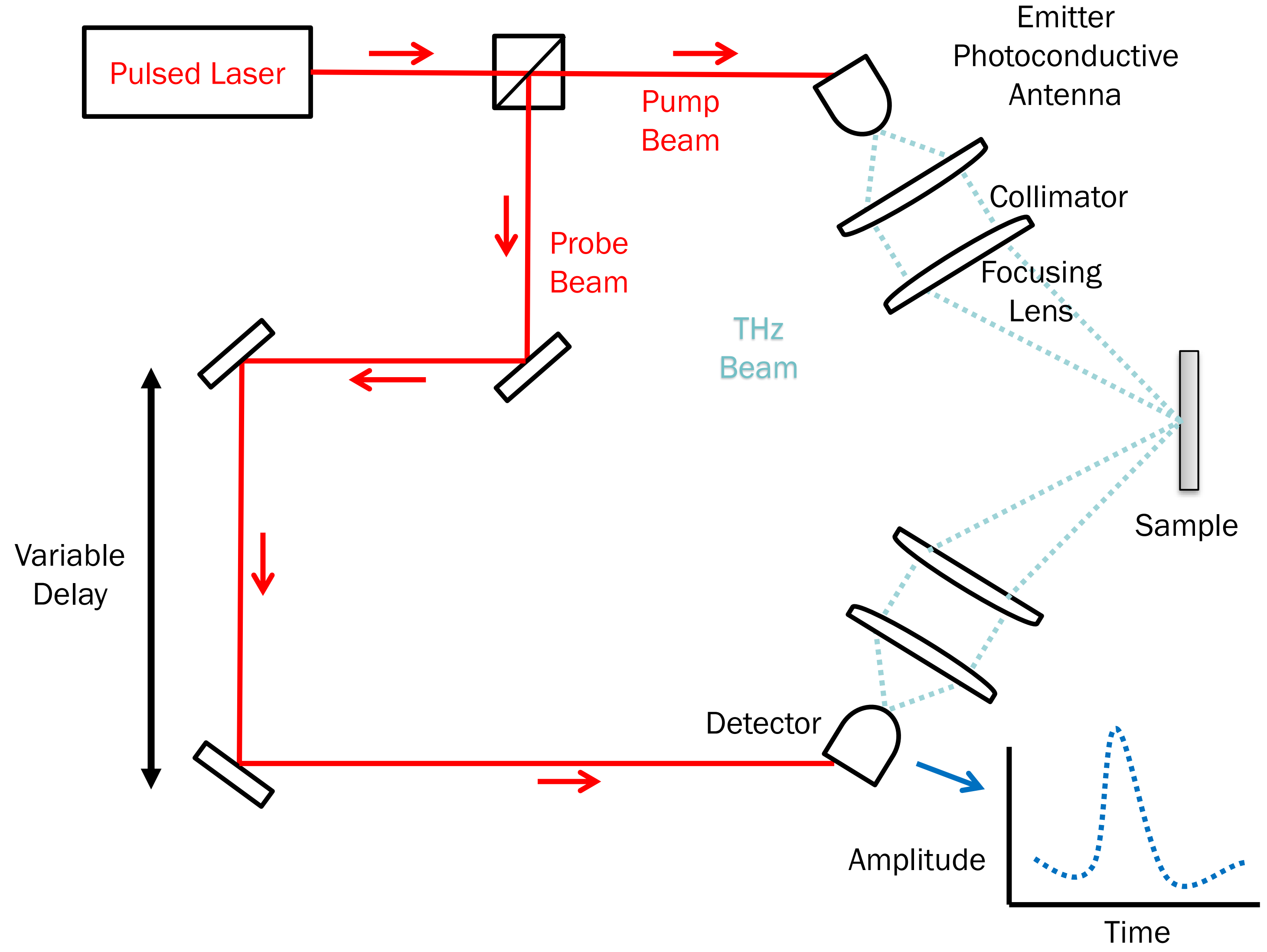
https://www.recendt.at/en/THz.html

Schematics for THz Spectroscopy set up





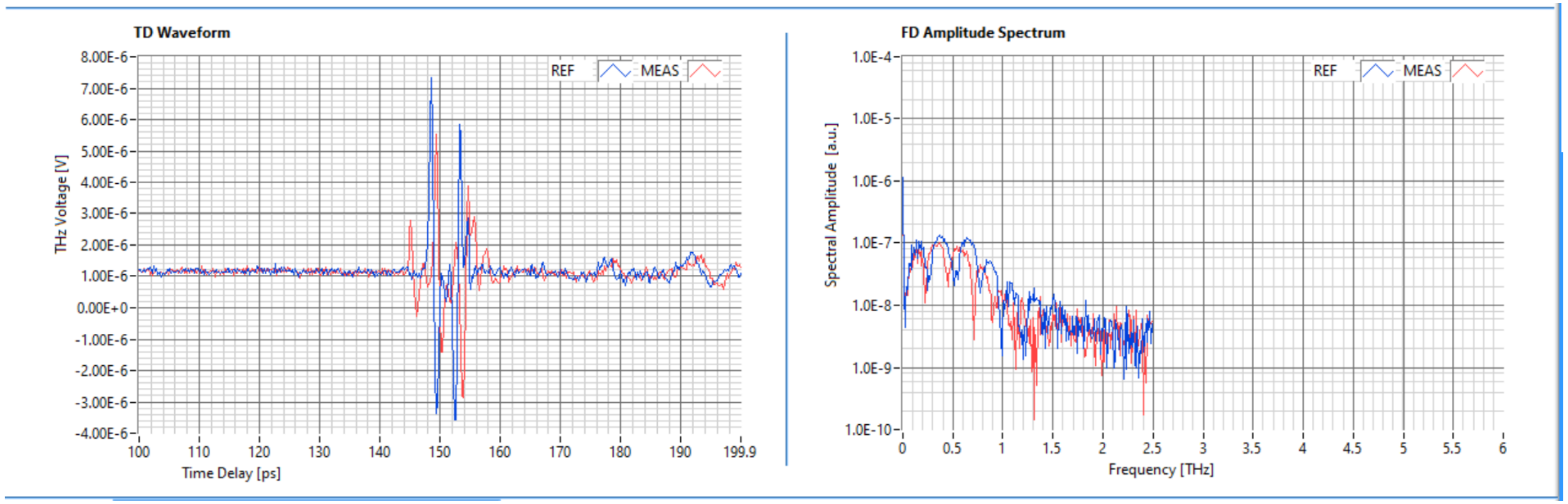
1. Introduction – Schematics for THz Spectroscopy set up

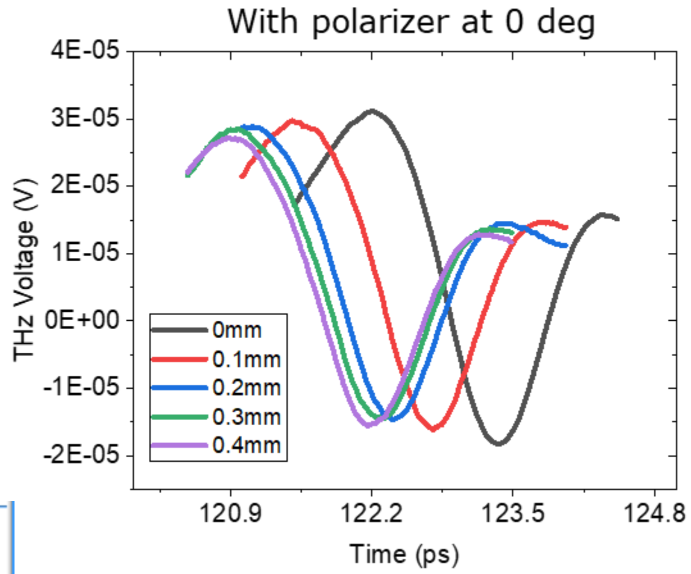


- A THz TDS set-up samples the amplitude of the wave as it reaches the detector antenna
- It works by splitting a pulsed laser for THz radiation generation into pump and probe beams and making a time domain measurements for the reflected/transmitted beam.
- Our set-up produces a resolution of 0.4mm through focusing lenses – measured using the knife edge method

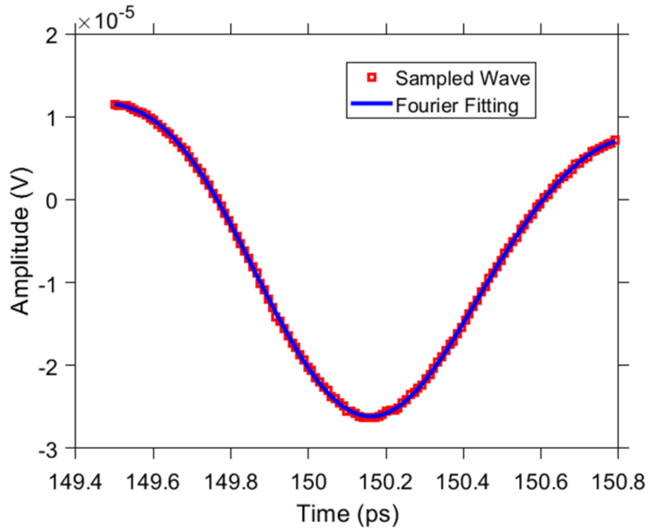
1. Introduction

THz temporal wave form data measured at each loading step → Curve smoothing and Fourier curve fitting to obtain peak positions → Computing ΔToA and correlation to strain response





THz wave form shift for deformation in a tensile test for dog bone specimen

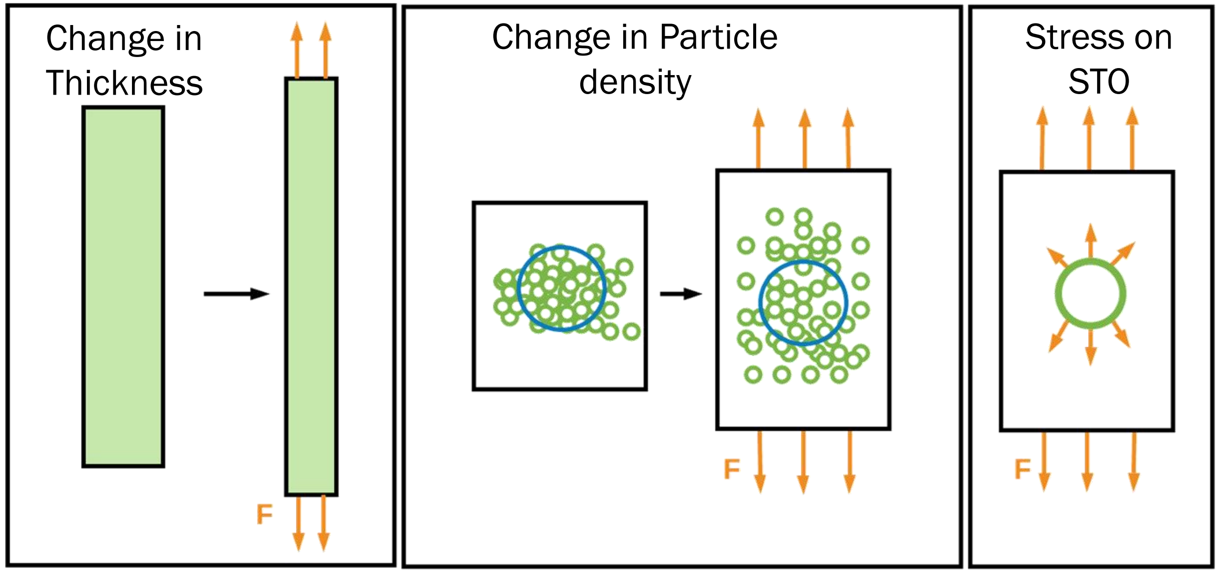


Literature Review: Other Remote Strain Sensing Methods

Strain Mapping Method	Comparison with THz TDS
Strain Gauges: • Optical Fiber Strain Sensors • Radio Wave Strain Sensors	-Sensors are highly reliable and widely available -Low spatial resolution
Optical Whole-Field Techniques: • Holography • Laser Speckle • DIC • Moiré • CT Scanning	-THz TDS will have lower resolution -THz TDS is not able to measure a whole-field at once -THz TDS could measure through opaque media
X-Ray Diffraction	-X-ray has high transmittivity and resolution -X-ray measures axial strain in a crystal -X-ray produces ionizing radiation
Raman Spectroscopy	-Raman has high resolution -Measures stresses -Does not penetrate opaque media

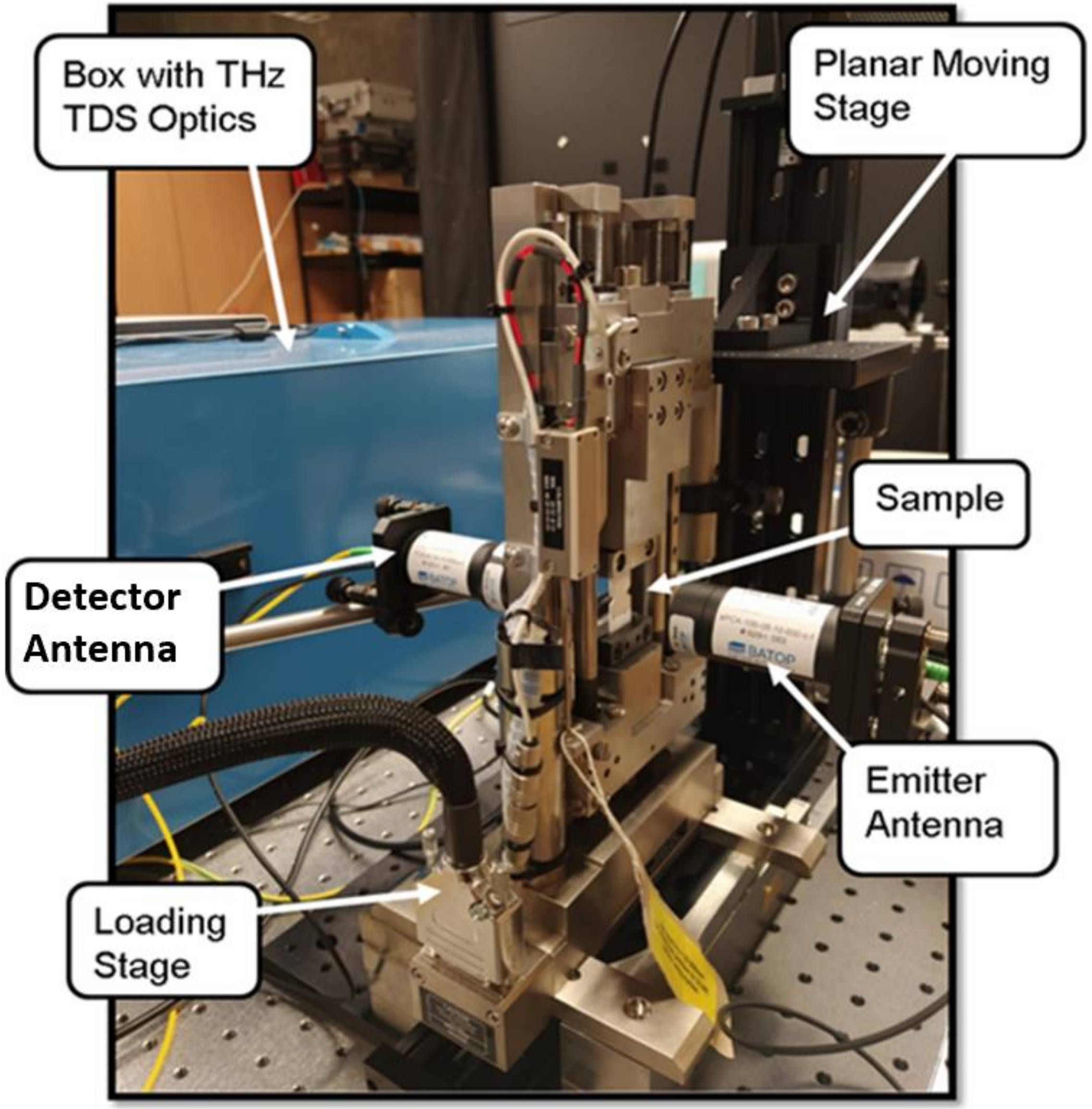
Presentation flow

THz Strain Measurement through STO Dielectrostrictive Composite



- Our sensor consists of high dielectric **strontium titanate (STO)** particles dispersed in an elastomer matrix (8% by wt)
- Strain will produce changes in the THz TDS response by:
  1. Change in thickness by Poisson’s effect
  2. Dielectrostriction by change in high dielectric particles density.
  3. ~~Dielectrostriction by stress on STO~~

Measuring the THz wave response in time domain at different strain levels - Transmission set up

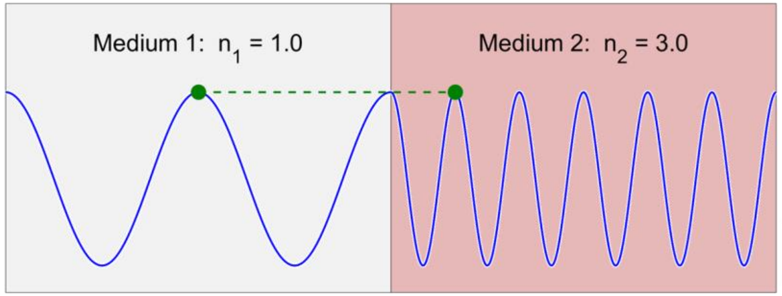


Mathematical modelling and data reduction

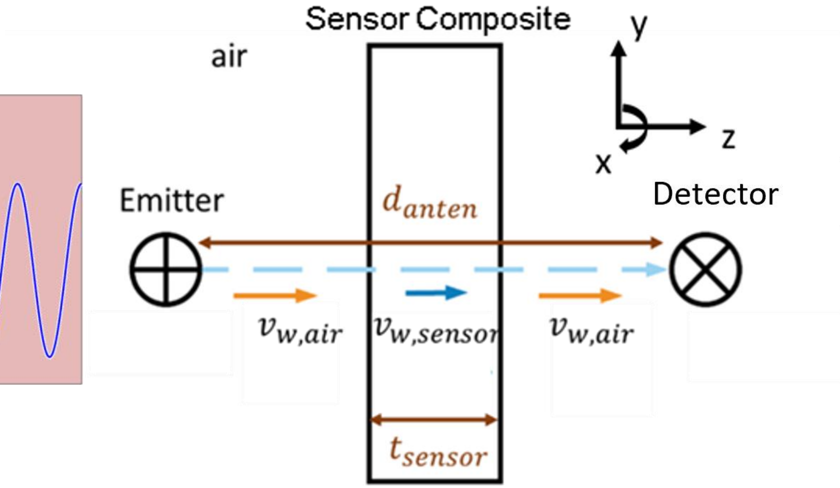
Velocity of wave in a media

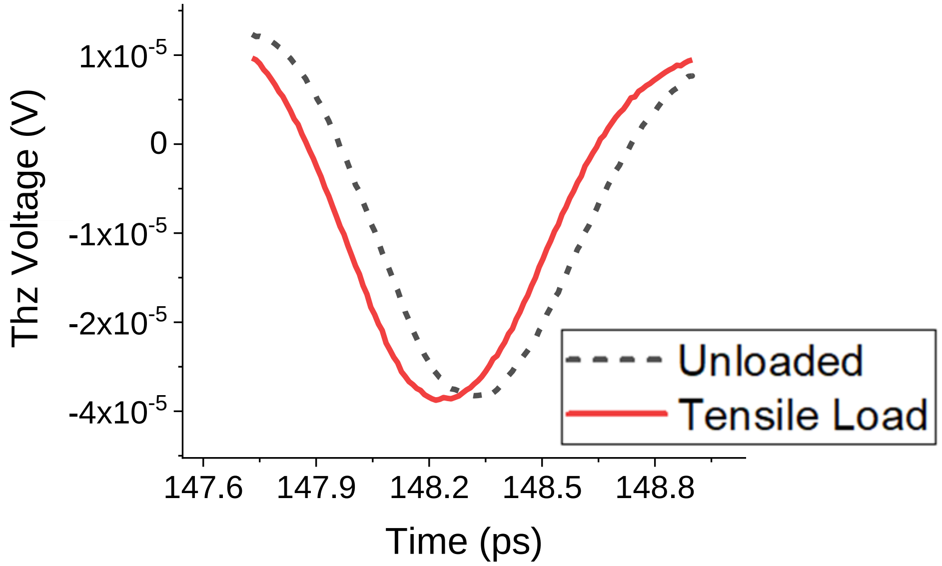
$$v_w = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r \, \mu_r}} \simeq \frac{c}{\sqrt{\varepsilon_r}}$$

Time of arrival $$ToA = \frac{d_{anten} - t_{sensor}}{v_{w,air}} + \frac{t_{sensor}}{v_{w,sensor}}$$



https://empossible.net/academics/emp4303/





So, we measure $ToA_{xx}^{deformed}$ and $ToA_{xx}^{undeformed}$

Note that all the dielectric permitivities $, a_1, a_2$ (since $a_1, a_2 \rightarrow f(\varepsilon^0, \varepsilon^m)$) are directionally d pendent. Using corr lation equations, we compute the $\Delta ToA = ToA_{xx}^{deformed} - ToA_{xx}^{undeformed}$ simplified follows

$$\Delta ToA_{xx} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

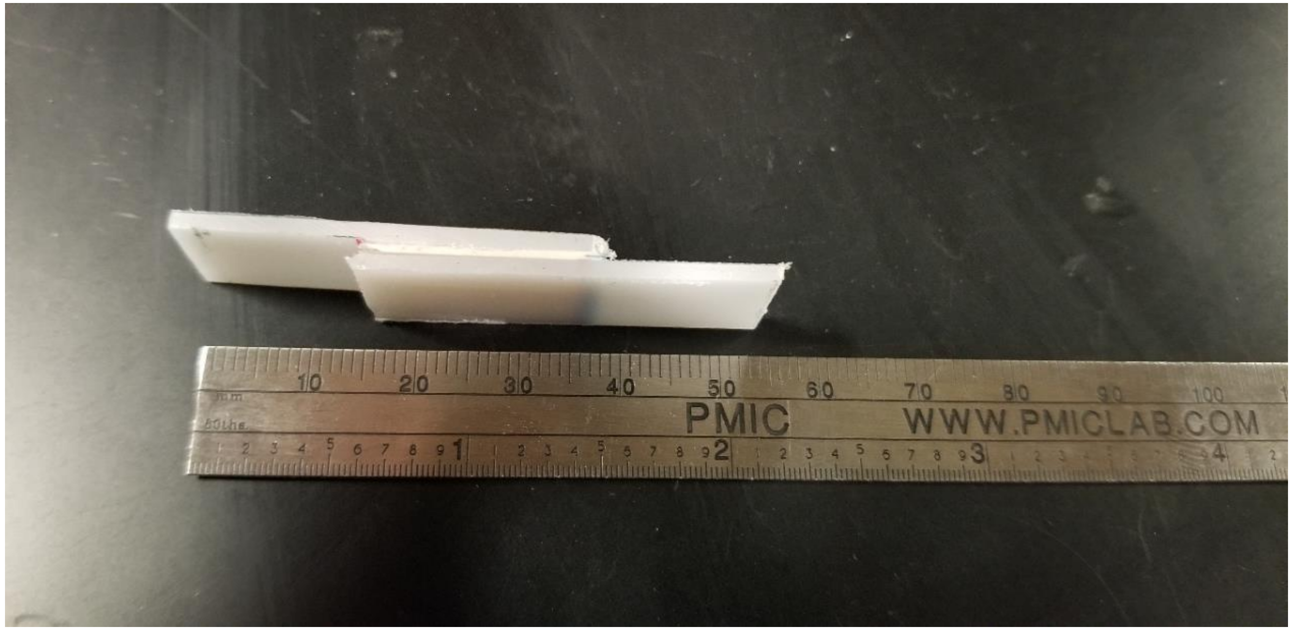
$$\Delta ToA_{yy} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

Presentation flow

Measurement of volumetric strain for a simple open hole tensile and lap shear specimens

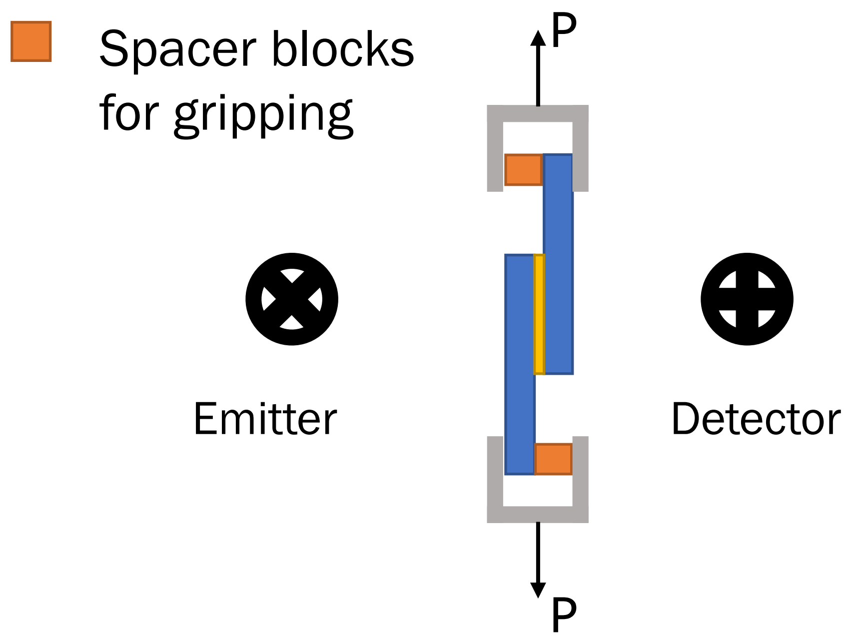
Circular Hole Tensile Testing

Lap Shear specimen

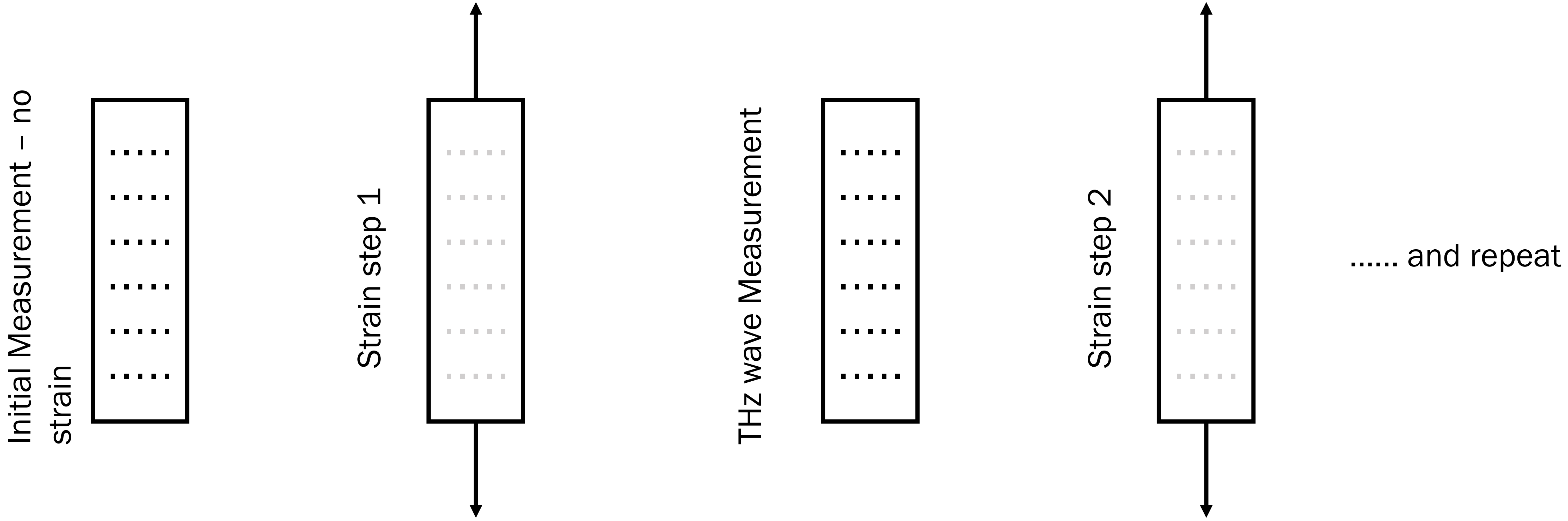


Experimental set up – STO (8% wt) + PDMS composite ‘adhesive’ on a HDPE base plate –transmission mode

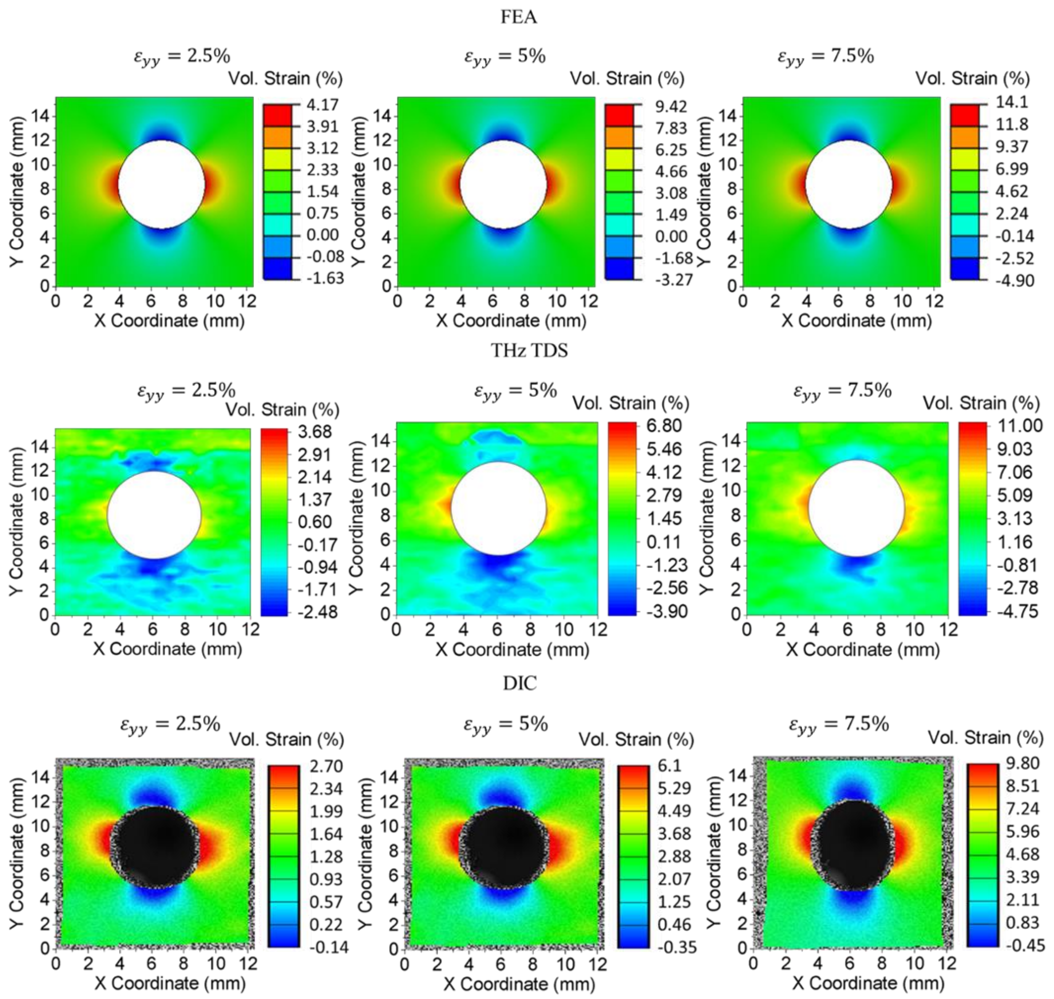
Single Lap Shear Testing



Measurement methodology

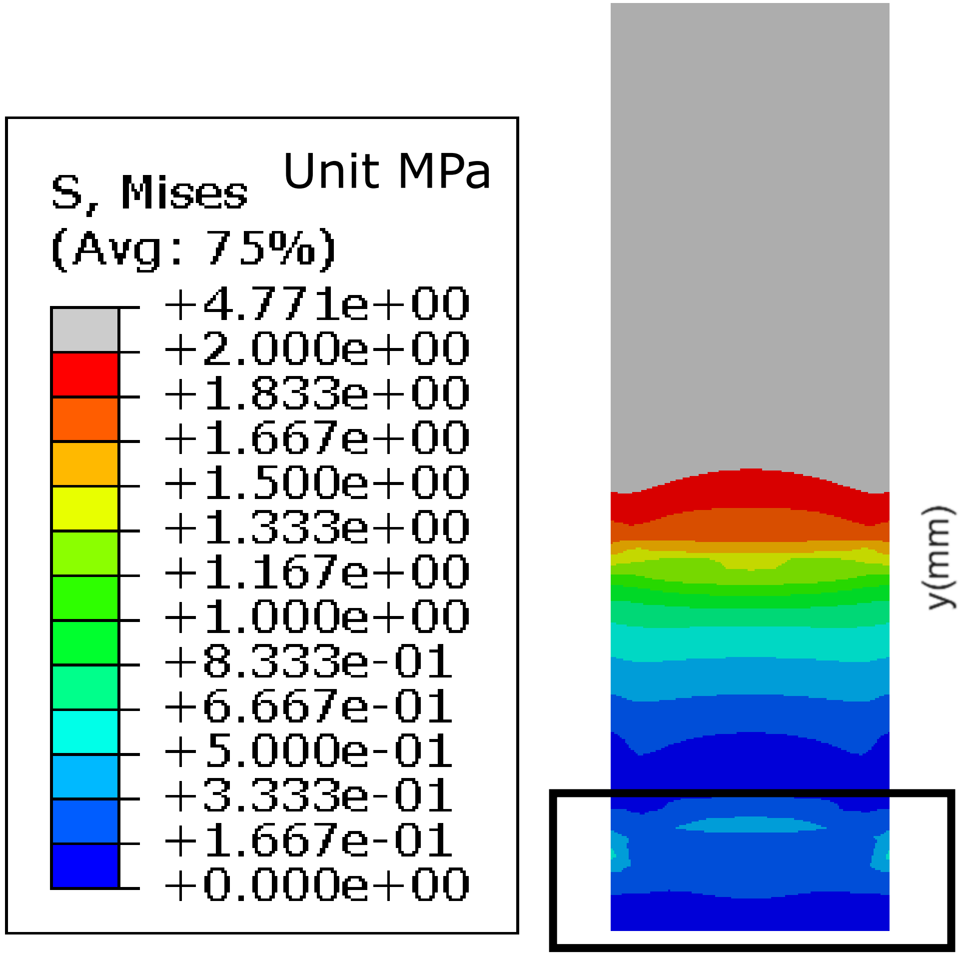


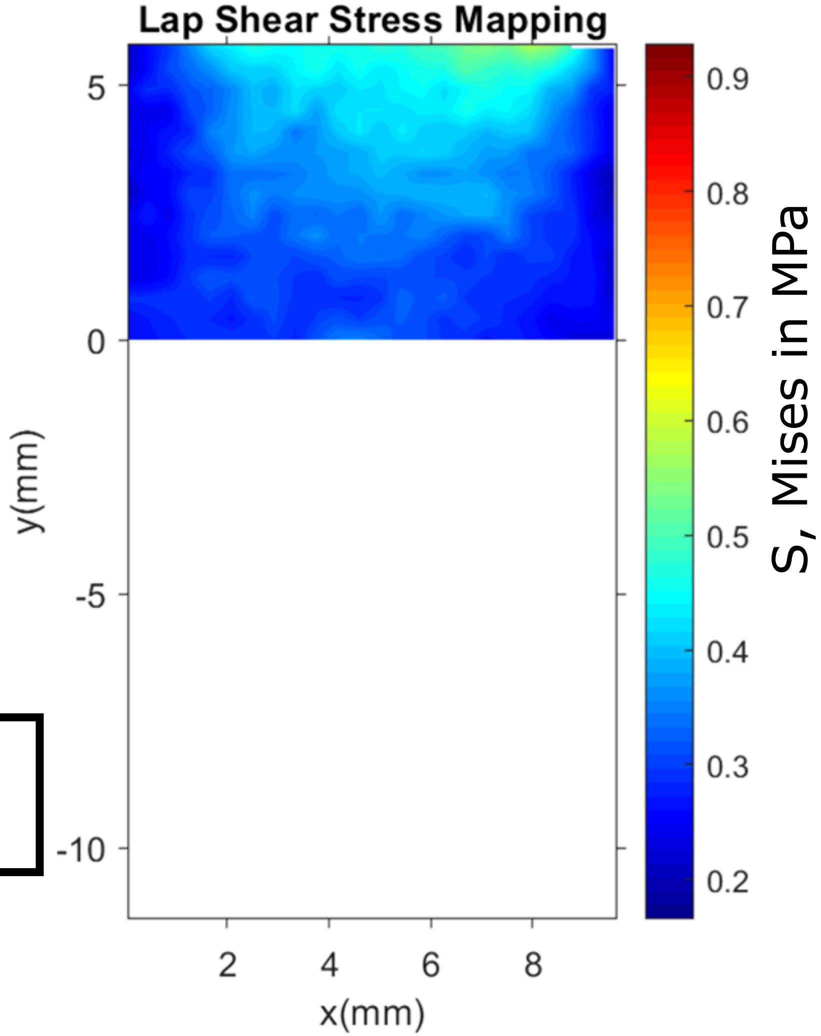
Open hole tensile test

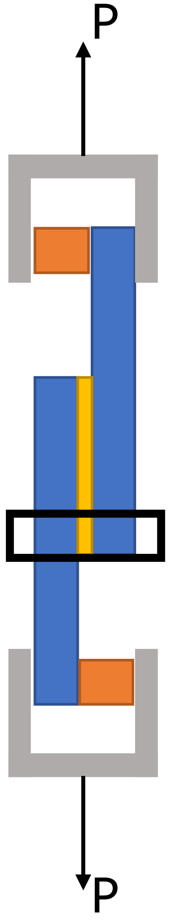


- Test results for a TRANSMISSION mode measurement with sample made from STO + PDMS
- We can capture good results for tensile load cases. Good correlation seen between the THz-TDS measurements, FEA and DIC measurements

Lap Shear Test – FEA analysis – Cohesive surface model – comparison to THz- TDS scan







PRELIMINARY RESULTS

Conclusions and summary

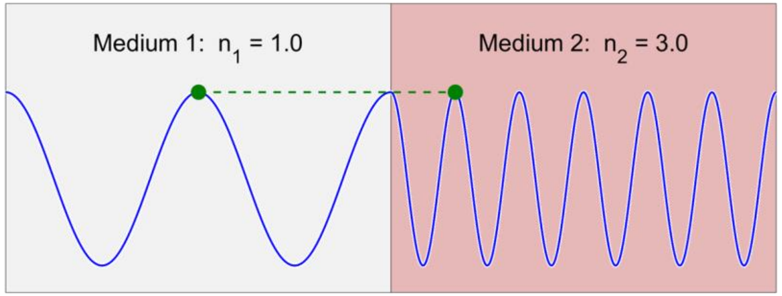
1. Tera-hertz time domain spectroscopy shows promise for interface strain and stress measurements by using passive sensor media, a baseline approach for the same has been established in this study.
2. The corelation of time or arrival and the strain/stress state in a loaded state (either thermal or mechanical or combined loading) is the novelty of this research.
3. Future research will enable in-situ measurement of interface strain in bi-material and multi-material interfaces.

Thank you

Questions ?

Back up slides

Mathematical modelling and data reduction



https://empossible.net/academics/emp4303/

v_w – velocity of wave

n – refractive index

ε_r – dielectric permittivity

$e_{vol}, e_{xx}, e_{yy}, e_{zz}$ – strains in local coordinate system

t_f, t_o – final thickness and initial thickness of sample

$\varepsilon^0 = \varepsilon^i$ – dielectric permittivity of undeformed composite (here PDMS + 8% STO)

ε_{eff} – effective dielectric permittivity of deformed composite as a function of strain

c – speed of light

μ_r – magnetic permeability

ToA – time of arrival of a wave

e_{11}, e_{22}, e_{33} – principal strains

ν – Poisson's ratio

ε^m – dielectric permittivity of matrix material (here PDMS)

d_{anten} – distance between the antennae

v_w – velocity of wave
n – refractive index
ε_r – dielectric permittivity
$e_{vol}, e_{xx}, e_{yy}, e_{zz}$ – strains in local coordinate system
t_f, t_o – final thickness and initial thickness of sample
$\varepsilon^0 = \varepsilon^i$ – dielectric permittivity of undeformed composite (here PDMS + 8% STO)
ε_{eff} – effective dielectric permittivity of deformed composite as a function of strain
c – speed of light
μ_r – magnetic permeability
ToA – time of arrival of a wave
e_{11}, e_{22}, e_{33} – principal strains
ν – Poisson's ratio
ε^m – dielectric permittivity of matrix material (here PDMS)
d_{anten} – distance between the antennae

The velocity of a wave in a media is given by

$$v_w = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r\, \mu_r}} \simeq \frac{c}{\sqrt{\varepsilon_r}} \quad \text{(i.)}$$

The volumetric strain in a thin plate can be approximated to

$$e_{vol} = e_{xx} + e_{yy} + e_{zz} \quad \text{(ii.)}$$

$$e_{xx} = \frac{-\nu \cdot e_{vol}}{1 - 2\nu}$$

$$e_{yy} = \frac{e_{vol}}{1 - 2\nu}$$

$$e_{zz} = \frac{-\nu \cdot e_{vol}}{1 - 2\nu}$$

On tensile loading of the sample there is a thickness change in the sample that is given by

$$t_f = t_0\left(1 - \frac{\nu \cdot e_{vol}}{1 - 2\nu}\right) \quad \text{(iii.)}$$

The effective dielectric permittivity will be dependent on the volumetric strain at each step and is given by Shkel Y.M. and Klingenberg D.J. (1998) as follows

$$\varepsilon_{ij} = \varepsilon^0 \cdot \delta_{ij} + a_1 \cdot e_{ij} + a_2 \cdot e_{kk} \cdot \delta_{ij} \rightarrow \begin{cases} \varepsilon_{11} = \varepsilon^0 + a_1 \cdot e_{11} + a_2 \cdot (e_{vol}) \\ \varepsilon_{22} = \varepsilon^0 + a_1 \cdot e_{22} + a_2 \cdot (e_{vol}) \\ \varepsilon_{33} = \varepsilon^0 + a_1 \cdot e_{33} + a_2 \cdot (e_{vol}) \end{cases} \quad \text{(iv.)}$$

$$a_1 = -\frac{2}{5}\frac{\left(\varepsilon^0 - \varepsilon^m\right)^2}{\varepsilon^m}$$

$$a_2 = -\frac{1}{3}\frac{\left(\varepsilon^i - \varepsilon^m\right)\left(\varepsilon^i + 2\varepsilon^m\right)}{\varepsilon^m} + \frac{2}{15}\frac{\left(\varepsilon^i - \varepsilon^m\right)^2}{\varepsilon^m}$$

The time of arrival of a wave is given by

$$ToA = \frac{d_{anten} - t_{sensor}}{v_{w,air}} + \frac{t_{sensor}}{v_{w,sensor}} \quad \text{(v.)}$$

Hence for undeformed sample with no strain, which is the initial case we have

$$ToA^{undeformed} = \frac{d_{anten}}{\mathrm{c}} - \frac{t_o}{c} + \frac{t_o}{\mathrm{c}}\sqrt{\varepsilon^0} \quad \text{(vi.)}$$

for the deformed sample we use the final thickness given by equation iii.

$$ToA_{xx}^{deformed} = \frac{d_{anten}}{\text{c}} - \frac{t_f}{c} + \frac{t_f}{\text{c}}\sqrt{\varepsilon_{11}} \tag{vii.}$$

$$ToA_{xx}^{deformed} = \frac{d_{anten}}{\text{c}} - \frac{t_0\left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right)}{c} + \frac{t_0\left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right)}{\text{c}}\sqrt{\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})}$$

Note that all the dielectric permittivities ε^0, a_1, a_2 (since $a_1, a_2 \rightarrow f(\varepsilon^0, \varepsilon^m)$) are directionally dependent. Using these equations, we compute the $\Delta ToA = ToA_{xx}^{deformed} - ToA_{xx}^{undeformed}$ simplified follows

$$\Delta ToA_{xx} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1 \tag{viii.}$$

$$\Delta ToA_{yy} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

References

[1] Fischer B., Hoffmann M., Helm H., Modjesch G. and Jepsen P.U. (2005) Chemical recognition in terahertz time-domain spectroscopy and imaging. *Semiconductor Science and Technology* **20**: S246-S253.

[2] Naftaly M. and Miles R.E. (2007) Terahertz Time-Domain Spectroscopy for Material Characterization. *Proceedings of the IEEE* **95**: 1658-1665.

[3] Palka N., Szustakowski M., Kowalski M., Trzcinski T., Ryniec R., Piszczek M., Ciurapinski W., Zyczkowski M., Zagrajek P. and Wrobel J. (2012) THz spectroscopy and imaging in security applications. Proc. 2012 19th International Conference on Microwaves, Radar & Wireless Communications, 265-270.

[4] Parrott E.P.J., Sun Y. and Pickwell-MacPherson E. (2011) Terahertz spectroscopy: Its future role in medical diagnoses. *Journal of Molecular Structure* **1006**: 66-76.

[5] Neu J. and Schmuttenmaer C.A. (2018) Tutorial: An introduction to terahertz time domain spectroscopy (THz-TDS). *Journal of Applied Physics* **124**: 231101.

[6] Shi Q., Tian K., Zhu H., Li Z.-R., Zhu L.-G., Deng H., Huang W. and Fu Q. (2020) Flexible and Giant Terahertz Modulation Based on Ultra-Strain-Sensitive Conductive Polymer Composites. *ACS applied materials & interfaces* **12**: 9790-9796.

[7] Moriwaki A., Okano M. and Watanabe S. (2017) Internal triaxial strain imaging of visibly opaque black rubbers with terahertz polarization spectroscopy. *APL Photonics* **2**: 106101.

[8] Ambhire S., Palkhivala S., Agrawal A., Gupta A., Rana G., Mehta R., Ghindani D., Bhattacharya A., Achanta V. and Prabhu S. (2018) “Pattern and Peel” method for fabricating mechanically tunable terahertz metasurface on an elastomeric substrate. *Optical Materials Express* **8**: 3382-3391.

[9] Everitt H.O., Tyler T., Caraway B.D., Bingham C.M., Llopis A., Heimbeck M.S., Padilla W.J., Smith D.R. and Jokerst N.M. (2019) Strain sensing with metamaterial composites. *Advanced Optical Materials* **7**: 1801397.

[10] Jang S.-D., Kang B.-W. and Kim J. (2013) Frequency selective surface based passive wireless sensor for structural health monitoring. *Smart Material Structures* **22**: 025002.

[11] Khatib O., Tyler T., Padilla W.J., Jokerst N.M. and Everitt H.O. (2020) Strain Sensing with THz Metamaterial Composites. Proc. Optical Sensors, SM4E. 5.

[12] Li J., Shah C.M., Withayachumnankul W., Ung B.S.-Y., Mitchell A., Sriram S., Bhaskaran M., Chang S. and Abbott D. (2013) Flexible terahertz metamaterials for dual-axis strain sensing. *Optics letters* **38**: 2104-2106.

[13] Li J., Shah C.M., Withayachumnankul W., Ung B.S.-Y., Mitchell A., Sriram S., Bhaskaran M., Chang S. and Abbott D. (2013) Mechanically tunable terahertz metamaterials. *Applied Physics Letters* **102**: 121101.

[14] Zhao X., Yang B., Liu J., Pitchappa P., Hasan D., Ho C.P., Yang C. and Lee C. (2016) A multiband flexible terahertz metamaterial with curvature sensing functionality. *Journal of Optics* **18**: 075101.

[15] Wei X., Gao S., Zhang N. and Zhao H. (2020) Dimensional effect of SrTiO3 particles on functional performance optimization of polydimethylsiloxane-based composites for dielectric elastomer actuators. *Materials Research Express* **7**: 105012.

References

[16] Dhiman A., Sharma A., Shashurin A. and Tomar V. (2018) Strontium Titanate Composites for Microwave-Based Stress Sensing. *JOM - Journal of the Minerals, Metals and Materials Society* **70**: 1811.

[17] Wang Z., Kang K., Wang S., Li L.a., Xu N., Han J., He M., Wu L. and Zhang W. (2016) Determination of plane stress state using terahertz time-domain spectroscopy. *Scientific Reports* **6**: 36308.

[18] Choudhury D., Mukherjee S., Mandal P., Sundaresan A., Waghmare U.V., Bhattacharjee S., Mathieu R., Lazor P., Eriksson O., Sanyal B., Nordblad P., Sharma A., Bhat S.V., Karis O. and Sarma D.D. (2011) Tuning of dielectric properties and magnetism of SrTiO${}_{3}$ by site-specific doping of Mn. *Physical Review B* **84**: 125124.

[19] Zamudio-Lara A., Koshevaya S.V., Grimalsky V.V. and Yañez-Cortes F. (2015) Frequency multiplication of terahertz radiation in the crystals of strontium titanate paraelectric. *Radioelectronics and Communications Systems* **58**: 411-416.

[20] Samara G.A. and Giardini A.A. (1965) Pressure Dependence of the Dielectric Constant of Strontium Titanate. *Physical Review* **140**: A954-A957.

[21] Shaw T., Suo Z., Huang M., Liniger E., Laibowitz R. and Baniecki J. (1999) The Effect of Stress on the Dielectric Properties of Barium Strontium Titanate Thin Film. *Applied Physics Letters* **75**: 2129-2131.

[22] Hu T., Juuti J., Jantunen H. and Vilkman T. (2007) Dielectric properties of BST/polymer composite. *Journal of the European Ceramic Society* **27**: 3997-4001.

[23] Shkel Y.M. and Klingenberg D.J. (1998) Electrostriction of polarizable materials: Comparison of models with experimental data. *Journal of Applied Physics* **83**: 415-424.

[24] Samara G.A. (1966) Pressure and Temperature Dependences of the Dielectric Properties of the Perovskites BaTi${\mathrm{O}}_{3}$ and SrTi${\mathrm{O}}_{3}$. *Physical Review* **151**: 378-386.

[25] Haeni J.H., Irvin P., Chang W., Uecker R., Reiche P., Li Y.L., Choudhury S., Tian W., Hawley M.E., Craigo B., Tagantsev A.K., Pan X.Q., Streiffer S.K., Chen L.Q., Kirchoefer S.W., Levy J. and Schlom D.G. (2004) Room-temperature ferroelectricity in strained SrTiO3. *Nature* **430**: 758-761.

[26] Silverman B.D. (1962) Microwave Absorption in Cubic Strontium Titanate. *Physical Review* **125**: 1921-1930.

[27] Lasko D.Y.a.G. (2012) Field of Stresses in an Isotropic Plane with Circular Inclusion under Tensile Stress. *Engineering* **4**: 583-589.

[28] Wang Z., Volinsky A.A. and Gallant N.D. (2014) Crosslinking effect on polydimethylsiloxane elastic modulus measured by custom-built compression instrument. *Journal of Applied Polymer Science* **131**.

[29] Dogru S., Aksoy B., Bayraktar H. and Alaca B.E. (2018) Poisson's ratio of PDMS thin films. *Polymer Testing* **69**: 375-384