Ming Hsieh Department of Electrical Engineering

USC Viterbi School of Engineering

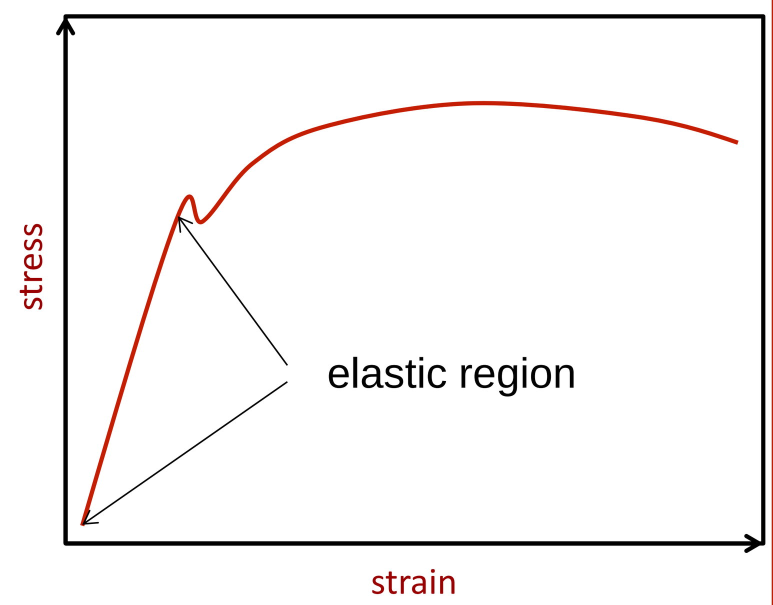
Fiber-based polarimetric stress sensor for measuring the Young's modulus of biomaterials

Mark C. Harrison, Andrea M. Armani

Ming Hsieh Department of Electrical Engineering

Background

Recently, it has been shown that the Young's modulus, a measure of the elasticity of a material, can be used to distinguish between cancerous and non-cancerous tissue. Researchers have also used polarization-maintaining optical fiber to measure stress in materials. By using a simplified setup and generalizing the theoretical analysis of these types of sensors, we are building a tool that will allow us to easily measure the Young's modulus of tissue samples for potential diagnostic purposes.



The Young's modulus is the slope of the linear, elastic region of a stress-strain curve

Testing Setup

This diagram schematically shows the various parts of the experimental setup. Laser light is coupled into an in-line polarizer connected to polarization-maintaining fiber. The fiber, which is the transducing element, is strung through the sample and connected to a polarimeter. A load frame compresses the sample while simultaneously measuring reference data.

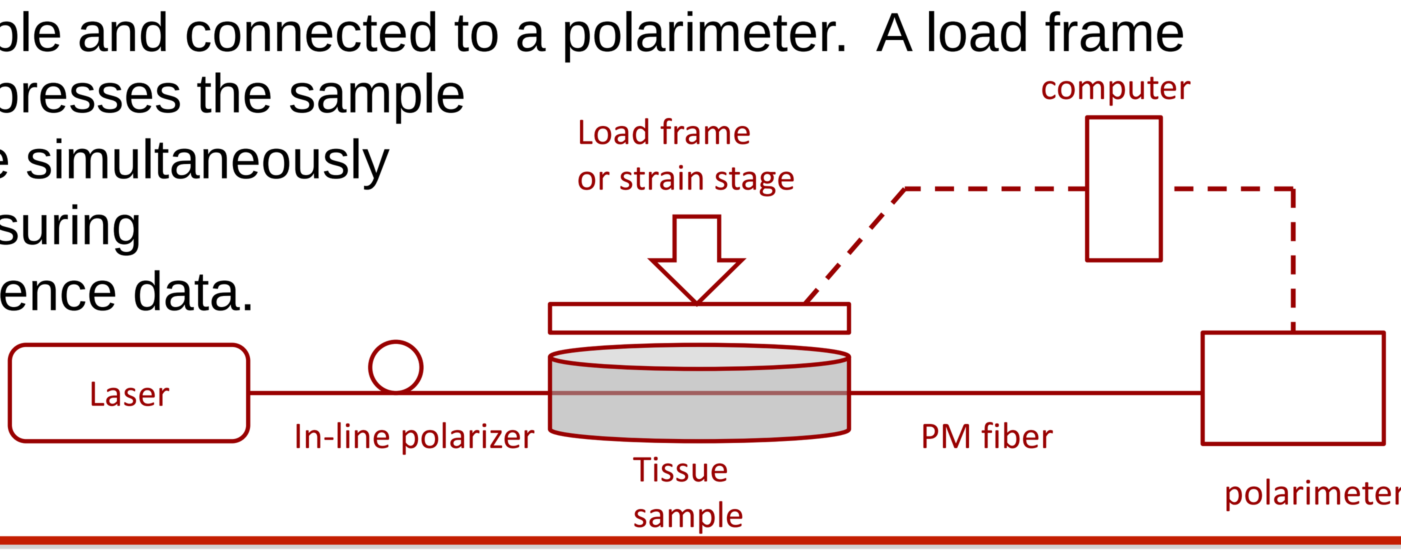
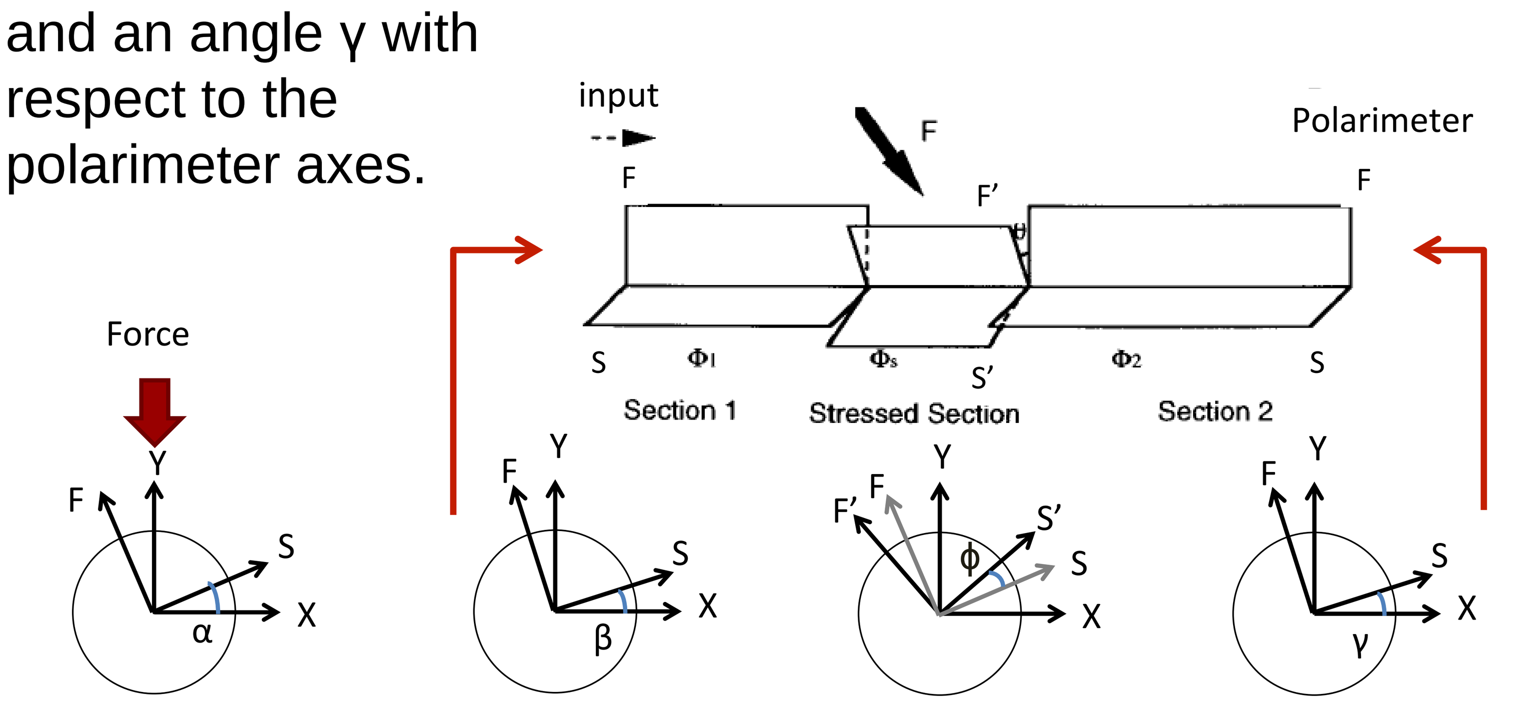


Diagram of Stress Effects

An applied force rotates the birefringent axes of the stressed region (ϕ) and changes the beat length of the fiber in that region. Additionally, the birefringent axes are rotated at an angle α with respect to applied force, an angle β with respect to the initial linear polarization axis, and an angle γ with respect to the polarimeter axes.



J. A. Zhang, et. Al., "Distributed sensing of polarization mode coupling in high birefringence optical fibers using intense arbitrarily polarized coherent light," *IEEE J. of Lightwave Tech.*, vol. 15, pp. 794-802, May 1997.

Transfer Matrix

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{j\delta} \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$$
$$* \begin{bmatrix} e^{-jkN_s l} & 0 \\ 0 & e^{-jkN_f l} \end{bmatrix} \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} E_{x0} \\ 0 \end{bmatrix}$$

Normalized force: $F = 2N^3(1+\sigma)(p_{12}-p_{11})L_{b0}\boldsymbol{f}/(\lambda\pi bY)$

Angle of rotated axes: $\tan 2\phi = \mathrm{F}\sin 2\boldsymbol{\alpha}/(1+F\cos 2\boldsymbol{\alpha})$

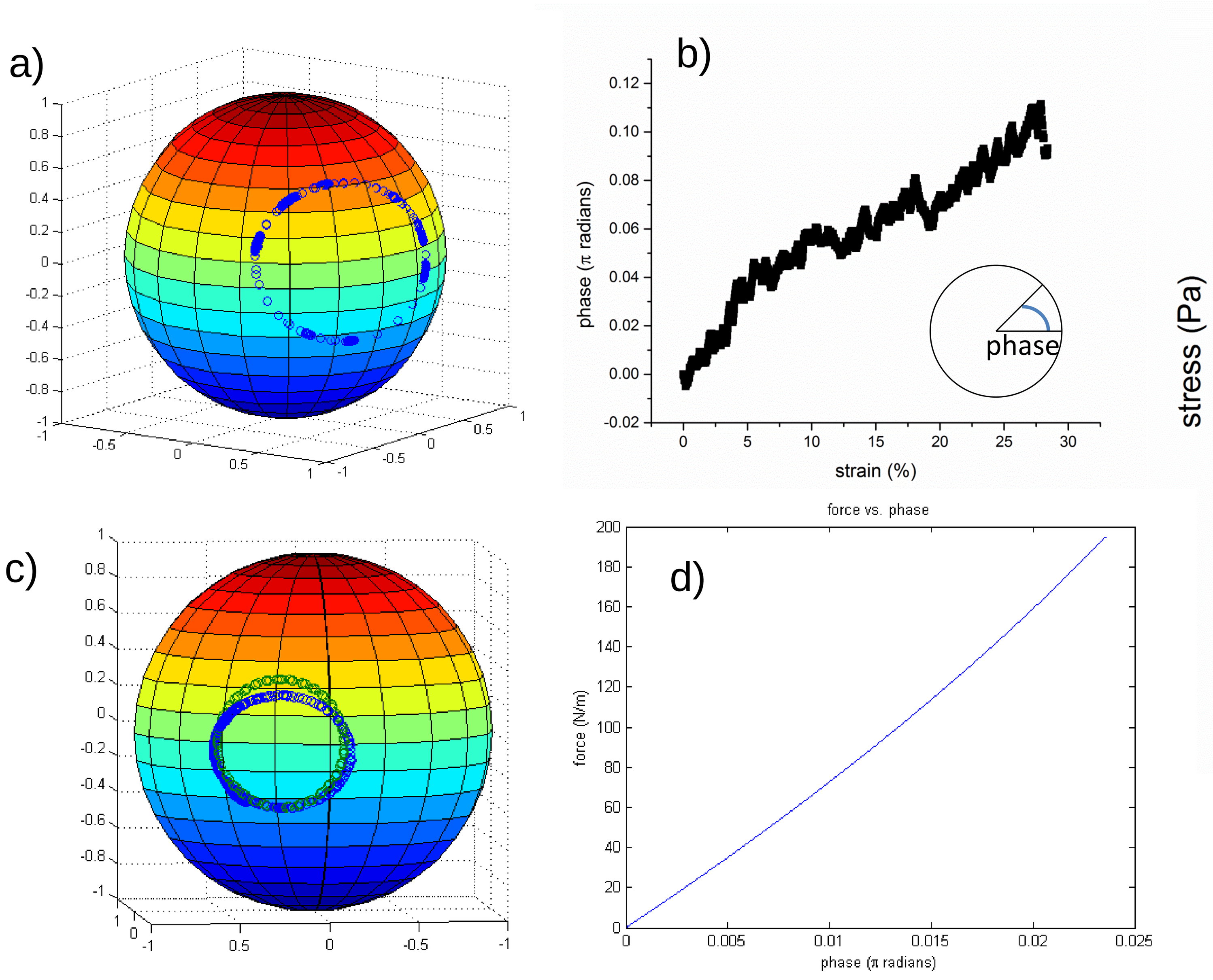
Modified beat length: $L_b = L_{b0}(1+F^2+2F\cos 2\boldsymbol{\alpha})^{-1\,2}$

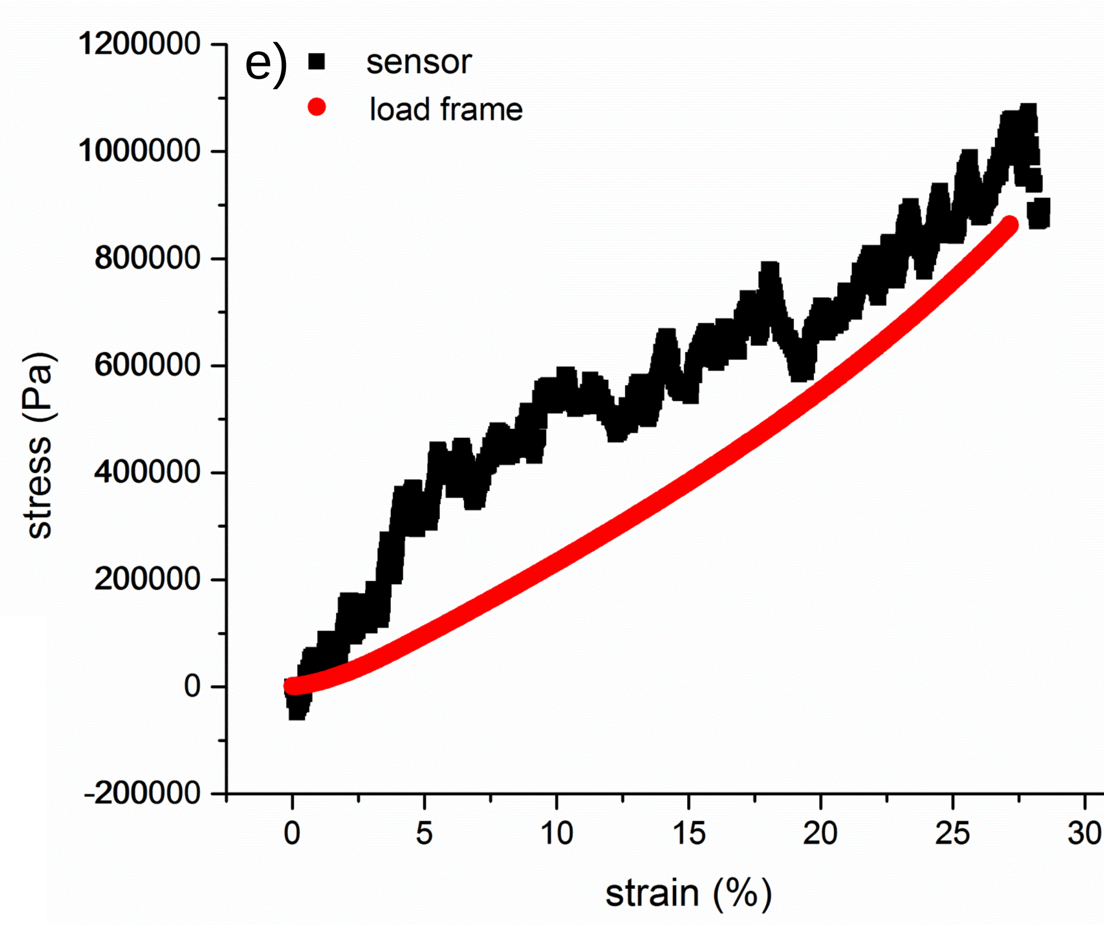
f = applied force in [N/m], N = refractive index of the fiber, σ = Poisson's ratio, Y = Young's modulus, L_{b0} = beat length of fiber without stress, p_{ij} = photoelastic constant

This transfer matrix and the associated equations fully describe how the polarization evolves as it passes through the fiber, as diagrammatically shown to the left, and stress is applied to the sample.

Data and Analysis

a) Raw sensor data is recorded as an arbitrary polarization state represented by three Stokes parameters shown plotted on a Poincaré sphere as a series of 3-dimensional points. b) The raw data is analyzed to produce a plot of phase-angle of the plotted circle vs. increasing strain.





	Young's modulus
Load frame	31.70 kPa
sensor	30.29 kPa

The Young's modulus can be measured directly from the slope of the stress-strain curve. The measured Young's modulus from the reference data (load frame) and experimental data (sensor) match well.

c) A plot of the theoretical fit (green) to the raw data (blue). This fit is used to produce a calibration curve. d) The calibration curve relates the applied force to the measured polarization changes. e) The analyzed experimental data is calibrated with the calibration curve and plotted alongside reference data from the load frame. Data shown here is an average of ten repeated runs.

Conclusions and Future Work

Right: A photo of one of our tested PDMS samples with an optical fiber embedded in it. These PDMS samples are a good analog to tissue samples that we plan to test with in the future.

We have demonstrated that our fiber-based polarimetric stress sensor can measure the Young's modulus of materials with different stiffnesses. The next step is to prepare the testing setup to accommodate tissue samples and to measure the Young's modulus of various real tissue samples. Based on these preliminary results, we believe our sensor will be able to distinguish between materials with different stiffness and will be a valuable tool for diagnostic researchers.

Thank you to the following organizations for their generous support: USC Provost's fellowship Program, NDSEG Fellowship Program.

More information is available at:
Armani Research Group: http://armani.usc.edu
Mark C. Harrison: http://www-scf.usc.edu/~markchar

Ming Hsieh Institute
Ming Hsieh Department of Electrical Engineering