COE CST Fourth Annual Technical Meeting

High-Temperature Pressure Sensors for Hypersonic Vehicles

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Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

- **University of Florida**
  - **Mark Sheplak** – Professor, Dept. of Mechanical and Aerospace Engineering
  - **David Mills** – Graduate Research Assistant
  - **Daniel Blood** – Graduate Research Assistant
- **Florida State University**
  - **William Oates** – Asst. Professor, Dept. of Mechanical Engineering
  - **Justin Collins** – Graduate Research Assistant

Task Description

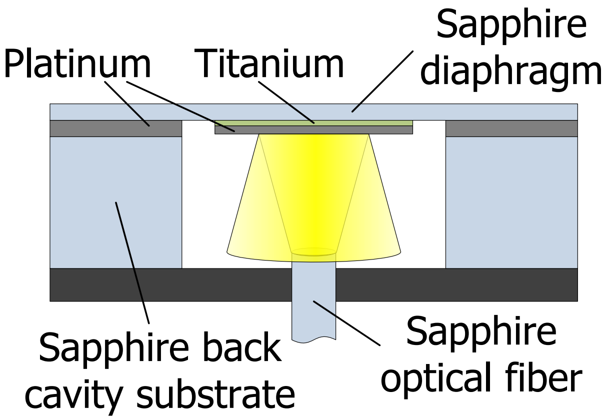
- Conventional instrumentation is unsuitable for continuous measurement in high-temperature environments such as:
  - High-speed reentry vehicles
  - Hypersonic transports
  - Gas Turbines
  - Scramjets
- Temperature mitigation techniques:
  - Stand-off tubes - cause signal attenuation and degradation
  - Water cooling - impart unknown aerothermal effects on the surrounding flow
- Pressure sensors capable of high-temperature operation (>1000°C) **without use of these techniques** will improve understanding of shock-wave/boundary layer interactions which directly influence critical vehicle characteristics such as lift, drag, and propulsion efficiency

Goals

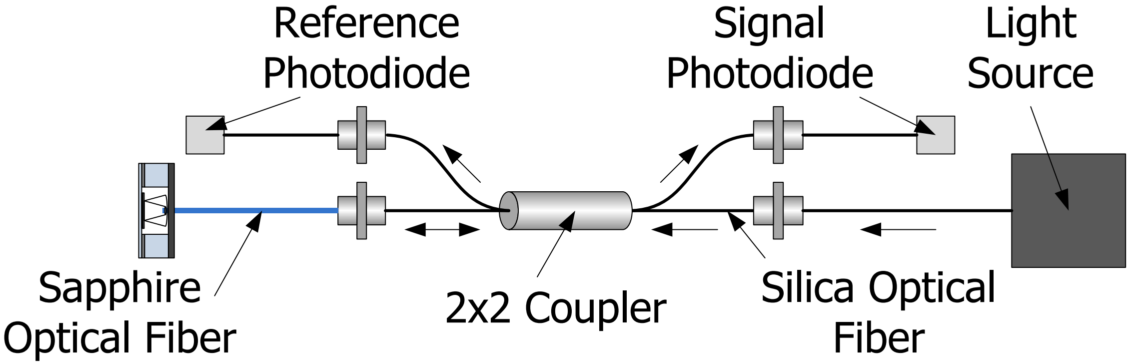
- Identify a suitable sensing method, material, and fabrication process for a high-bandwidth pressure sensor capable of continuous operation in temperatures in excess of 1000°C
- Fabricate a prototype sensor and create a robust high-temperature package
- Characterize the packaged sensor at room temperature and in high-temperature environments
- Implement the packaged sensor in a hypersonic or hot jet flow facility and/or a gas turbine

Sensor Overview

- Fiber-optic lever
  - Intensity modulation via diaphragm deflection
  - Single send/receive fiber



- Optical configuration
  - – 850 nm LED source with multimode fibers
  - – Silica optical fiber components reduce packaging costs
  - – Reference photodiode monitors drift in LED source

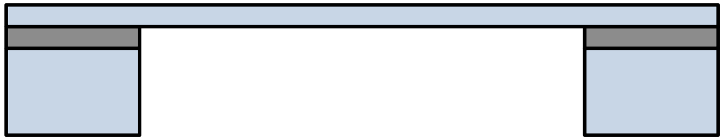


Fabrication

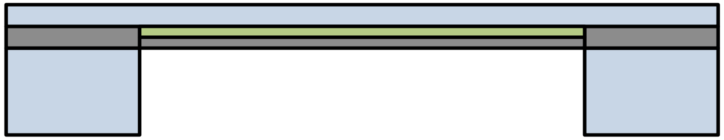
(a) Begin with 10 mm x 10 mm x 1 mm sapphire substrate.

(b) Machine 7 mm diameter hole to form back cavity.

(c) Sputter deposit 500 nm of platinum for bonding layer.



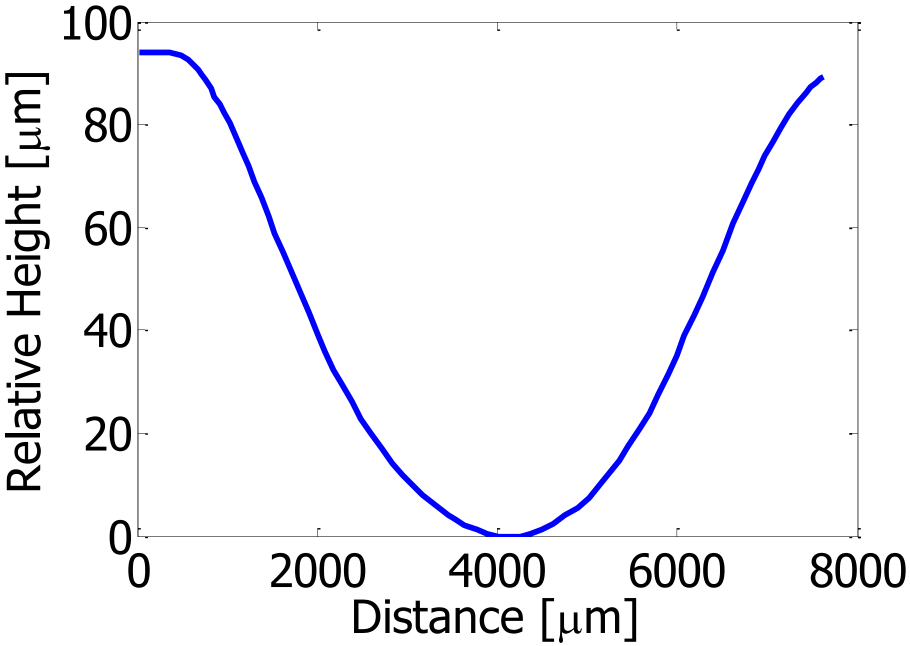
(d) Bond 50 µm thick diaphragm to back cavity using SPS.



(e) Sputter deposit 20 nm of Ti and 200 nm of Pt under continuous vacuum.

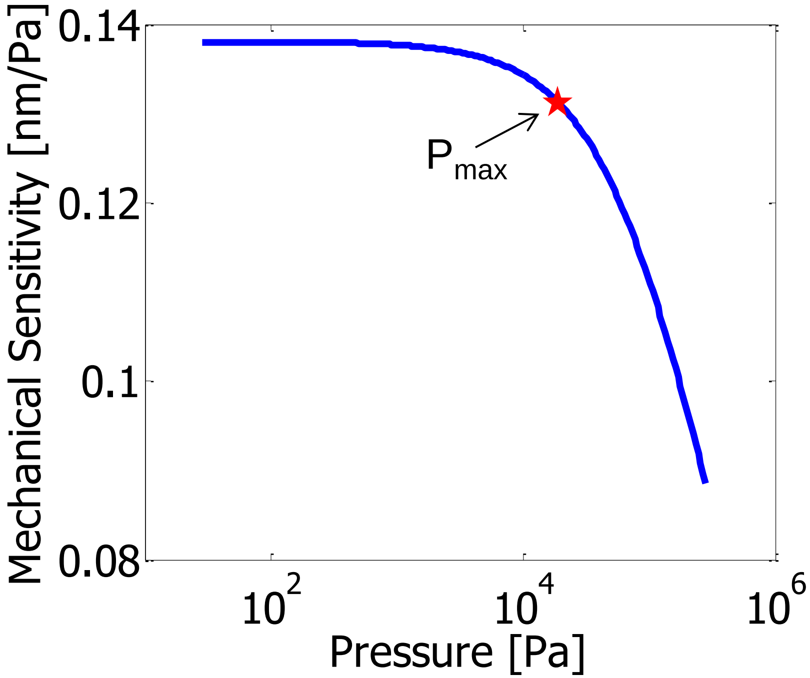
Post-bond Buckling Analysis

- Static deflection of the diaphragm measured using a scanning white-light interferometer
- Axisymmetric buckling profile – 94.1 μm center deflection



Post-bond Buckling Analysis

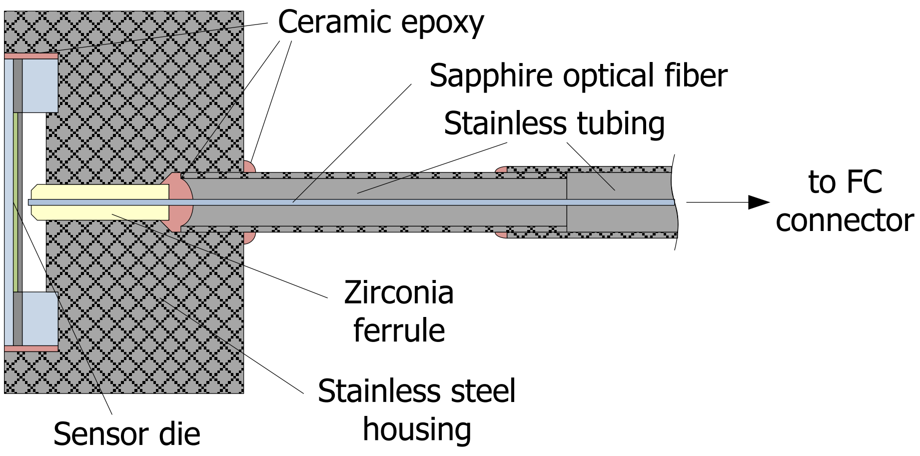
- Nonlinear plate model developed by Williams et al[1]
  - Compression factor, $k^2 = 42.8$
  - Residual compressive stress = 296 MPa
  - Mechanical sensitivity = 0.138 nm/Pa
    - 4x reduction in sensitivity compared to unstressed diaphragm
  - Max pressure (5% reduction in sensitivity) = 19.3 kPa

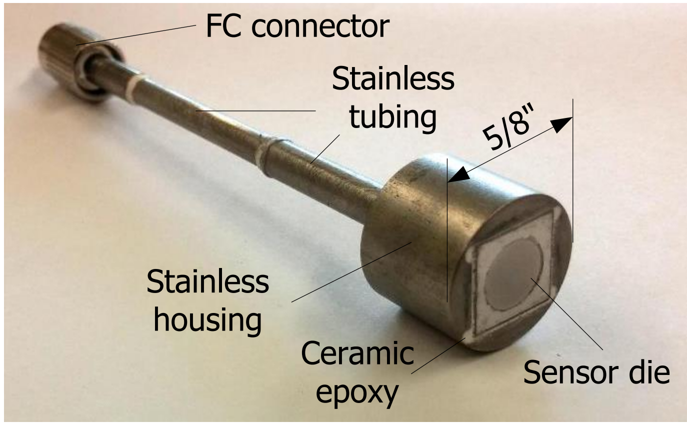


[1] Williams, M., Griffin, B., Homeijer, B., Sankar, B., and Sheplak, M., "The nonlinear behavior of a post-buckled circular plate," Sensors 2007 IEEE, 349–352 (2007).

Packaging

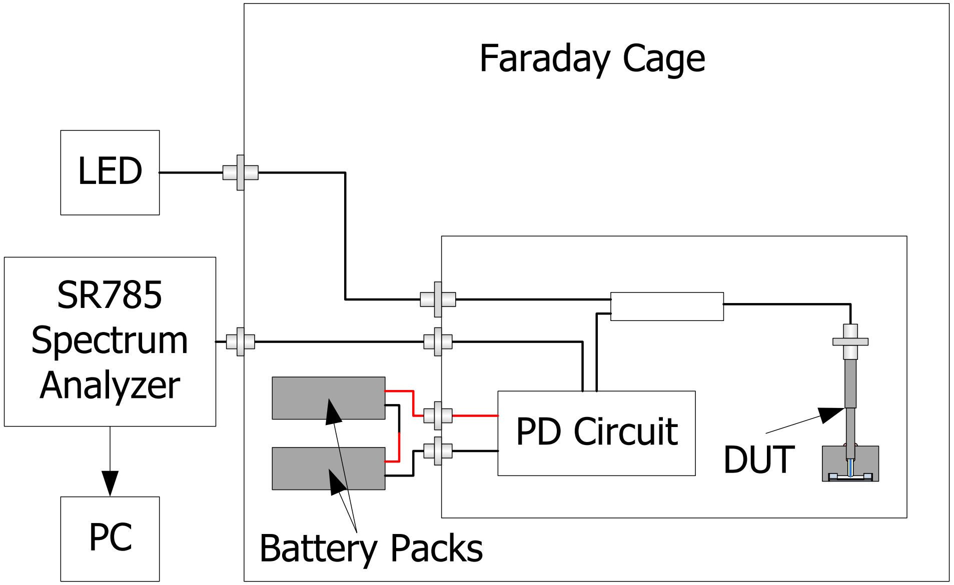
- High-temperature alumina ceramic epoxy used to package sensor in stainless steel housing
- Stainless steel tubing protects sapphire optical fiber and attaches to standard FC optical connector
- Package enables operation up to 900°C

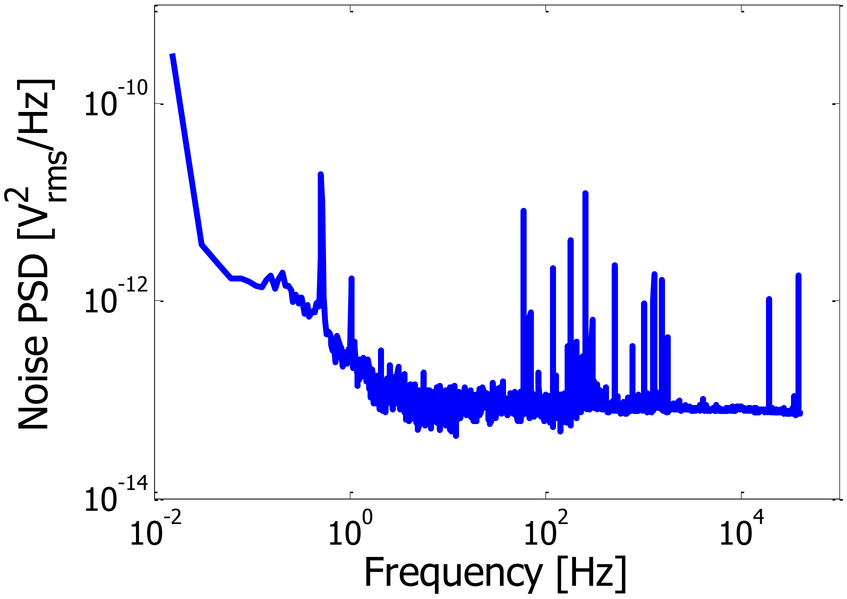




Noise Floor Measurement

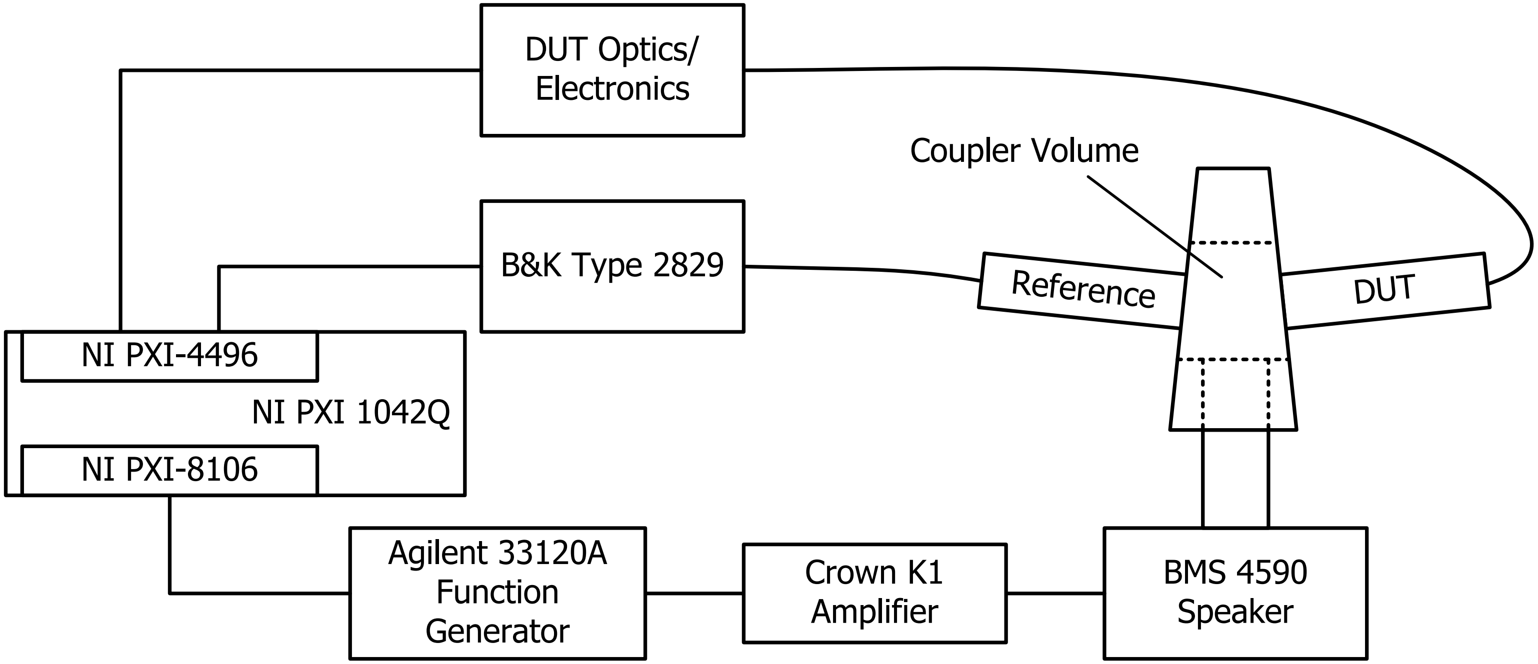
- Noise spectrum dominated by photodiode shot noise
- 1/f corner frequency: 8 Hz
- Noise floor: 1.2 µV @ 1 kHz w/ 1 Hz bin





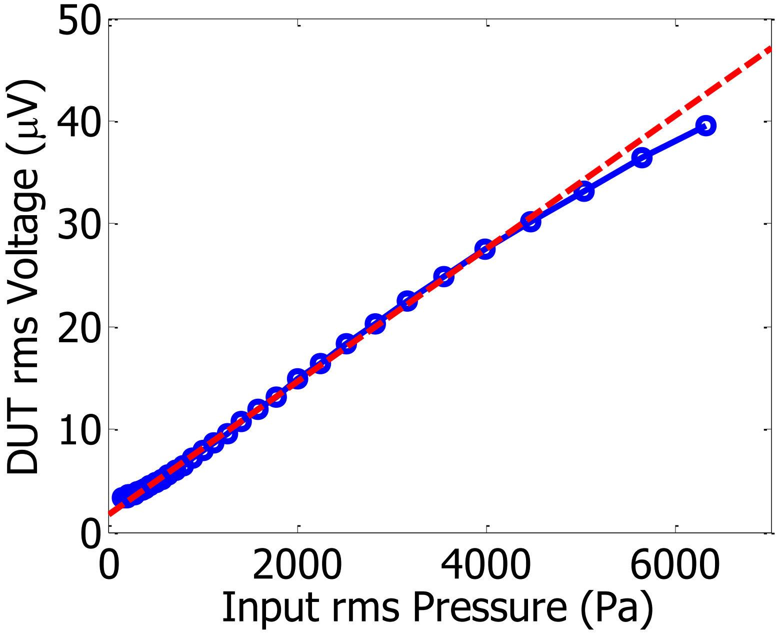
Acoustic Characterization – Setup

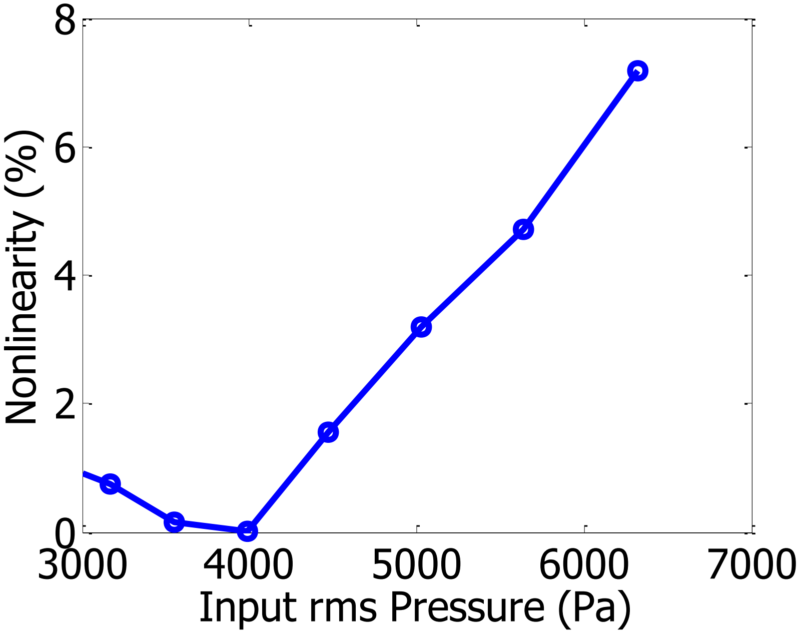
- Wedge-shaped acoustic coupler
  - Reduces number of supported modes within the cavity
  - Cavity volume: 0.5 cm^3



Acoustic Linearity

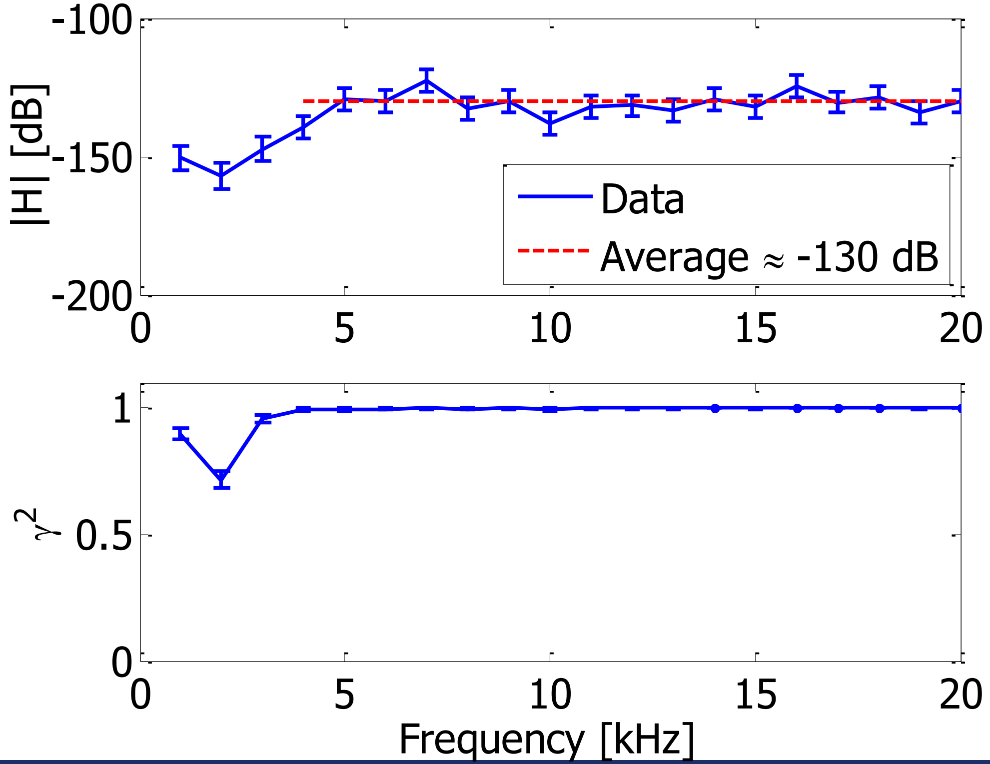
- Testing frequency: 1.9 kHz
- Input pressure level: 138-170 dB (ref 20 μPa)
- Sensitivity: -164 dB (ref 1 V/Pa)
- 5% acoustic nonlinearity: 5.7 kPa





Frequency Response

- Single-tone measurements from 1-20 kHz at 145 dB in 1 kHz steps
- Flat-band sensitivity: -130 dB re 1 V/Pa (0.32 μV/Pa)
- Minimum detectable pressure (MDP): 3.8 Pa



Conclusions and Future Work

- Summary
  - Demonstrated novel SPS bonding process for joining sapphire substrates
  - Developed high-temperature package for operation up to 900°C
  - Determined noise floor, linearity, and frequency response of the packaged sensor at room temperature
- Next Steps
  - Further modification of SPS bonding process to reduce residual stress and eliminate buckling in diaphragm
  - Fabricate thinner sapphire diaphragms to improve sensitivity
  - Packaging improvements to extend high-temperature capability and enable dc pressure measurement
  - High-temperature calibration
- Conference Publications
  - D. Mills, D. Blood, J. Collins, W. Oates, T. Schmitz, and M. Sheplak, “Development of processing technology for high-temperature optical pressure sensors,” Technical Digest of the 2012 Solid-State Sensor and Actuator Workshop, Hilton Head Isl., SC, 6/4-7/2012, pp. OP6.
  - D. Mills, D. Alexander, G. Subhash, and M. Sheplak, “Development of a sapphire optical pressure sensor for high-temperature applications,” Proc. SPIE 9113, Sensors for Extreme Harsh Environments, Baltimore, MD, 6/5/2014.