Wireless, Passive Ceramic Strain Sensors for Turbine Engine Applications

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Outline

- Motivation
- Strain Sensors - State of the Art
- Objectives
- Schedule and timelines
- Accomplishment
- Future Work
- Summary

Motivation – applications of turbines

- Turbine engines – key for energy generation and propulsion

Description	2007
Net Generation (thousand megawatthours)	
Coal[1]	2,016,456
Petroleum[2]	65,739
Natural Gas	896,590
Other Gases[3]	13,453
Nuclear	806,425
Hydroelectric Conventional[4]	247,510
Other Renewables[5]	105,238
Wind	34,450
Solar Thermal and Photovoltaic	612
Wood and Wood Derived Fuels[6]	39,014
Geothermal	14,637
Other Biomass[7]	16,525
Pumped Storage[8]	-6,896
Other[9]	12,231
All Energy Sources	**4,156,745**

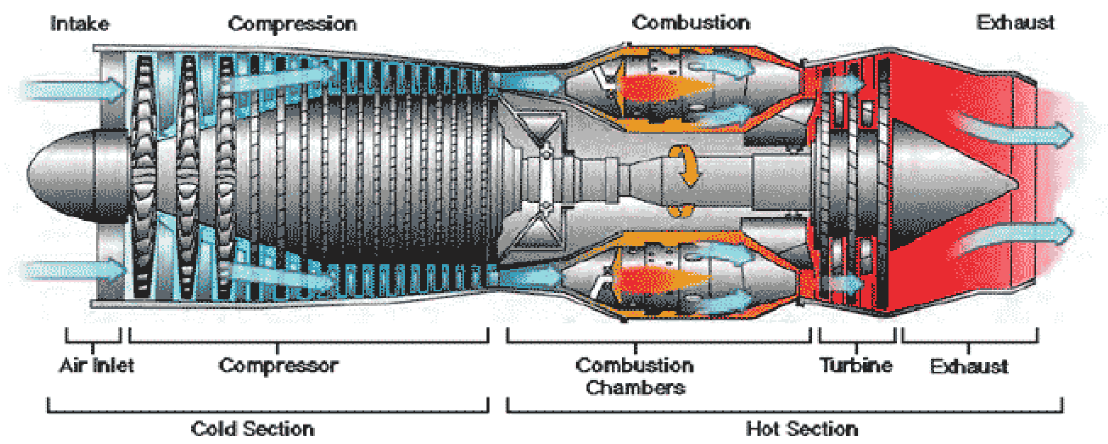
~50%

Major power generation techniques need turbine engines

2007 Energy Generation Statistics (DOE)

Motivation – need for wireless strain sensors

- Many parts in turbine engines subjected to severe strain/stress in extreme environments
- Strain sensors
  - Predict the failure
  - Reduce unnecessary out-of-service examination and replacement
- Moving parts/hidden areas – need wireless
- High temperatures – need passive



State of the Art

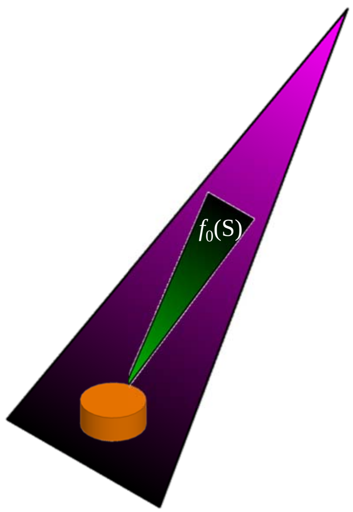
- Optical-Based Non-Contact Sensors
  - Lack of necessary accuracy
  - Not robust in harsh environments
- Strain gage
  - Piezoresistivity – changes in resistivity with strain/stress
  - Cannot be wireless
- Piezoelectric based load cell
  - Can be wireless
  - Piezoelectric materials cannot be used to high temperatures
- Capacitive based pressure sensor
  - Can measure pressure induced strain/stress
  - Cannot measure strain/stress of parts

Objectives

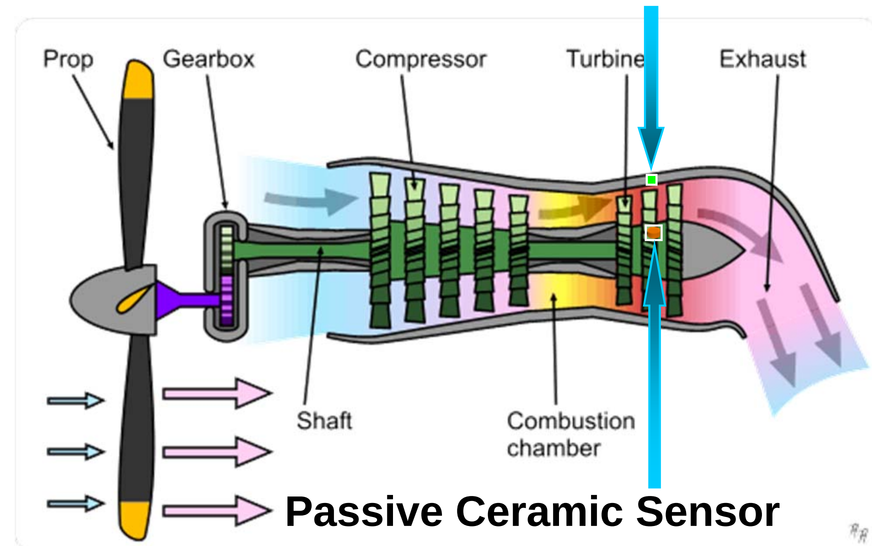
- Overall Objective

  Develop wireless passive polymer-derived ceramic strain/stress sensors based on cavity RF resonator

- Scientific Goals
  - Develop piezo-dielectric polymer-derived ceramics (p-PDCs)
  - Design and fabricate resonator sensors
  - Characterize the sensors in extreme environments

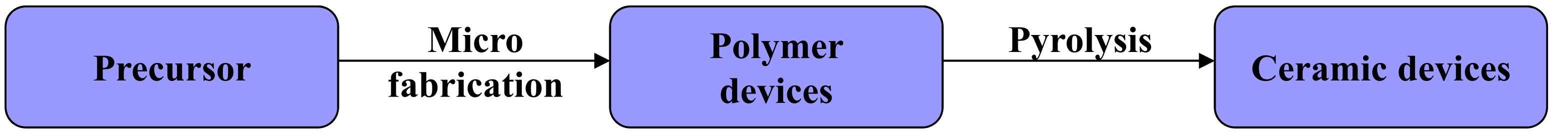


Passive Ceramic Sensor



Passive Ceramic Sensor

Background – polymer-derived ceramics

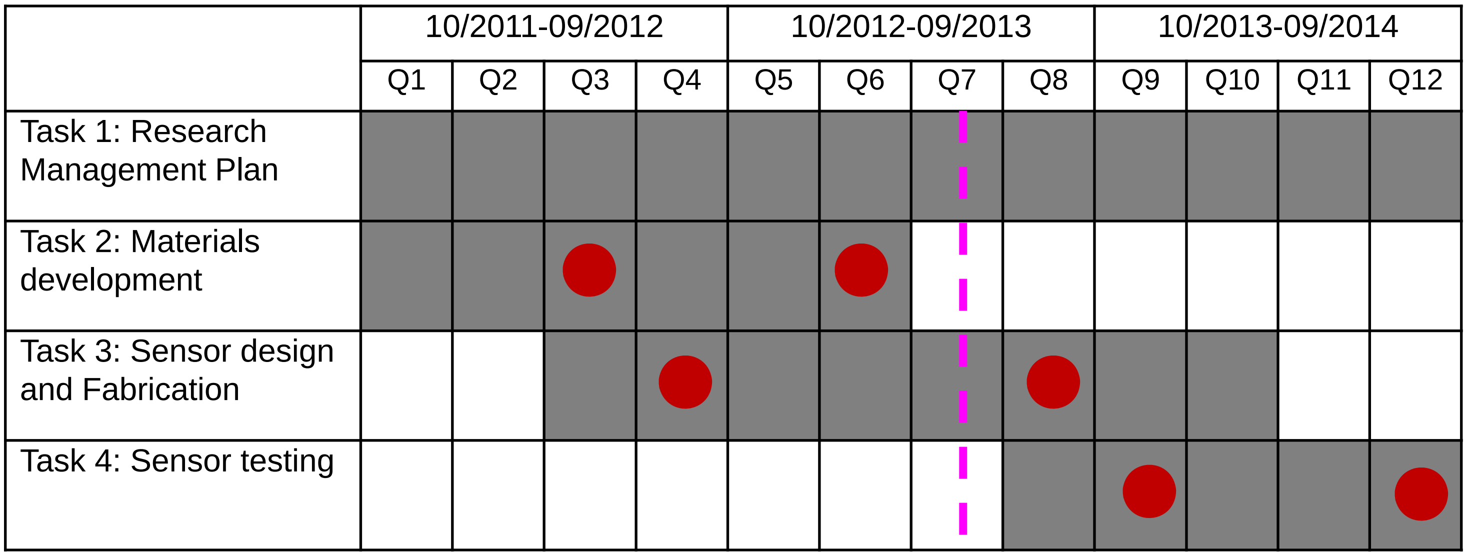


- Excellent high-temperature resistance
  - High thermal stability
  - Excellent high-temperature mechanical properties
  - High oxidation/corrosion resistance

- Microfabrication capability

- Unique electric/dielectric behavior
  - Resistivity varied in a large range
  - High piezoresistivity
  - High piezo-dielectricity

Schedule and Timeline



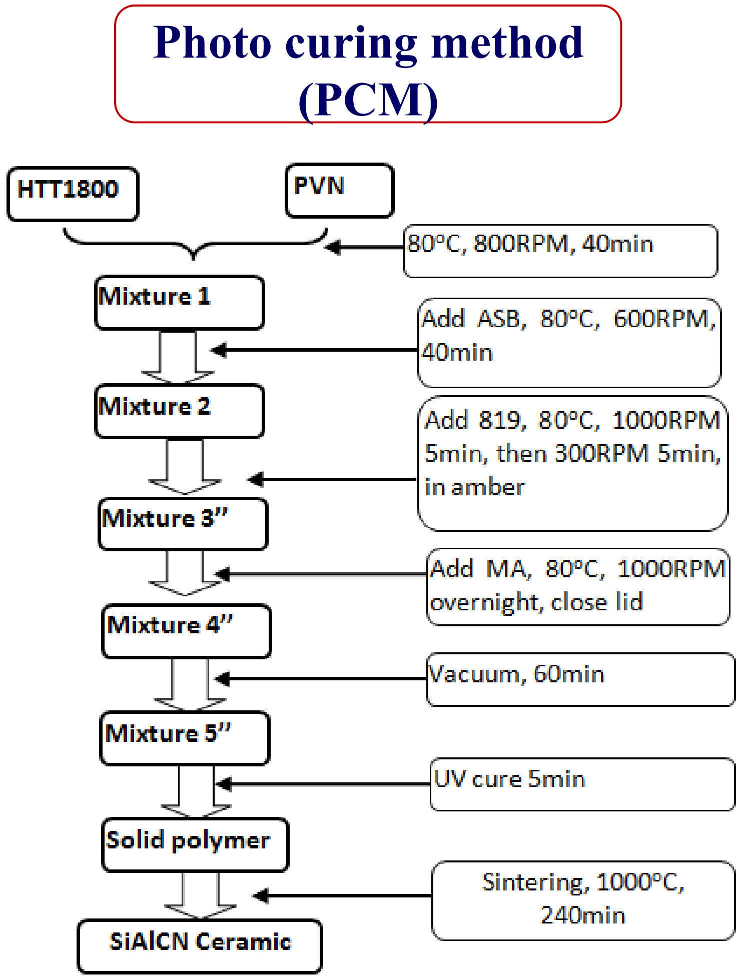
Milestone	Planned Completion Date	Verification Method
1: Finish room temperature material selection	06/30/2012	Report
2: Finish first run of sensor design	09/30/2012	Report
3: Finish final material selection	03/31/2013	Report
4: Finish final sensor design	09/30/2013	Report
5: Sensor fabrication	12/31/2013	Report Prototype
6: Sensor characterization	09/30/2014	Report Prototype

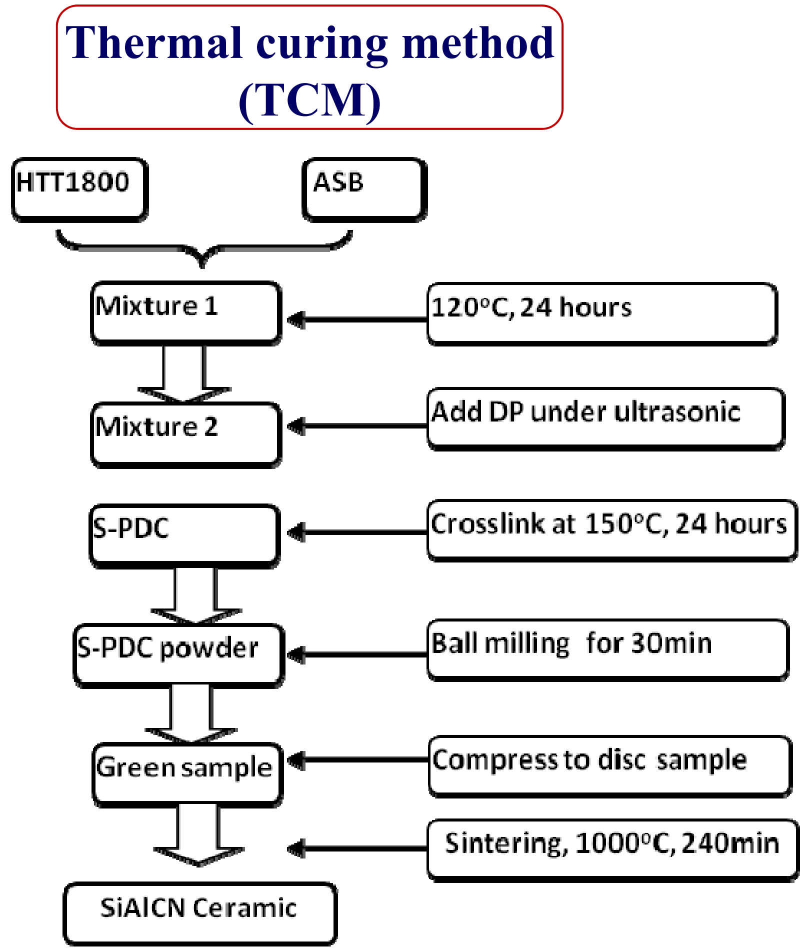
Finished

Accomplishments

- Material development
  - Starting chemicals
    - **Polysilazane (HTT1800) – main precursor**
    - **Phenylbis (2, 4, 6-trimethylbenzoyl) phosphine oxide (819) – photo initiator**
    - **Dicumyl peroxide (DP) – thermal initiator**
    - **Methacrylic Acid (MA) – photopolymerization enhancer**
    - **Aluminum-tri-sec-butoxide (ASB) – precursor for Al**
    - **Poly (melamine-co-formaldehyde) acrylated solution (PVN) –precursor for N**

□SiAlCN ceramic fabrication





☐Materials synthesized

PCM

Name	MA	ASB	819	HTT1800	PVN
S-1	2 wt%	5 wt%	5 wt%	78 wt%	10 wt%
S-2	2 wt%	5 wt%	5 wt%	68 wt%	20 wt%
S-3	2 wt%	5 wt%	5 wt%	58 wt%	30 wt%
S-4	2 wt%	10 wt%	5 wt%	53 wt%	30 wt%
S-5	2 wt%	20 wt%	5 wt%	43 wt%	30 wt%

TCM

Name	ASB	DP	HTT1800
S-6	5 wt%	5 wt%	90 wt%
S-7	1 wt%	0 wt%	99 wt%
S-8	5 wt%	0 wt%	95 wt%
S-9	10 wt%	0 wt%	90 wt%
S-10	1 wt%	2 wt%	97 wt%

Dielectric property measurements

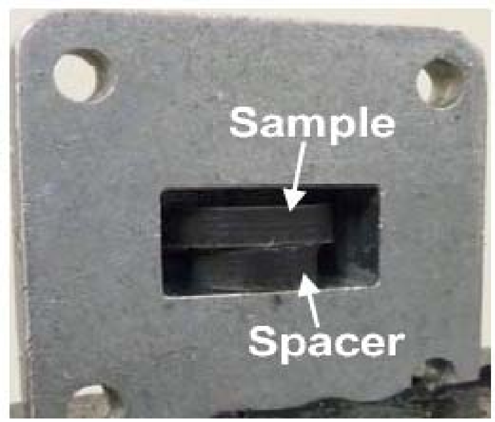
Waveguide cavity → Measured F and Q → HFSS simulation → Matched F and Q → Dielectric constant and loss

Dielectric Ceramic

F_0, Q_0 Empty cavity

F, Q Empty cavity

Detected by network analyzer



□Properties

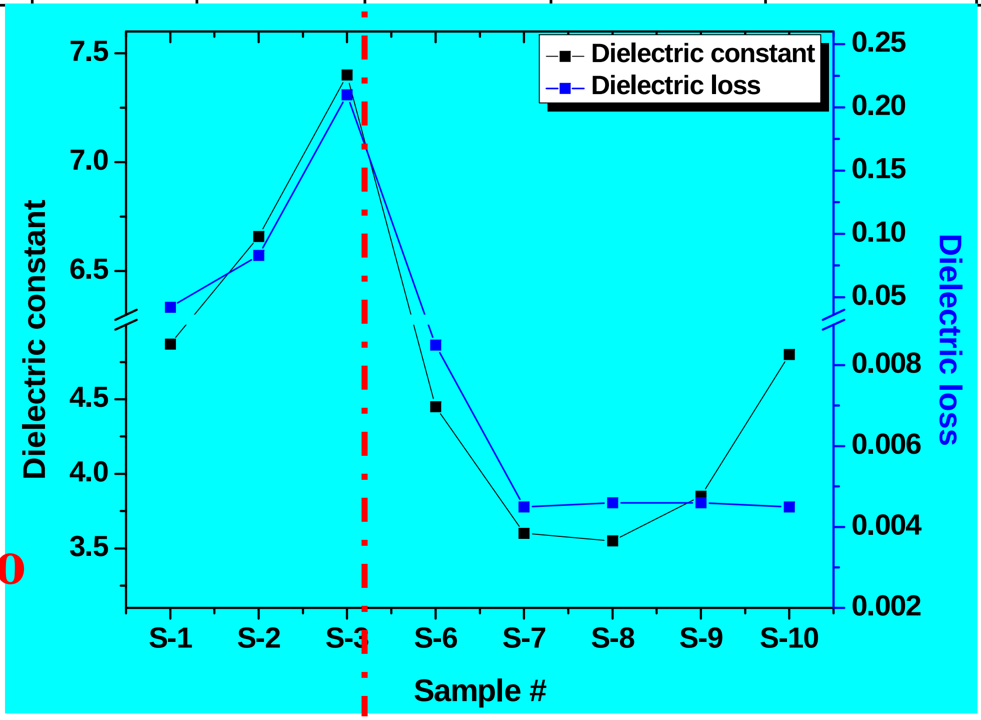
PCM TCM

Name	S-1	S-2	S-3	S-6	S-7	S-8	S-9	S-10
Dielectric constant	4.87	6.66	7.40	4.45	3.6	3.55	3.85	4.8
Dielectric loss	0.042	0.083	0.21	0.0085	0.0045	0.0046	0.0046	0.0045
Frequency (GHz)	9.767	9.743	9.718	8.826	9.028	9.221	9.337	9.0035
Q-factor	1452	978	445	557	1126	1370	1676	1386

High ε

Low F

Easy to detect



High ε

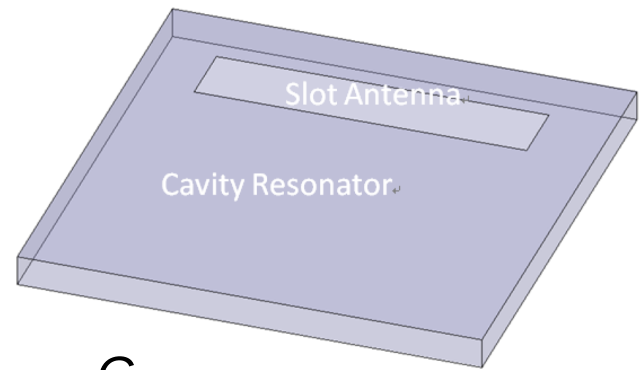
Low loss

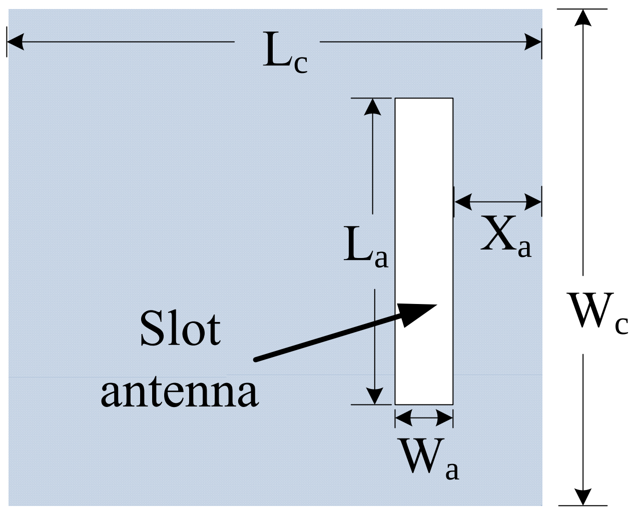
Low loss

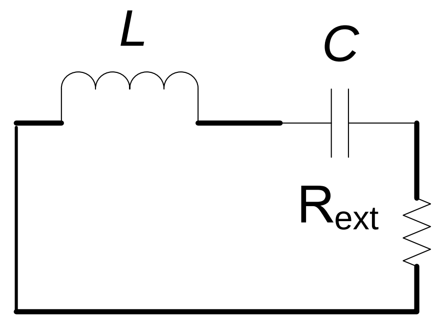
High S-to-N ratio

Easy to detect

- Sensor design
  - Proposed sensor structure





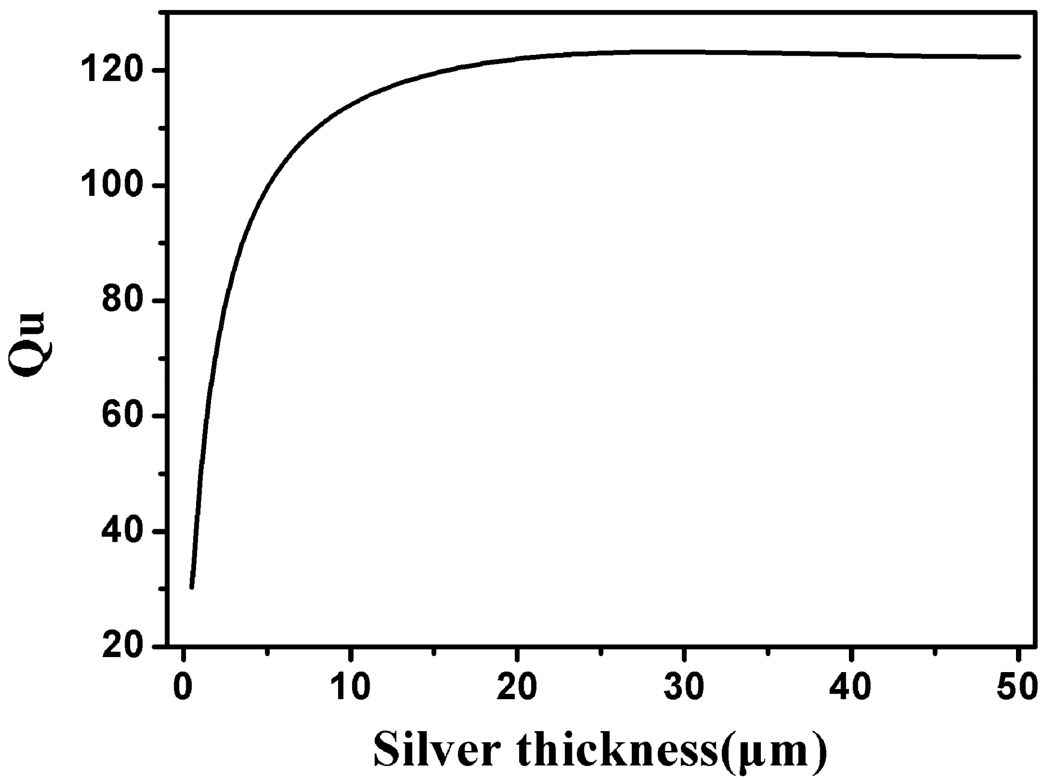


$$Q_{ext} = \frac{\omega_0 L}{R_{ext}}$$

<u>Factors that affect the Q-factor:</u>

✓Thickness of metal skin
✓Size of the substrat (Lc and Wc)
✓Size of the slot (La and Wa)
✓Position of the slot (Xa)

- Effect of metal skin thickness



Metal skin thickness has no effect on Q-factor when it > 20 μm

- Effect of geometries of the slots and substrate

$$\frac{1}{Q_L} = \frac{1}{Q_r} + \frac{1}{Q_u}$$

Calculated (Q_L) — **Need to design** (Q_r) — **Simulated** (Q_u)

***Q_L*: Loaded Q-factor, considered overall effect**
***Q_r*: Radiation Q-factor, from slot antenna**
***Q_U*: unloaded Q-factor, dielectric ceramic and metal loss**

- Effect of geometries of the slots and substrate

Q_L

$$Q_L = \frac{f_0}{\Delta f_{3dB}} \frac{1}{1 - mag(S_{21}(\omega_0))} \qquad f_0 = \frac{1}{2\pi\sqrt{\varepsilon_0 \mu_0 \varepsilon_r}} \frac{\chi_{01}}{r}$$

Q_U

$$Q_U = \left(\frac{1}{Q_{SiCN}} + \frac{1}{Q_{Ag}}\right)^{-1}$$

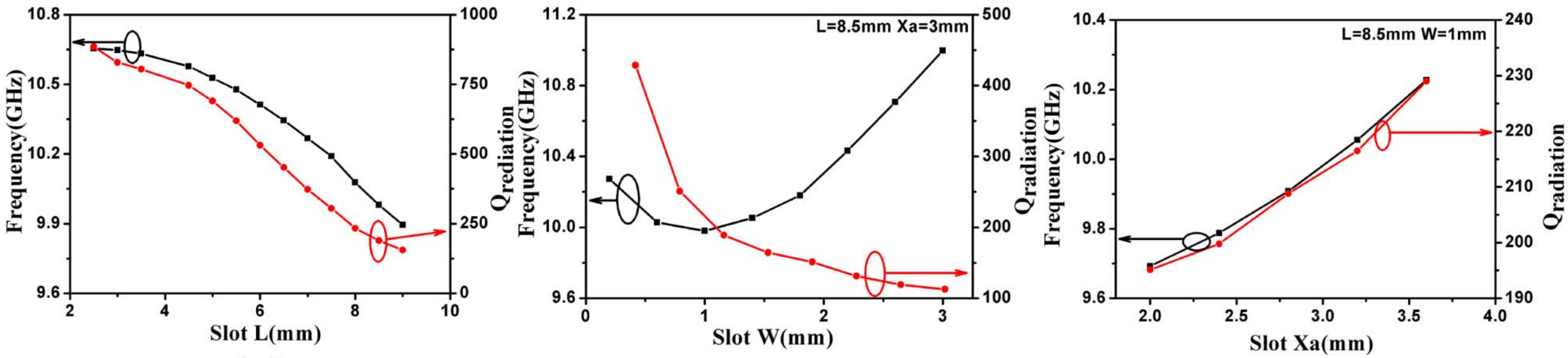
$$\frac{1}{Q_r} = \frac{1}{Q_L} - \frac{1}{Q_u}$$

Maximum energy coupling:

$$Q_r = Q_U$$

- Effect of geometries of the slots and substrate

Size and position of slot antenna



(a) (b) (c)

- ✓ **Q-factor decreases with increasing L or W – more radiation energy loss**
- ✓ **Q-factor increases with increasing Xa**

Future work

- Material development
  - Characterize high-temperature material properties

- Design and fabricate sensors
  - Final design the resonator based strain sensors
  - Fabricate the designed sensors

- Sensor characterization
  - Pack the sensor for testing
  - Test the sensors in different temperatures

Summary

- Polymer-derived ceramics possess necessary properties for making wireless, passive strain/stress sensors for high-temperature applications.
- We have finished materials selection.
- We have finished initial sensor design.
- The R&D progress follows the proposed schedule.

THANK YOU!