Frequency Selective Surface-Based Sensing for Concurrent Temperature and Strain Measurement: Benefits, Challenges, and Applications

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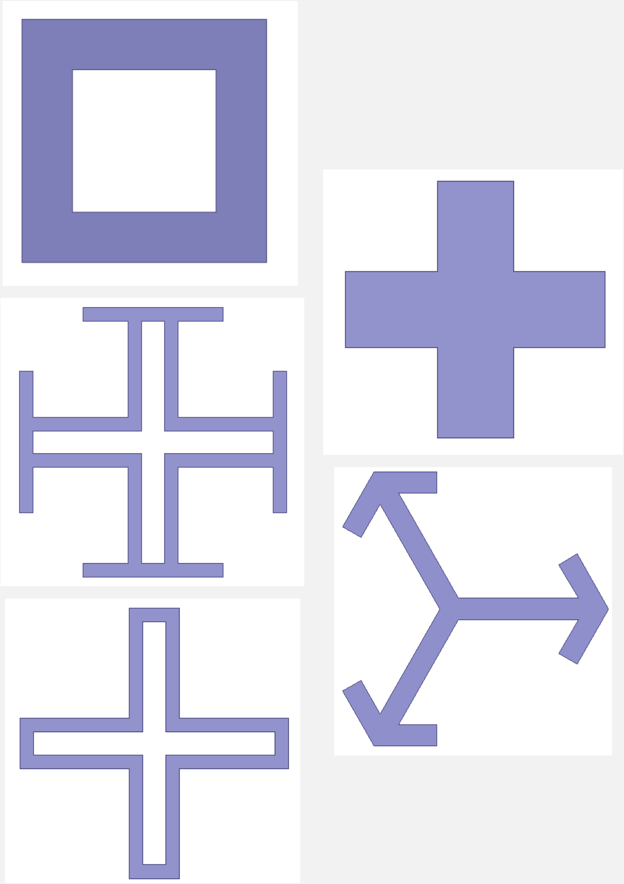
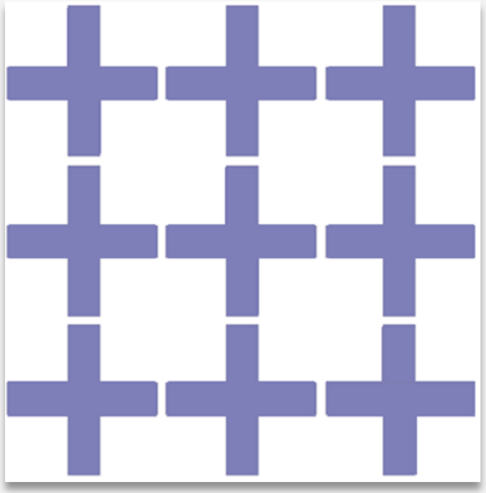
Outline

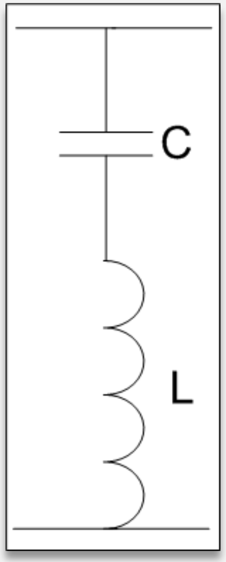
- Introduction to Frequency Selective Surfaces (FSSs) and FSS-based sensing
- Similar technologies
- FSS-based sensor designs
  - Concurrent temperature and strain sensing
- Practical challenges and solutions
  - Sensor resolution and key parameters
  - Sensor cell analysis and localized sensing
  - Performance improvement by FSS miniaturization
- Concluding remarks

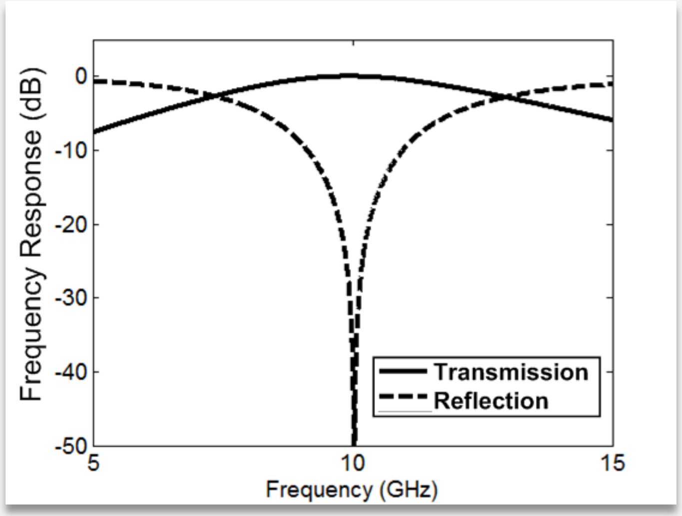
What is a Frequency Selective Surface?

Sample Elements | *Array* | *Model* | *Frequency Response*



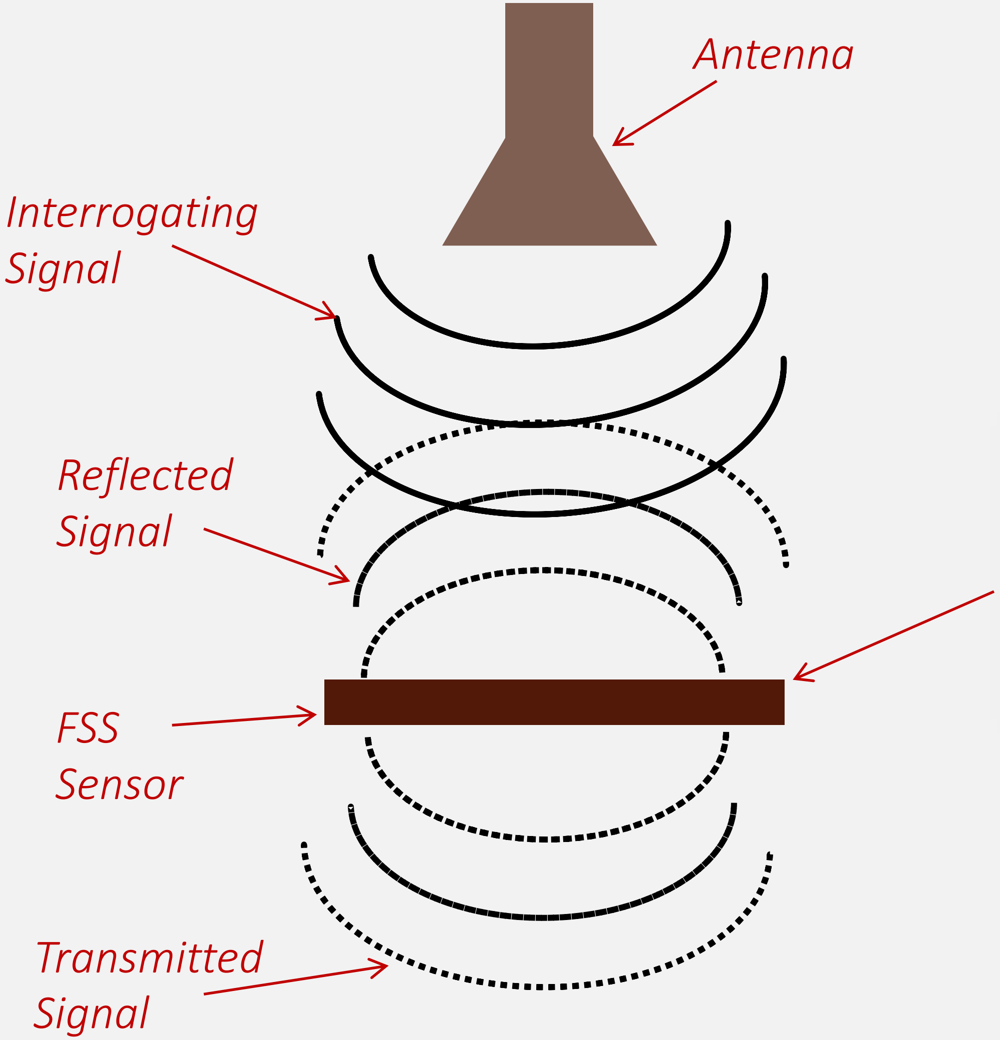






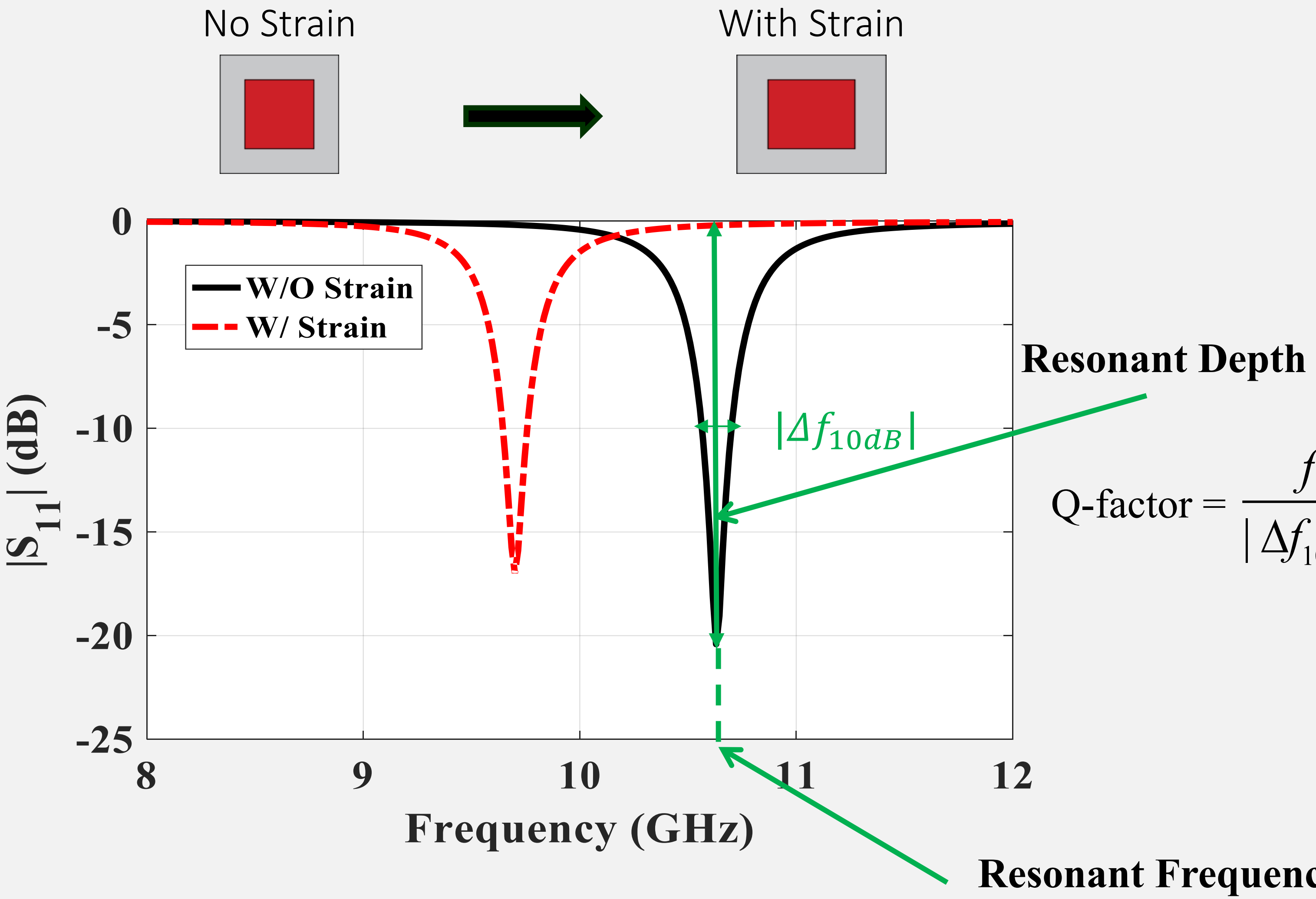
Why FSS-Based Sensing?

- FSS Sensor Advantages:
  - Passive sensing
  - Wireless (remote) interrogation
  - Sensitive to geometrical and physical parameters
  - Distributed sensing
  - Extreme design flexibility – the sky is the limit!!



Example FSS Sensing Applications

- 1D/2D strain
- Temperature
- Pressure
- Layered structure evaluation
- Moisture detection
- Multi-functional sensing (i.e. concurrent temperature and strain)
- Etc……

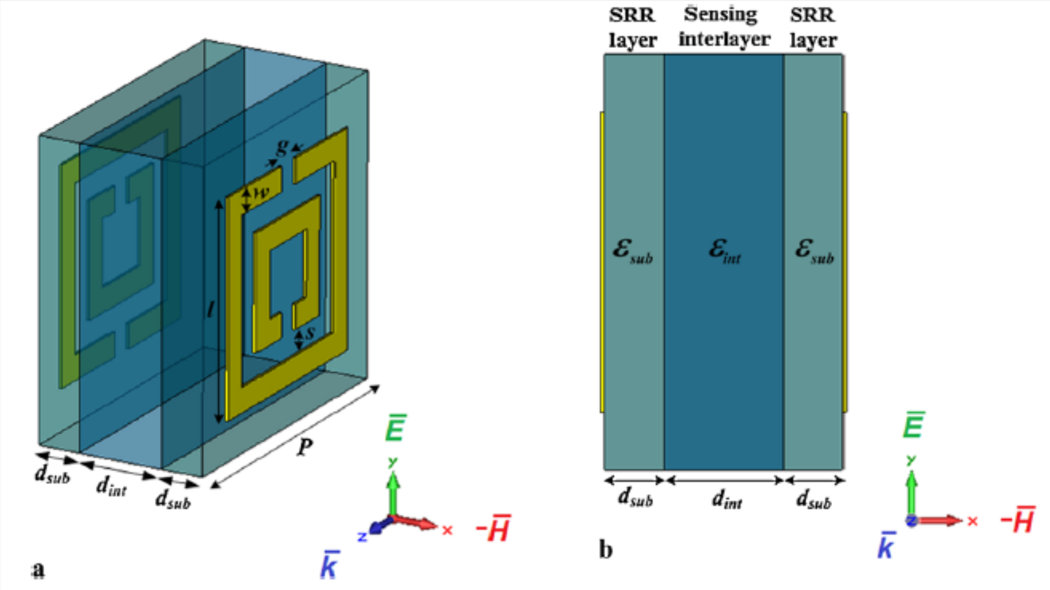


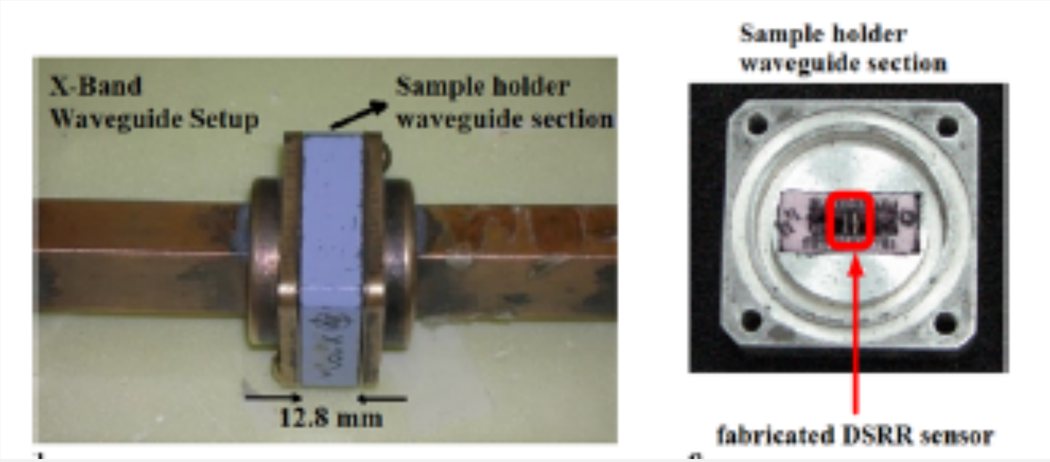
$$\text{Q-factor} = \frac{f_r}{|\Delta f_{10dB}|}$$

Why Microwave Frequencies?

- Microwave/millimeter wave components are commercially available and low-cost
- Interrogation systems are safe, low power, and easy to use
- Antenna size is inversely proportional to frequency.
  - Becomes prohibitive, along with the FSS element/unit cell size, for lower frequencies
  - Limits the resolution (all related to wavelength)
- Resolution can be improved with increasing frequency
  - Eventually (beyond mm-wave), increasing system cost/complexity is of concern (i.e, THz, optics/laser….)

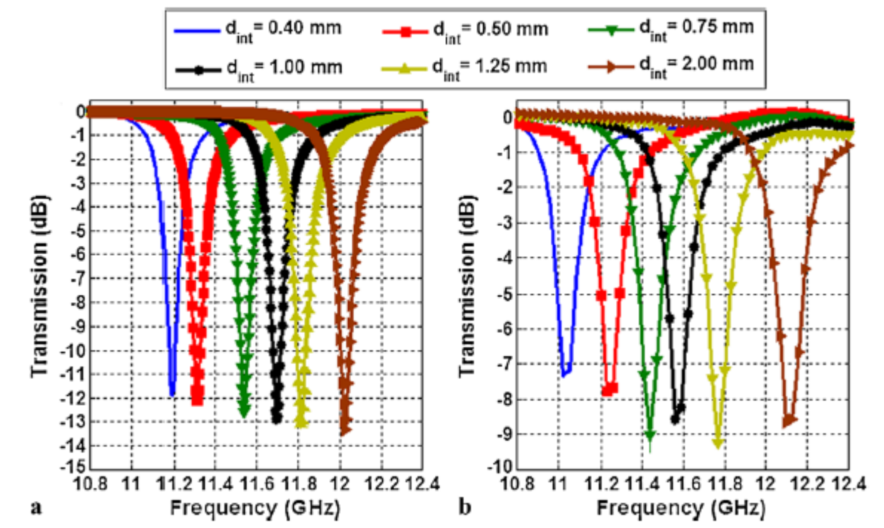
Similar Technologies - Metamaterials



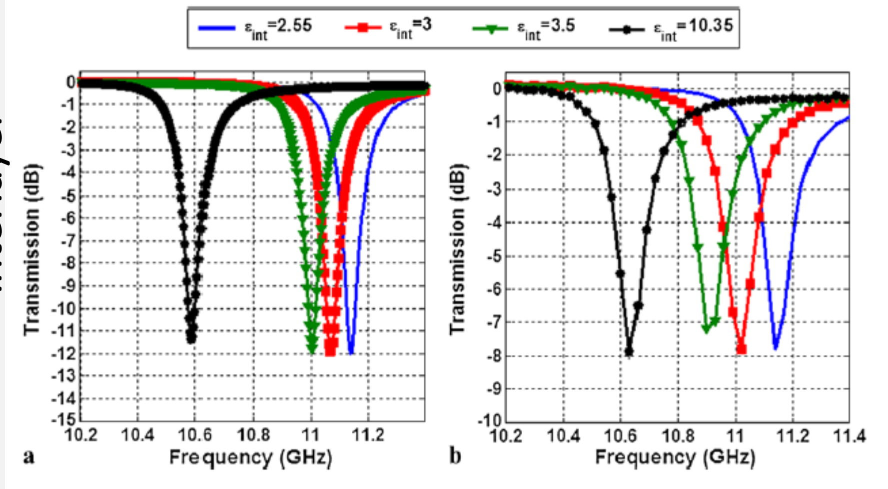


Simulation | **Measurement**

Sensitivity to thickness of sensing interlayer



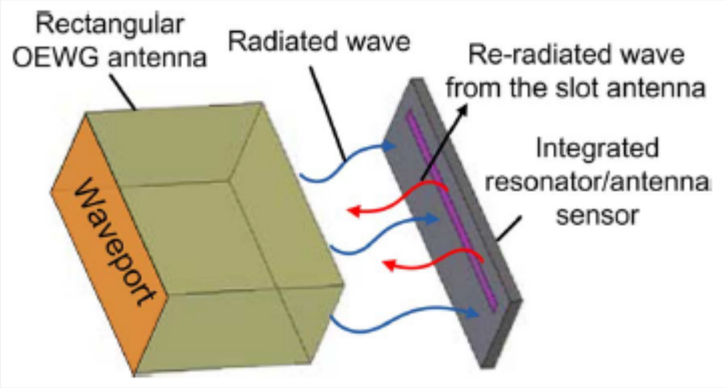
Sensitivity to permittivity of sensing interlayer

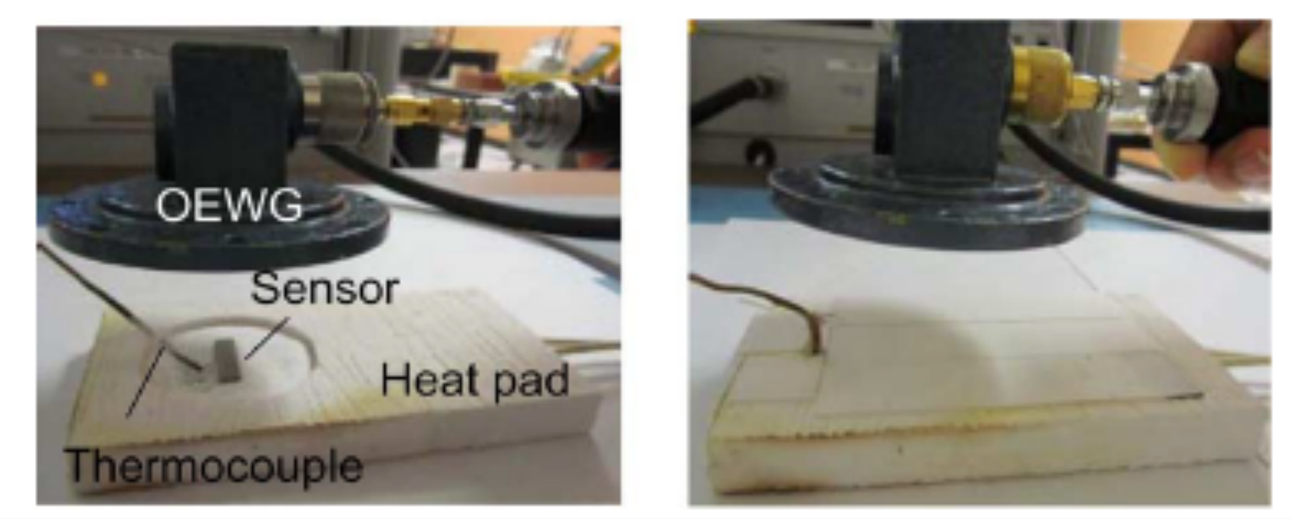


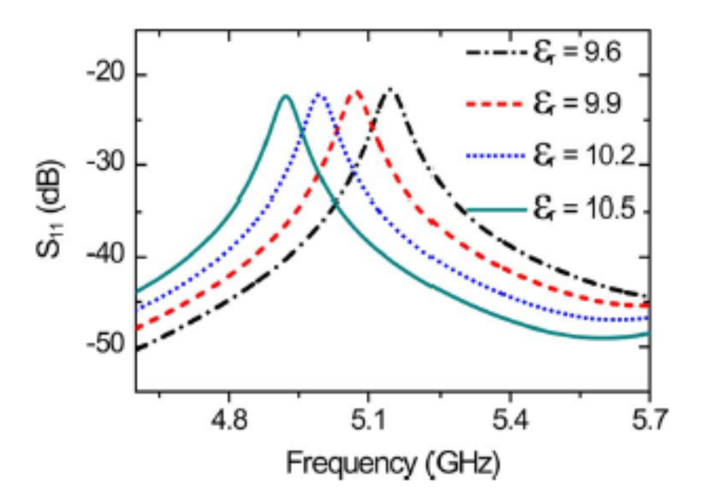
Ekmekci, Evren, and Gonul Turhan-Sayan. "Multi-functional metamaterial sensor based on a broad-side coupled SRR topology with a multi-layer substrate." Applied Physics A 110.1 (2013): 189-197.

Temperature Sensor by Resonator Integration

- Substrate is a temperature-dependent dielectric material.
- Resonant frequency of the sensor decreases from 5.12 GHz to 4.74 GHz for 50 °C to 1000 °C.
- This corresponds to a relative permittivity of 9.7 to 11.2 for the alumina substrate.





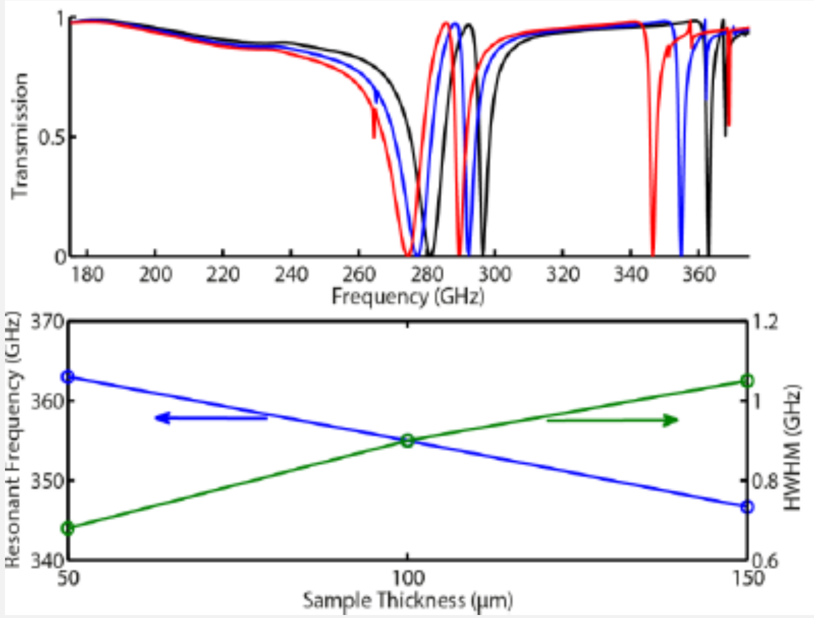


Cheng, Haitao, Siamak Ebadi, and Xun Gong. "A Low-Profile Wireless Passive Temperature Sensor Using Resonator/Antenna Integration Up to 1000˚C", IEEE Antennas and Wireless Propagation Letters 11 (2012): 369-372.

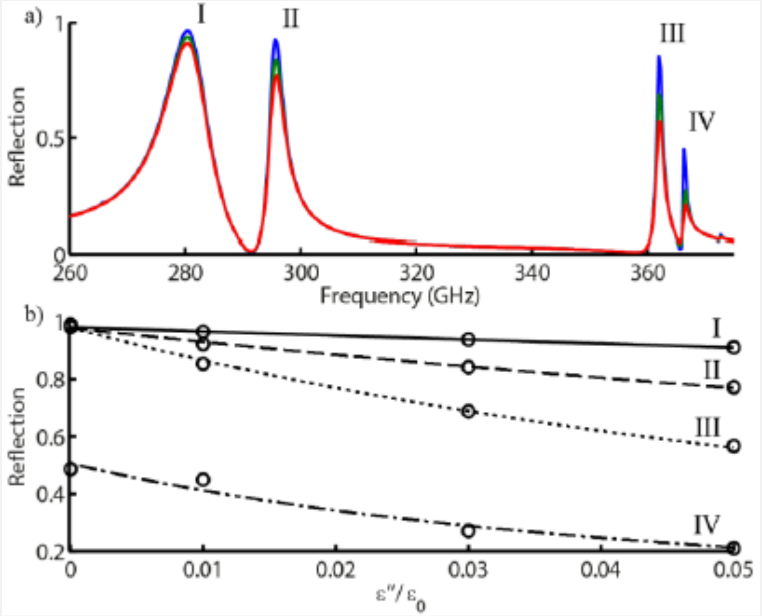
FSS in the THz Regime

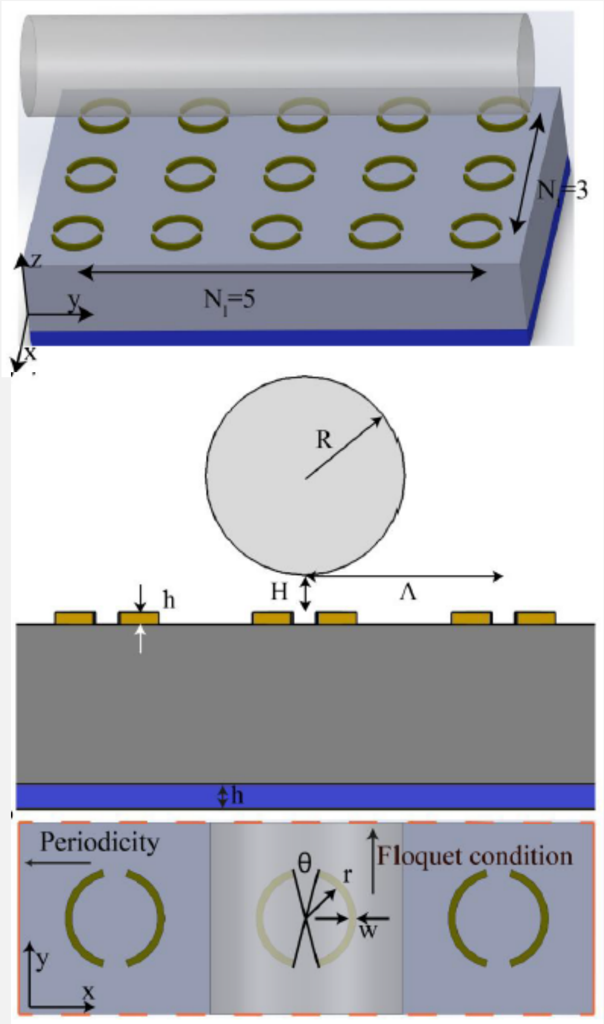
- Biomedical and chemical applications
- THz FSSs interrogated with THz subwavelength optical fibers
  - Used for monitoring optical properties of thick films

Film Thickness Sensing



Humidity Content Sensing

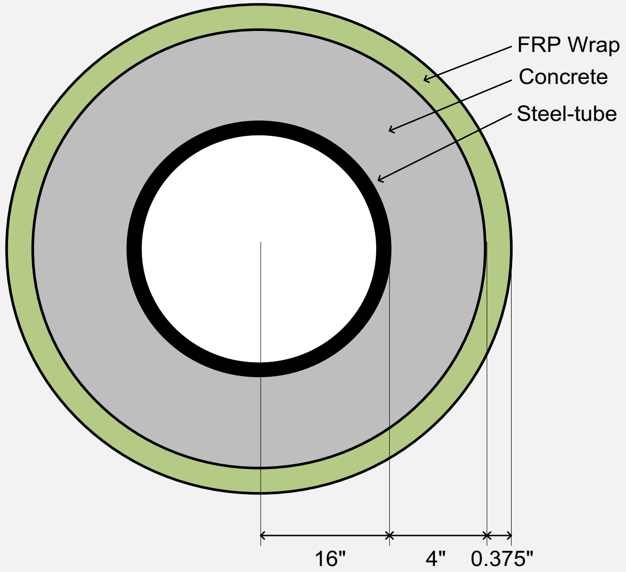




Girard, Martin, and Maksim Skorobogatiy. "Terahertz multiparameter sensor using fiber-interrogated frequency selective surface." arXiv preprint arXiv:1311.6390 (2013).

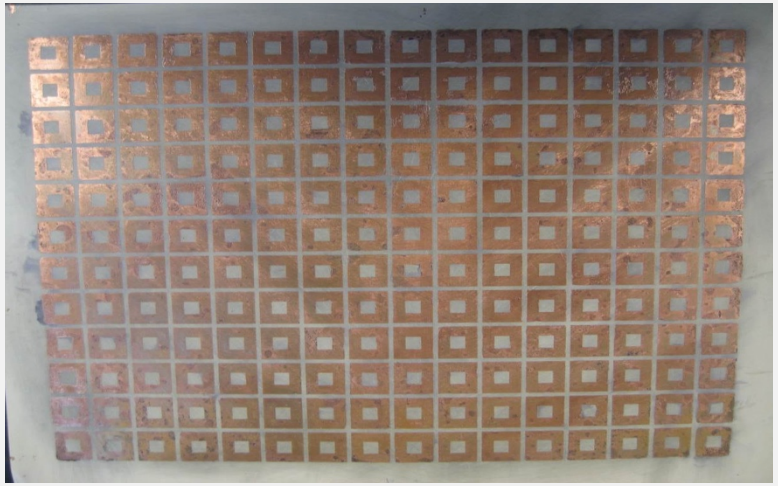
FSS for Structural Health Monitoring (SHM)

- Concrete column formed around a hollow steel core.
  - Structural stability is comparable to traditional solid concrete columns, but with reduced weight.
- Additionally, a fiber-reinforced polymer (FRP) layer surrounds the concrete.
  - Serves as a casing during casting and provides protection from the environment.



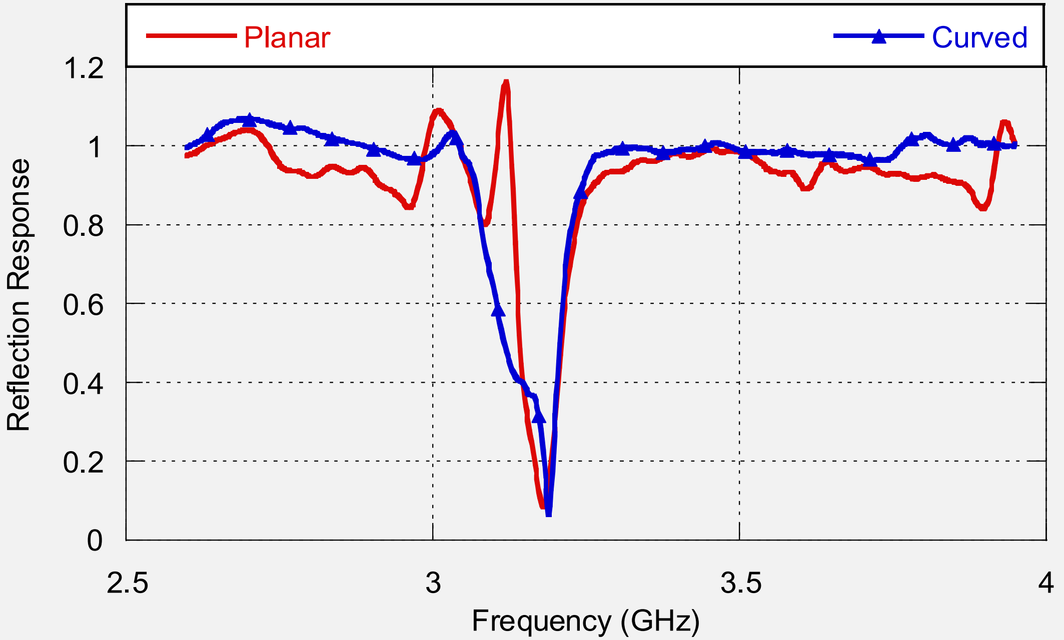
FSS for SHM – Curved Surfaces

FSS Sensor

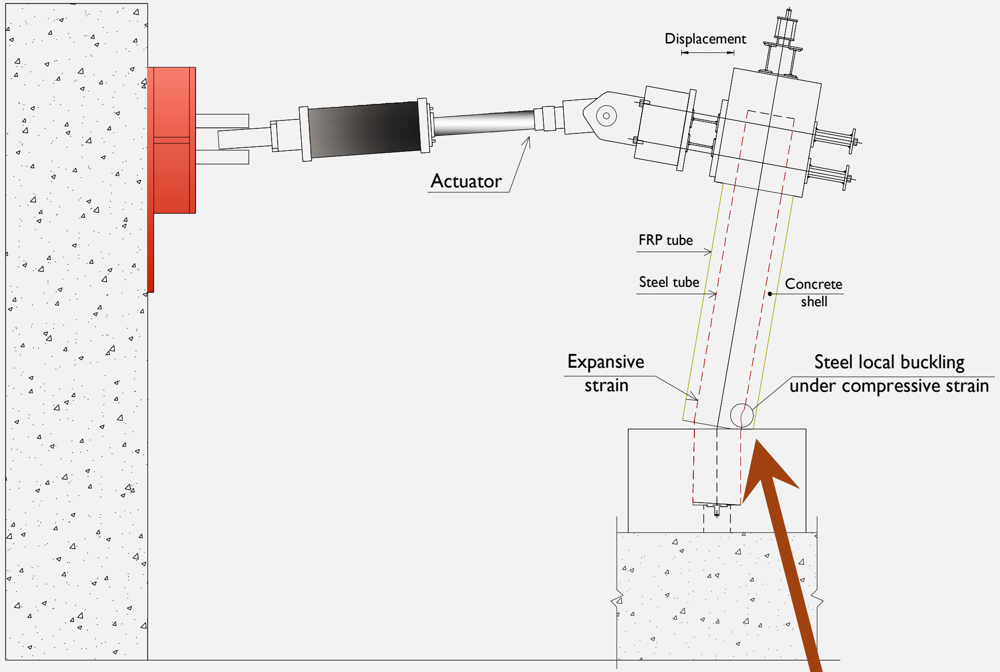


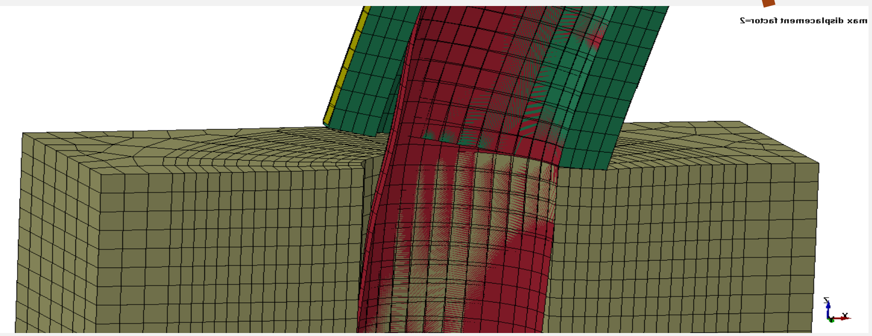
Sensor Placement

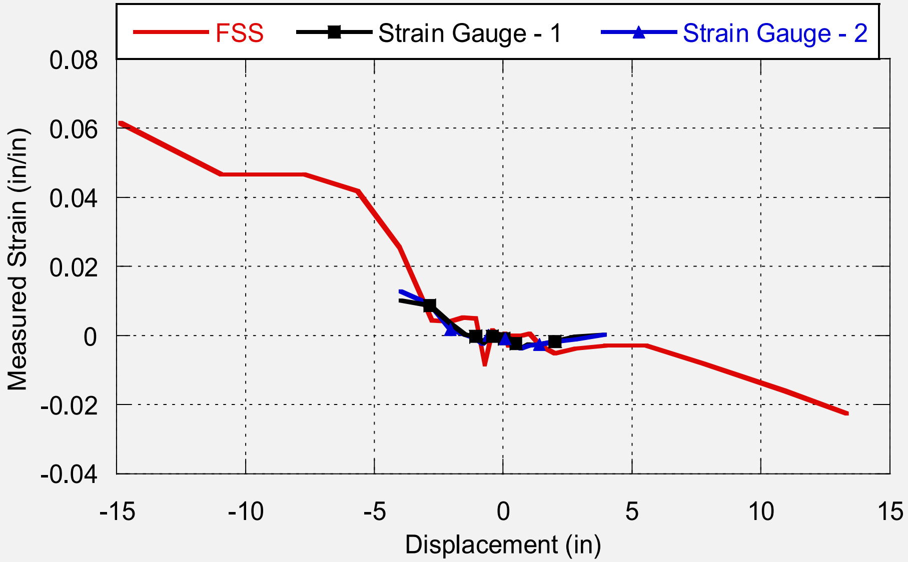
3D Printed Horn Antenna

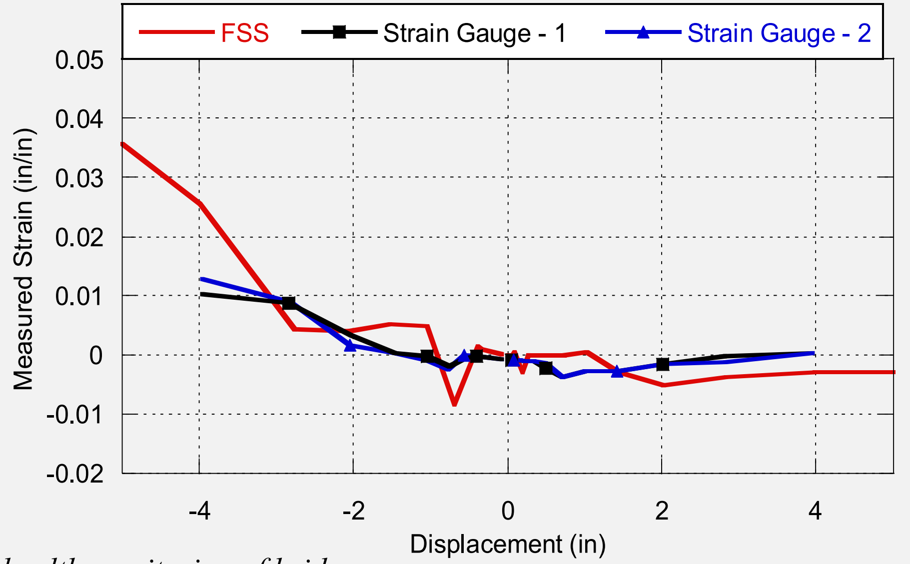


FSS for SHM





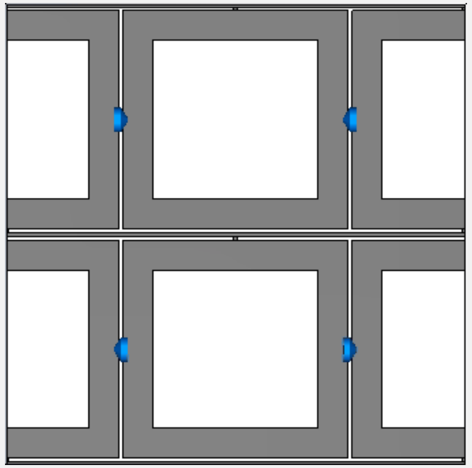


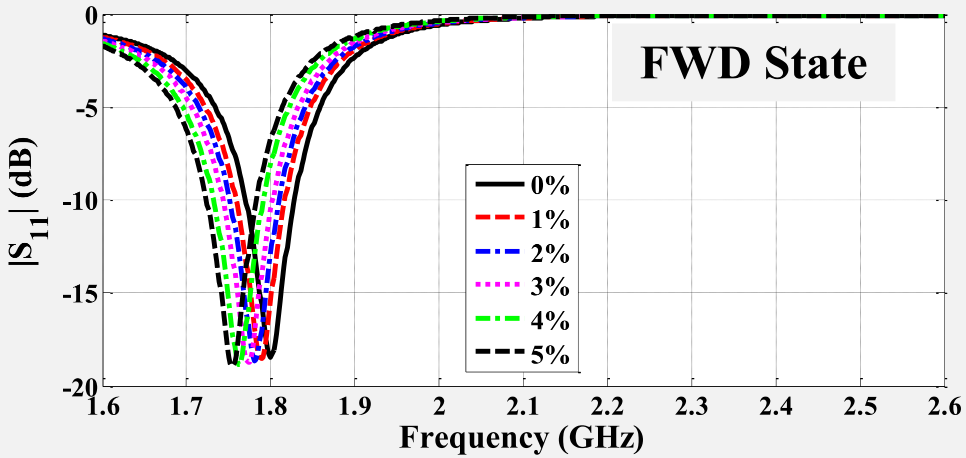


Pieper, Dustin, Donnell, K. M., Abdelkarim, O., & ElGawady, M. A., "Embedded FSS sensing for structural health monitoring of bridge columns." 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings. IEEE, 2016.

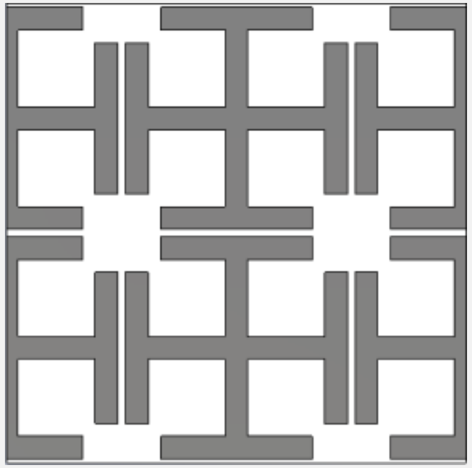
Active FSS for Strain Sensing

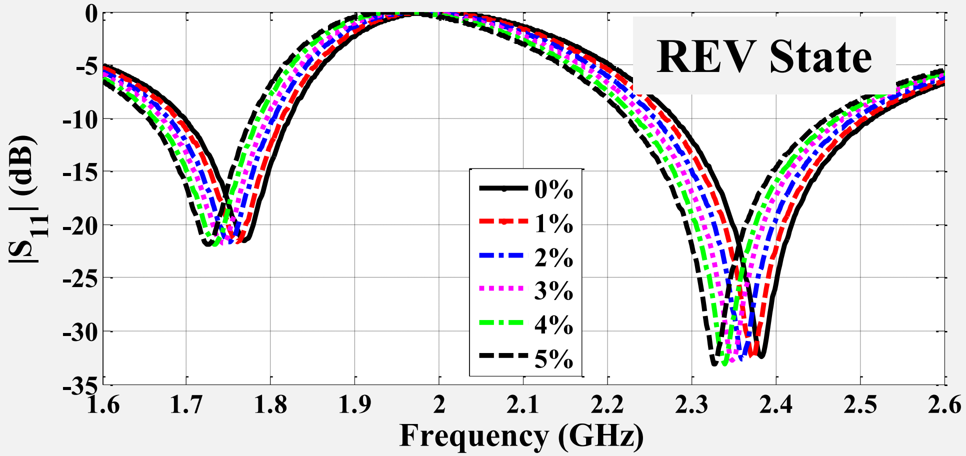
Active FSS
(Bottom Layer)





Passive FSS
(Top Layer)



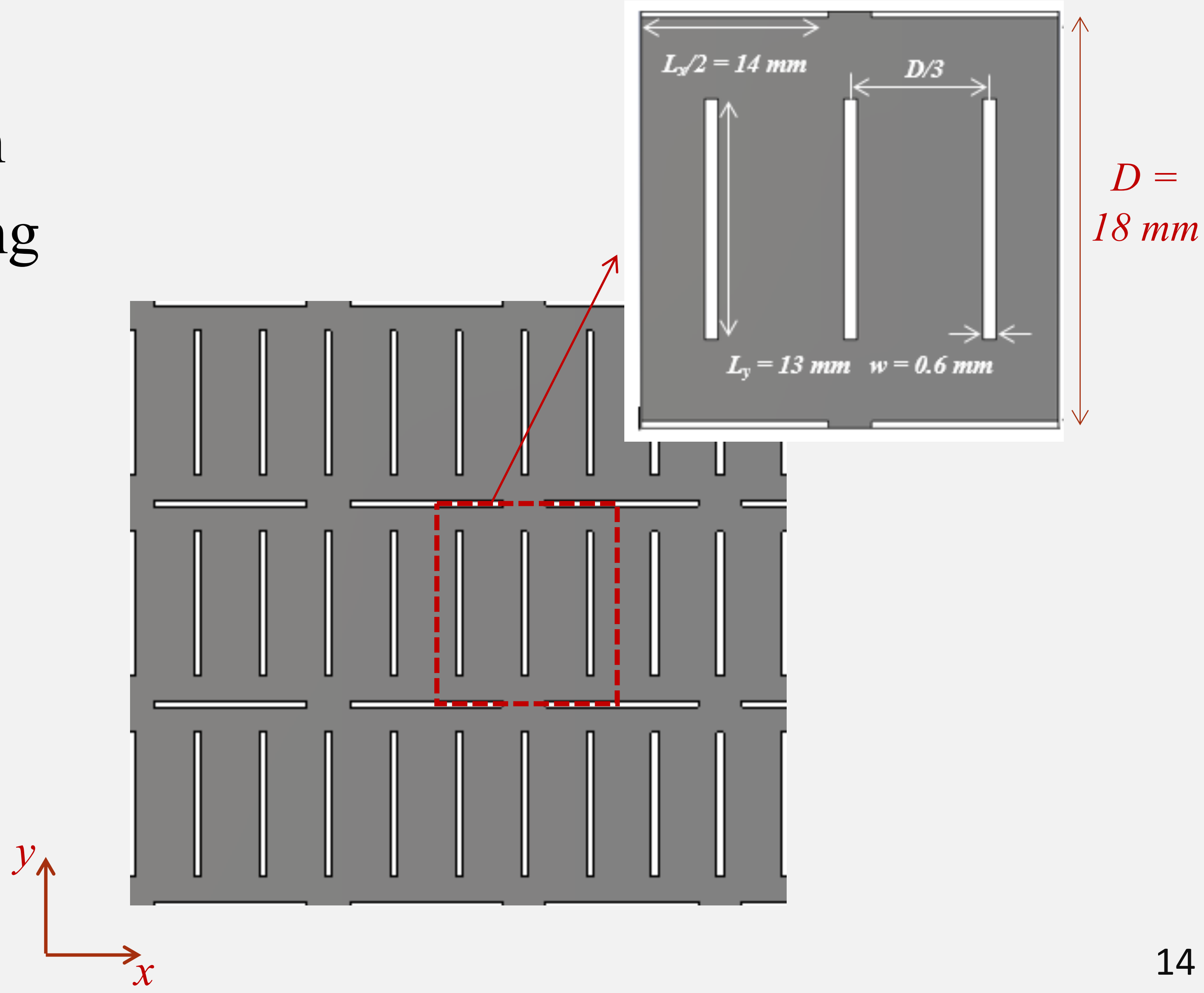


Substrate: Rogers 5880, 20 mils, $\varepsilon_r = 2.2$, tanδ = 0.0009

Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Active frequency selective surface for strain sensing," Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2017 IEEE International Symposium on. IEEE, 2017.

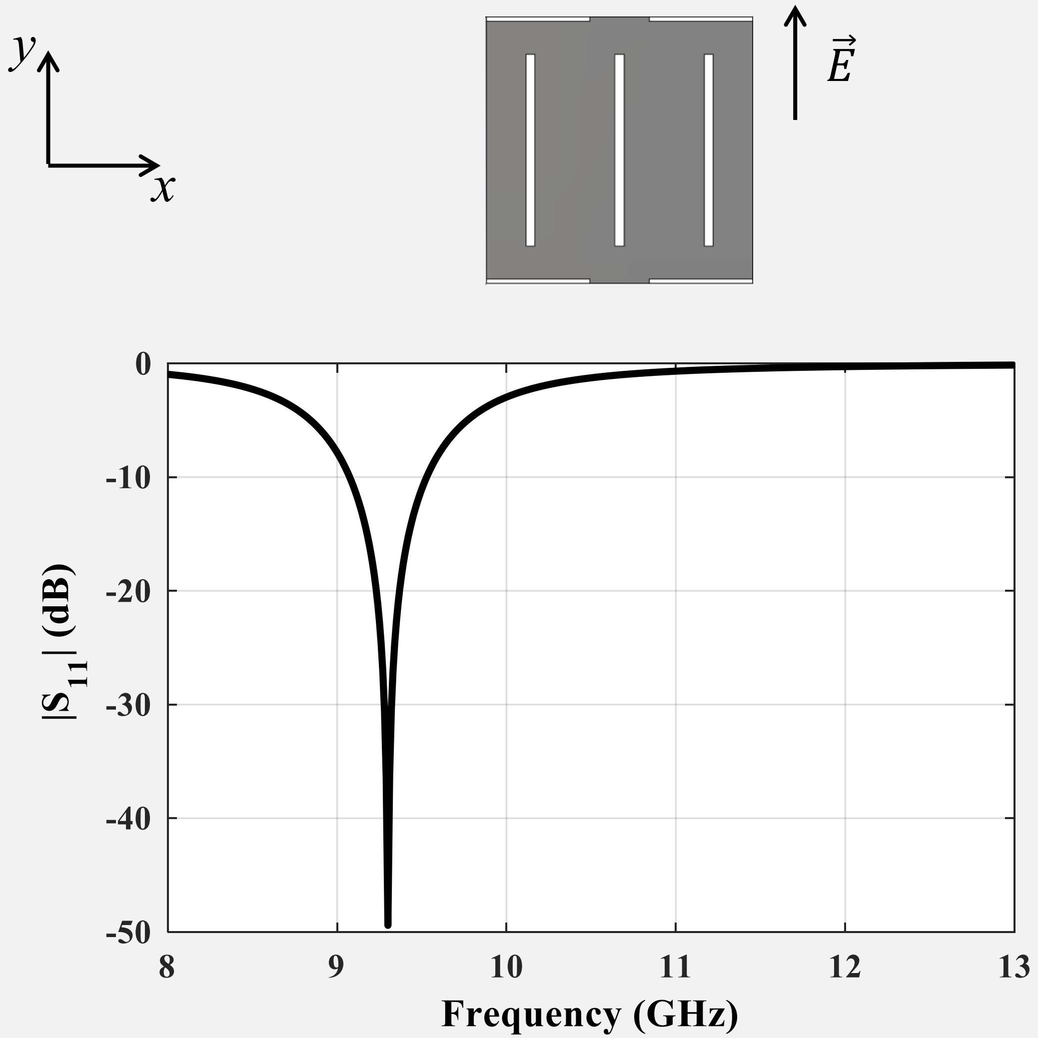
2D In-Plane Normal Strain Sensor

- ➢Flexibility to monitor 2D strain using dual-polarized FSS design
- ➢Provide reflection response using a slot-based element
- ➢Strain in each direction can be characterized by measuring the reflection response polarized perpendicular to the strain direction

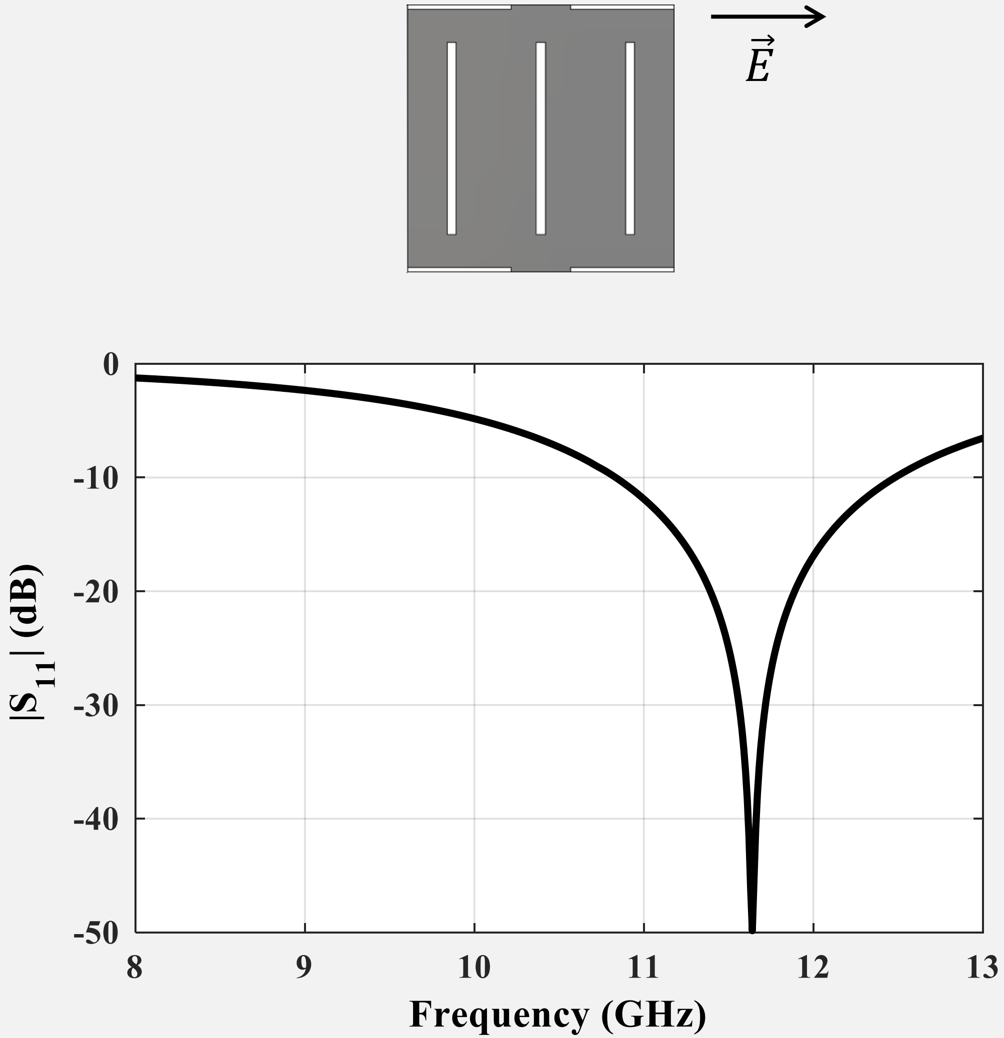


Frequency Response of the Sensor

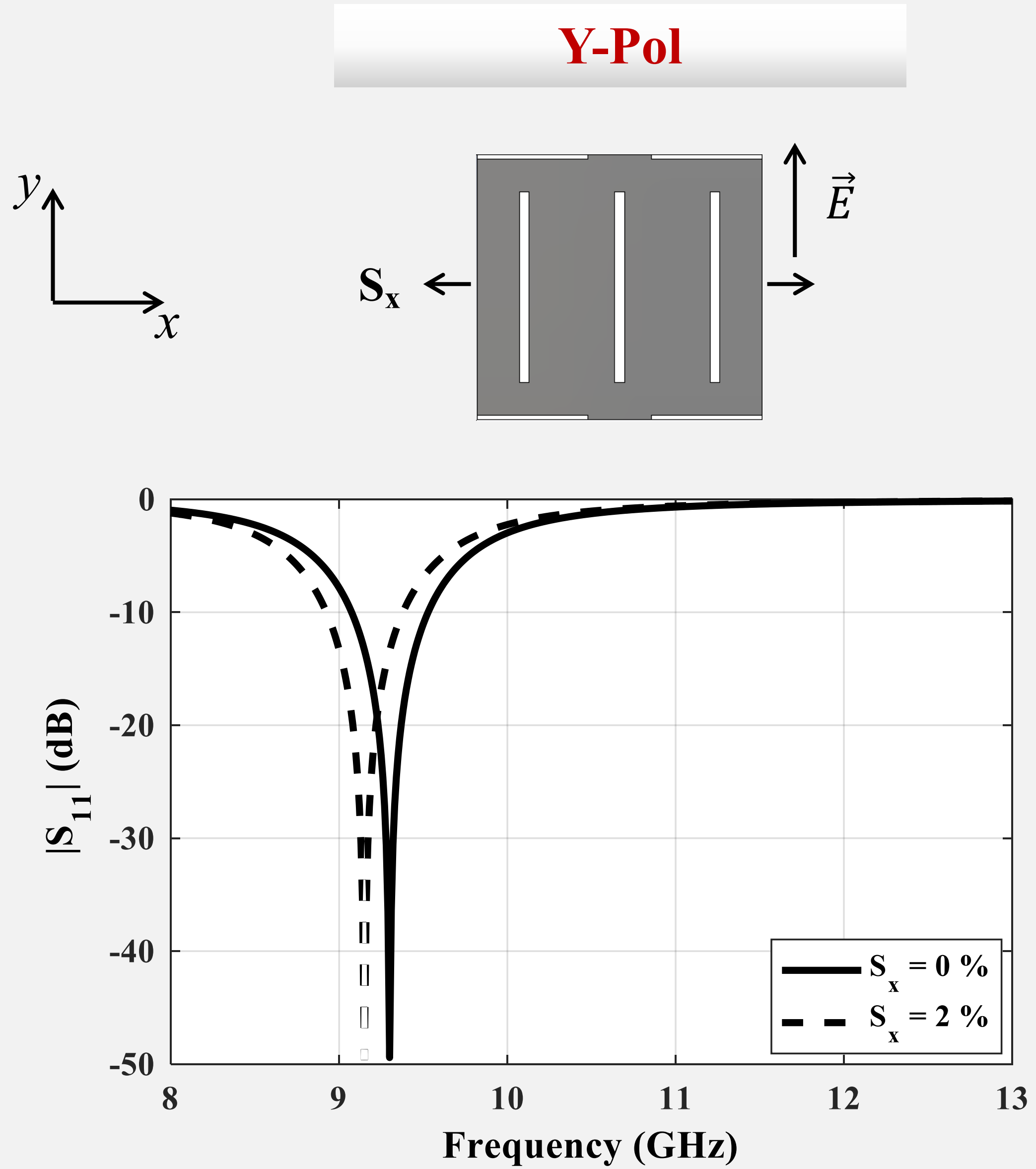
Y-Pol

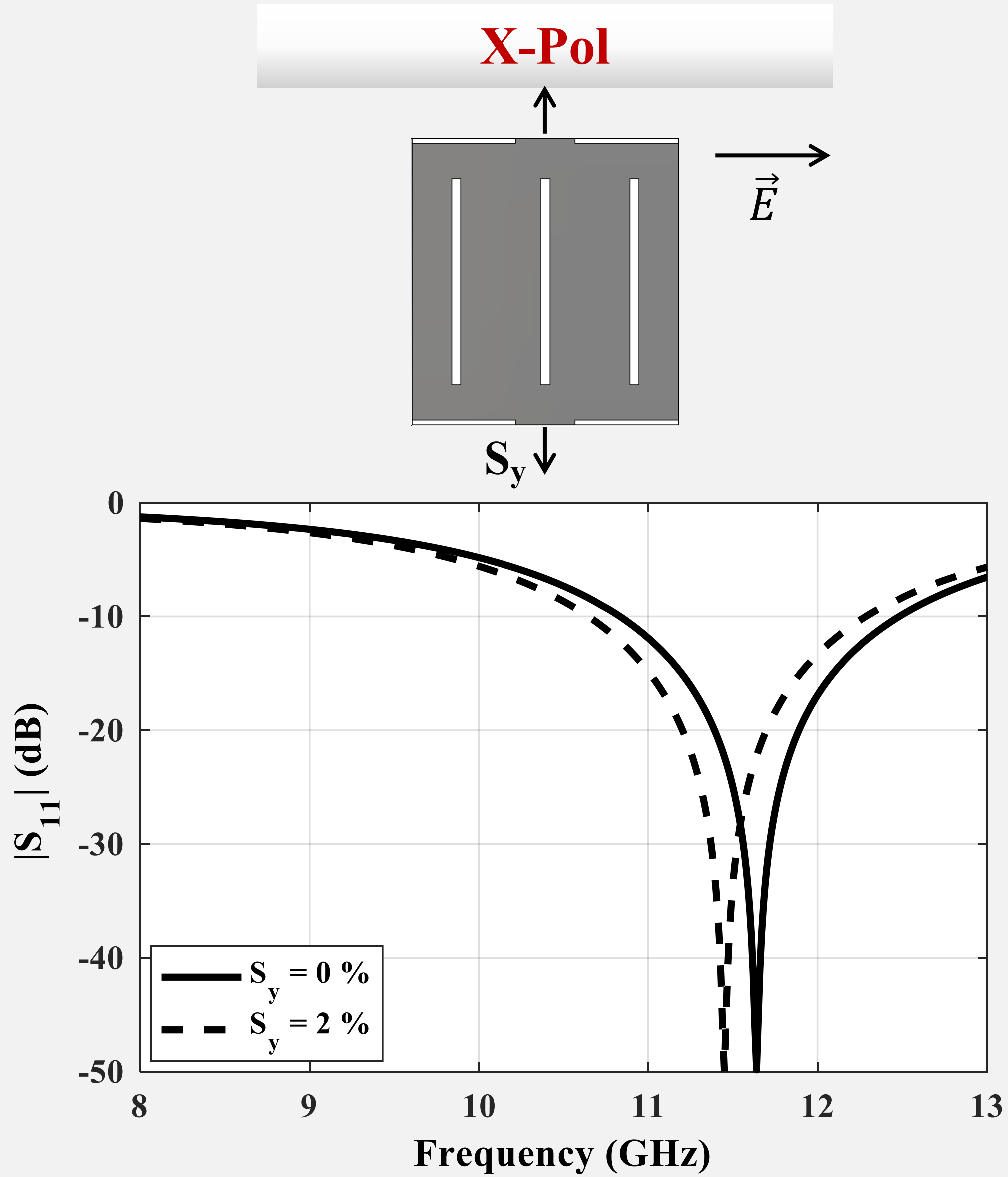


X-Pol

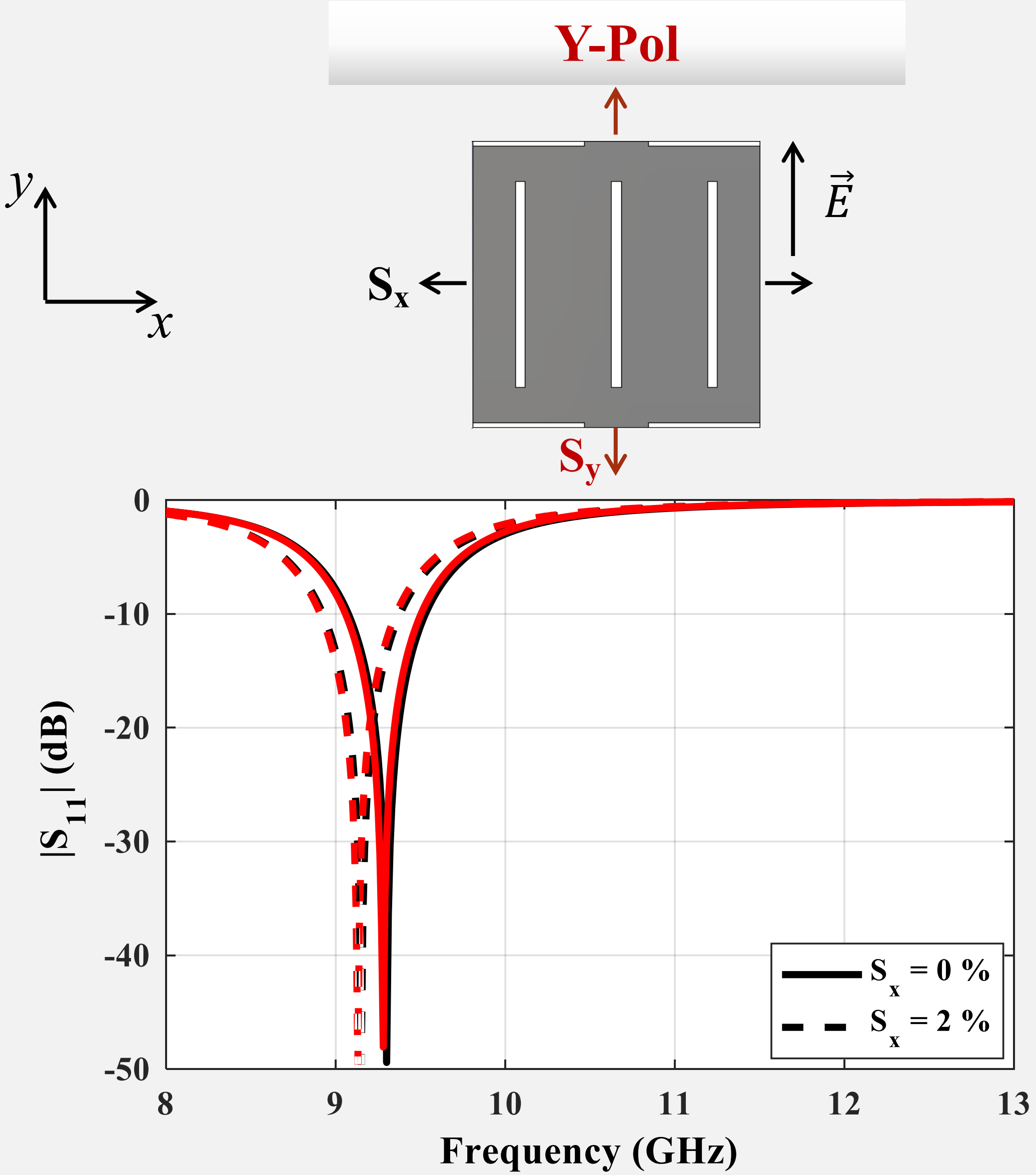


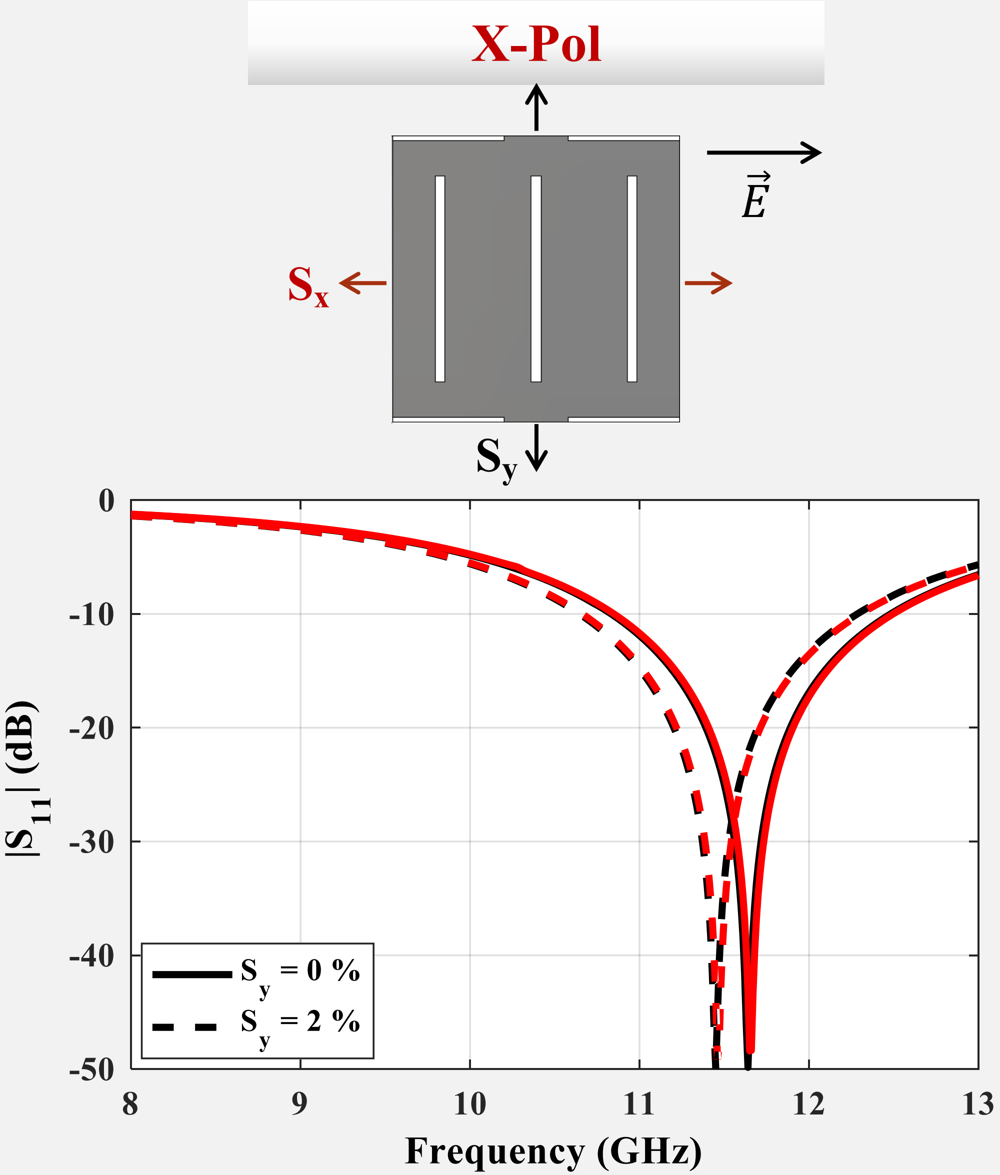
Frequency Response of the Sensor



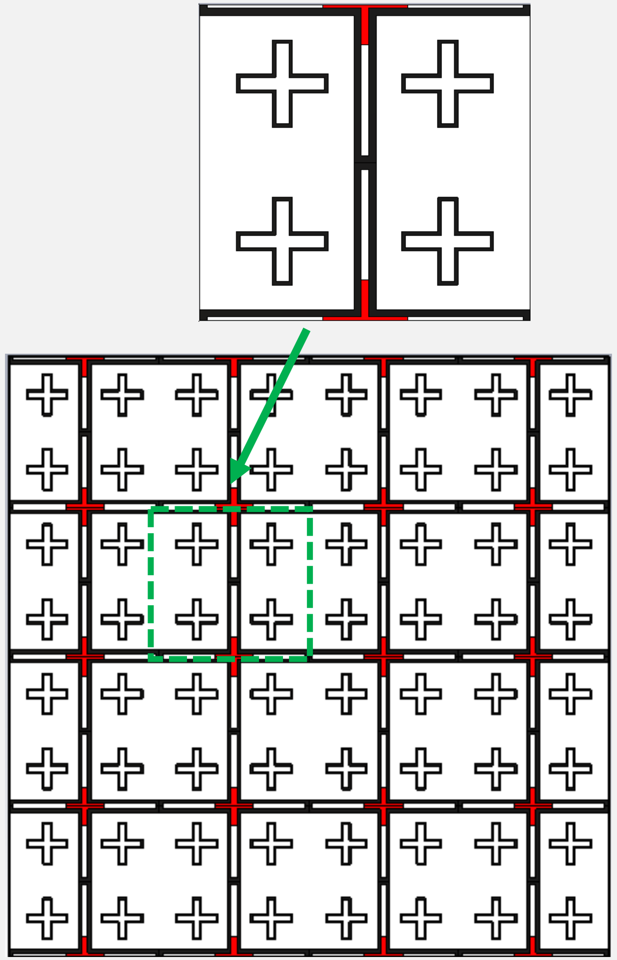


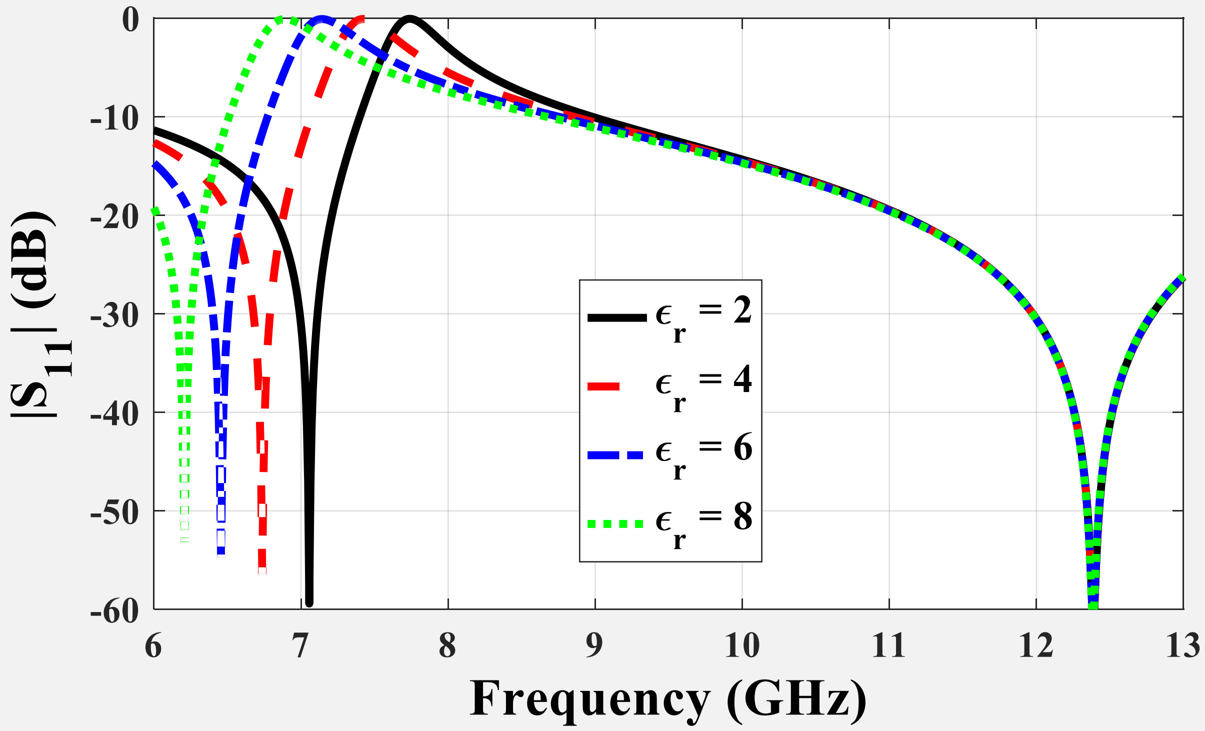
Frequency Response of the Sensor





Concurrent Temperature & Strain Sensing





Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Novel FSS-based sensor for concurrent temperature and strain sensing," Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2017 IEEE International Symposium on. IEEE, 2017.

Concurrent Temperature & Strain Sensing

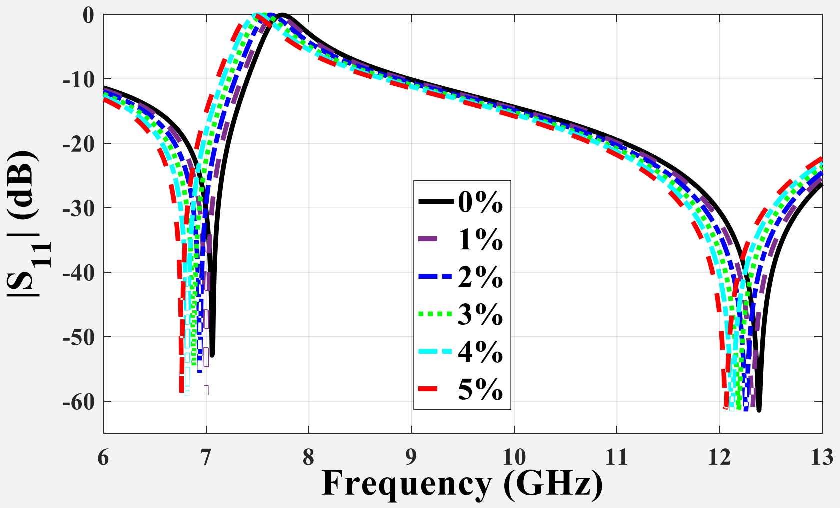
Case #1:

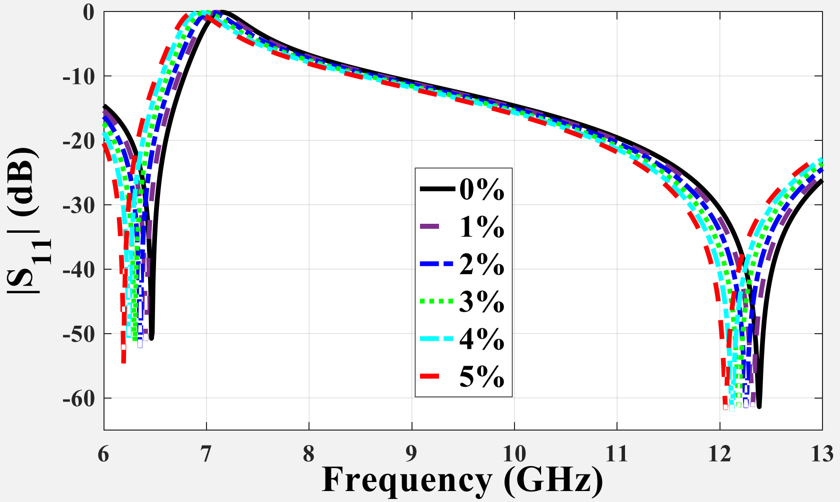
$$\varepsilon_{r1} = 2 \propto T_1$$

Case #2:

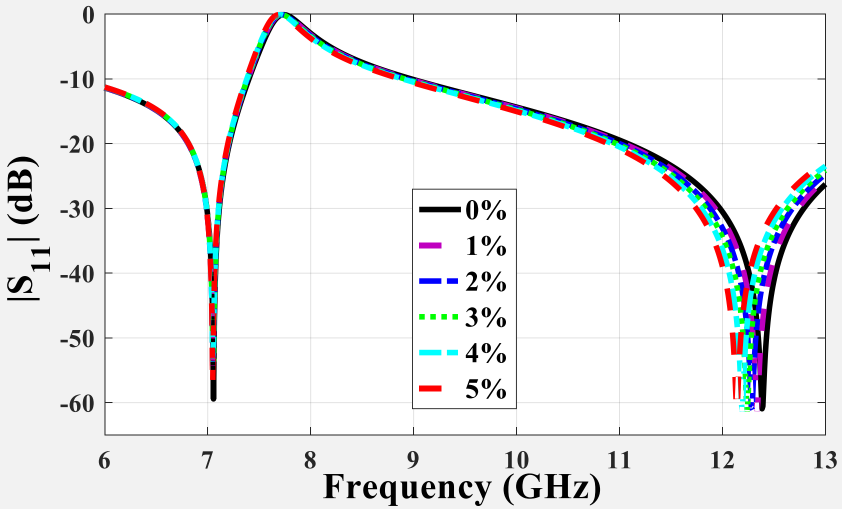
$$\varepsilon_{r2} = 6 \propto T_2$$

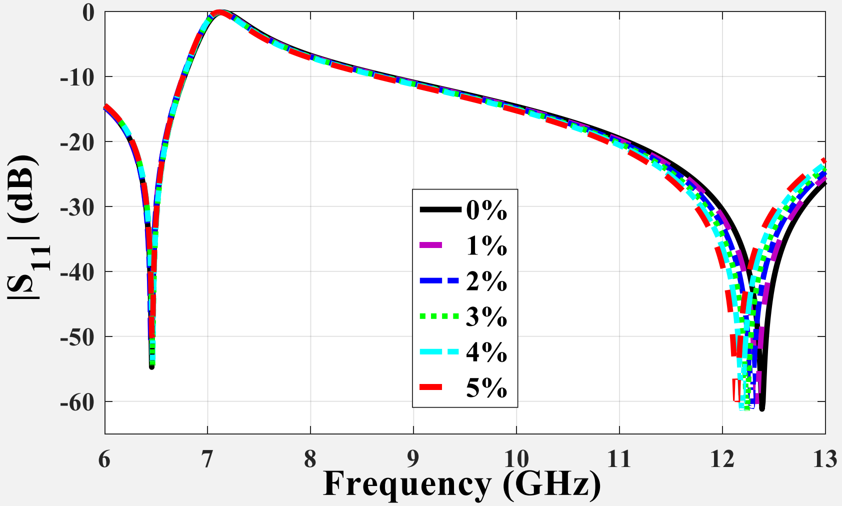
Perpendicular Reflection Response





Parallel Reflection Response





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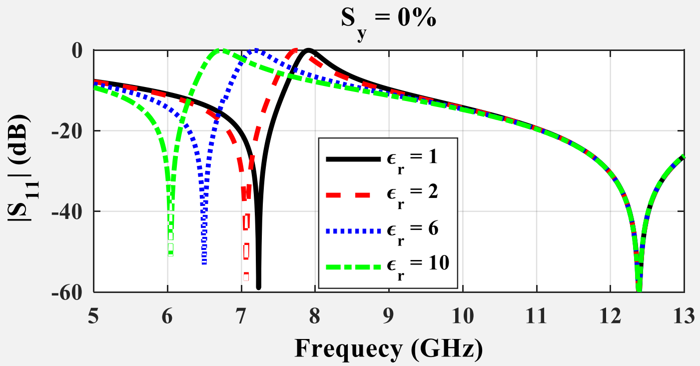
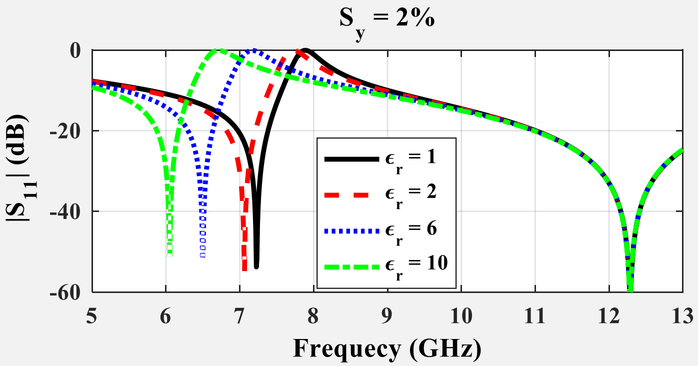
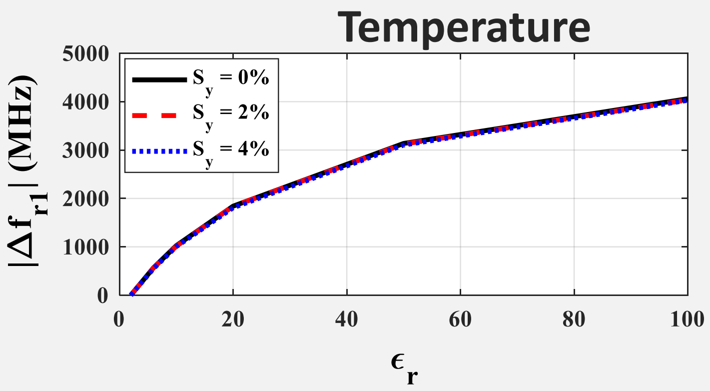
Simulated Sensor Performance

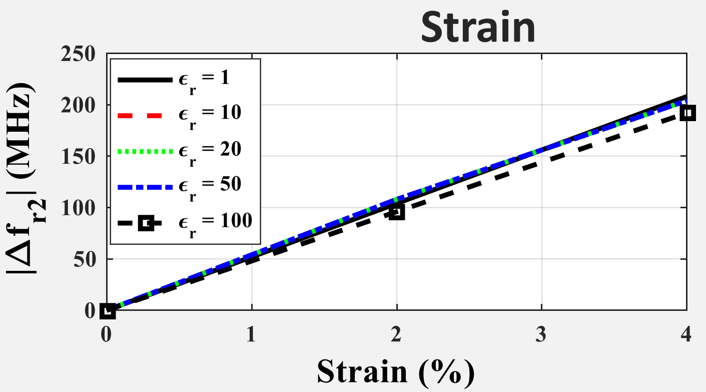
Frequency Response



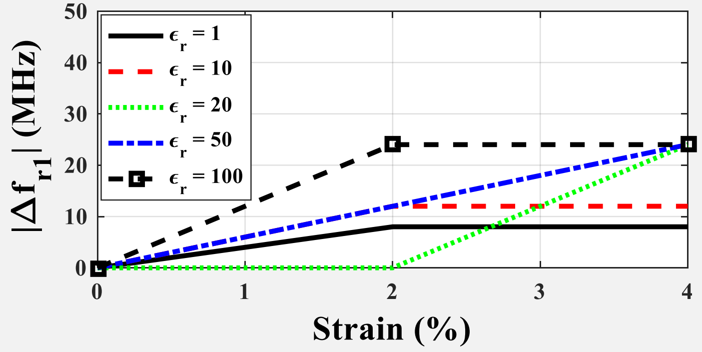


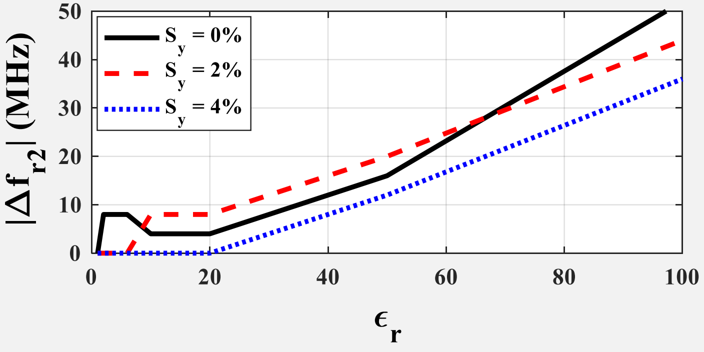
Sensitivity





Error

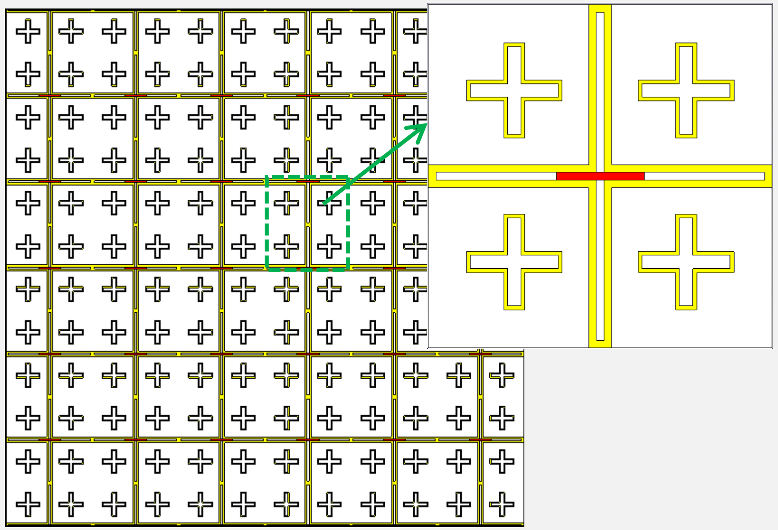




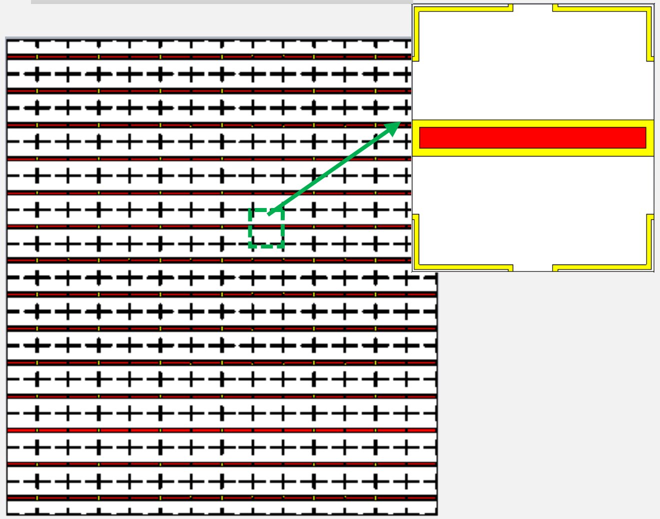
Improved Temperature & Strain Sensor

- ➢Upgraded to a grounded FSS in order to remove the effect of background material(s) on the sensor performance.
- ➢Operating frequency band has been increased to Ku-band (12.4 – 18 GHz) to improve resolution.
- ➢Improved sensitivity to temperature.

X-band Design

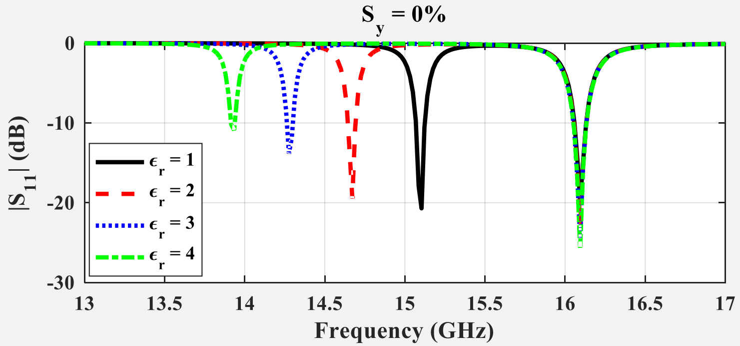


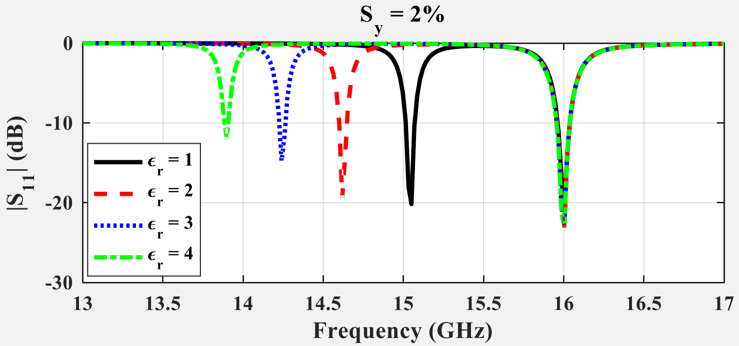
Ku-band Design



Simulated Ku-Band Sensor Performance

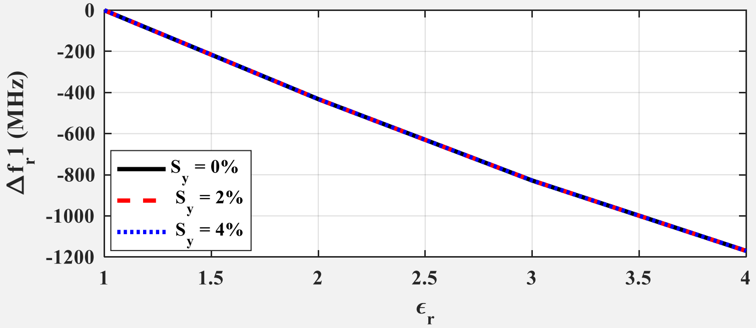
Frequency Response



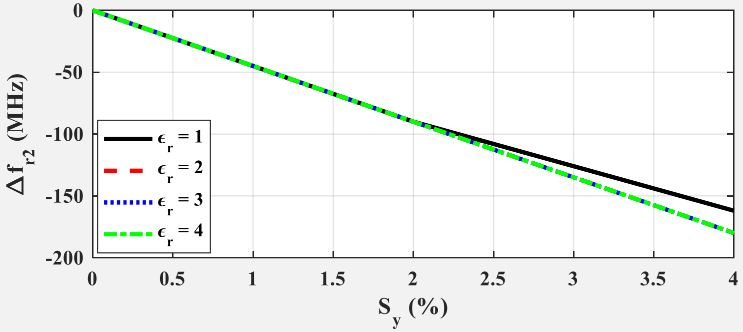


Sensitivity

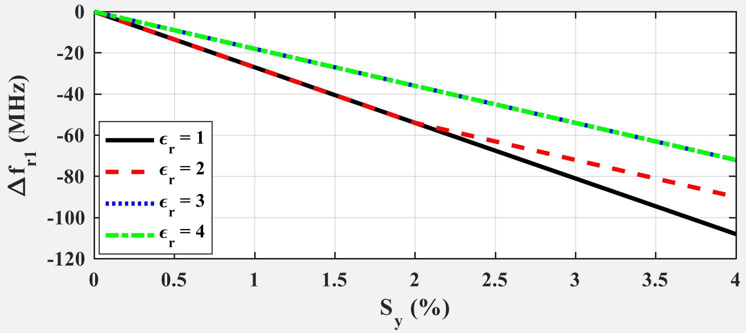
Temperature

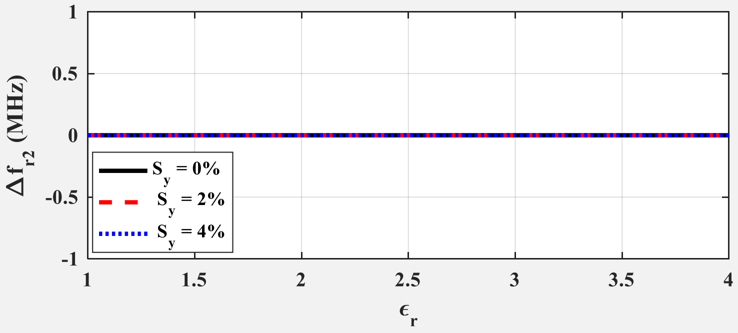


Strain



Error





Experimental Setup for Strain Measurement

VNA

Waveguide
Adapter

Horn

Test
specimen

Load cell

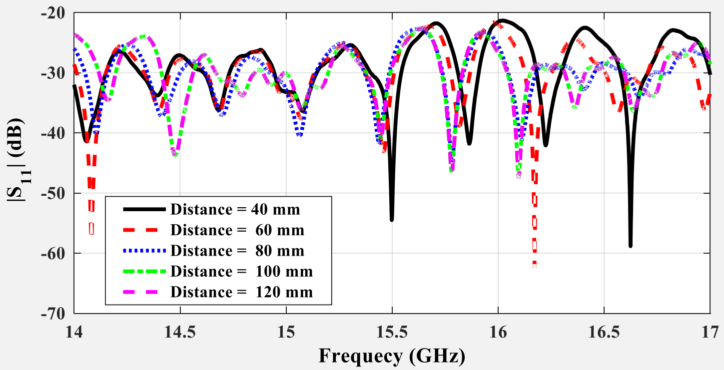
Grips
(top/bottom)

Test
specimen

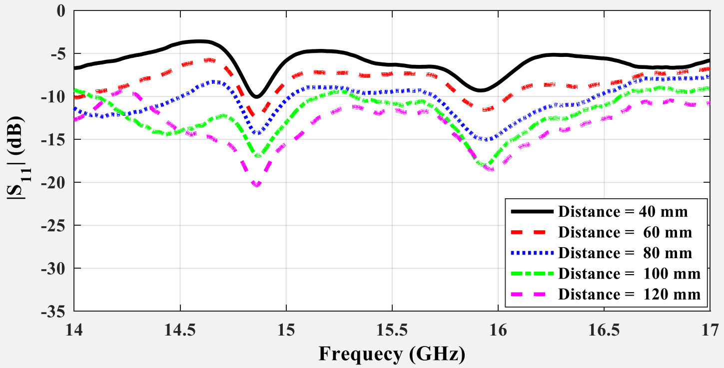
Servo-
hydraulic
piston

Measurements Prior to Load Testing

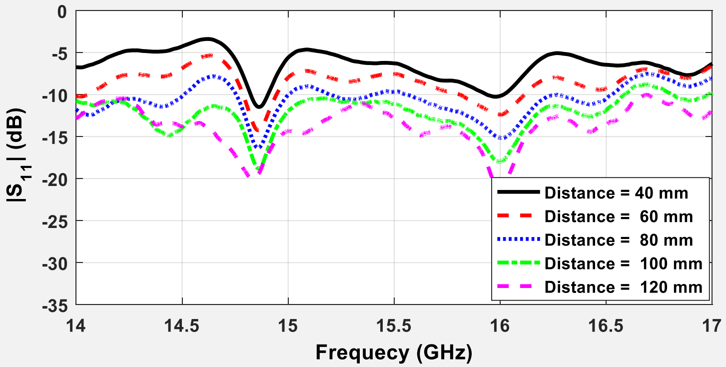
Background

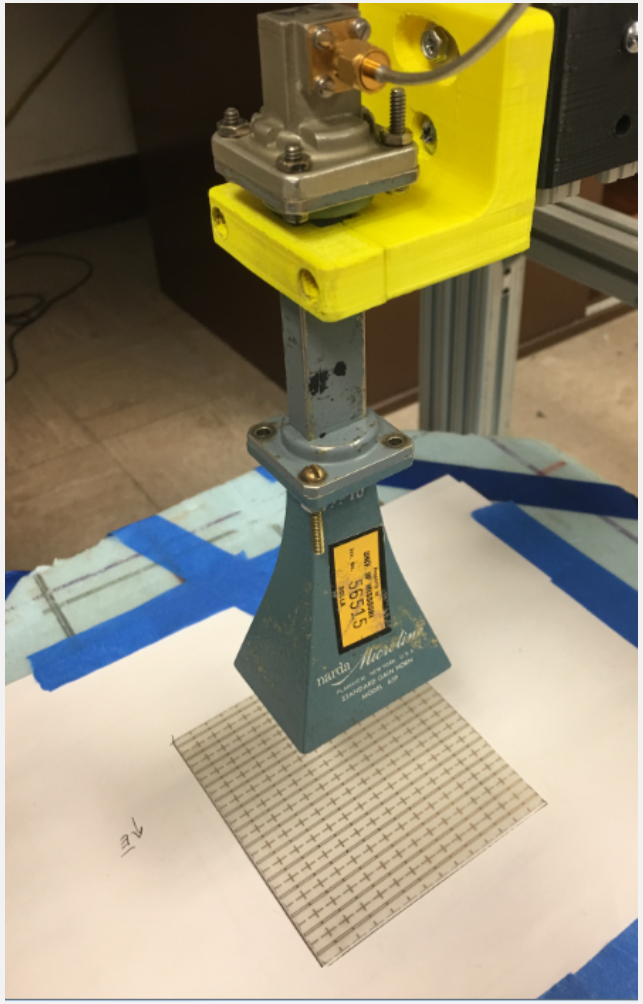


Entire FSS

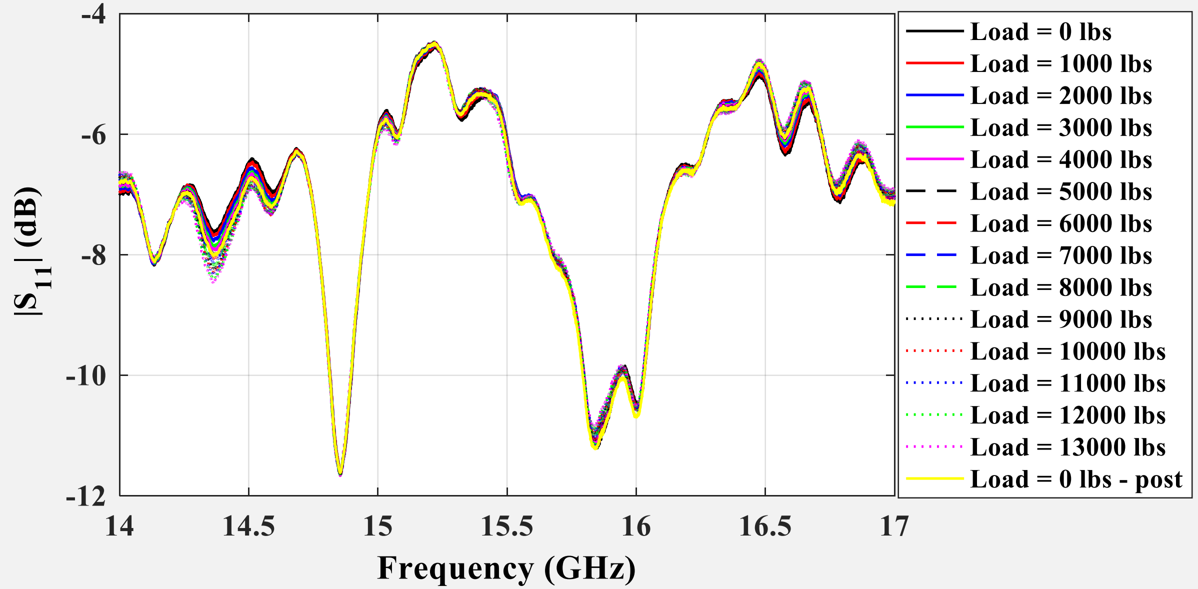


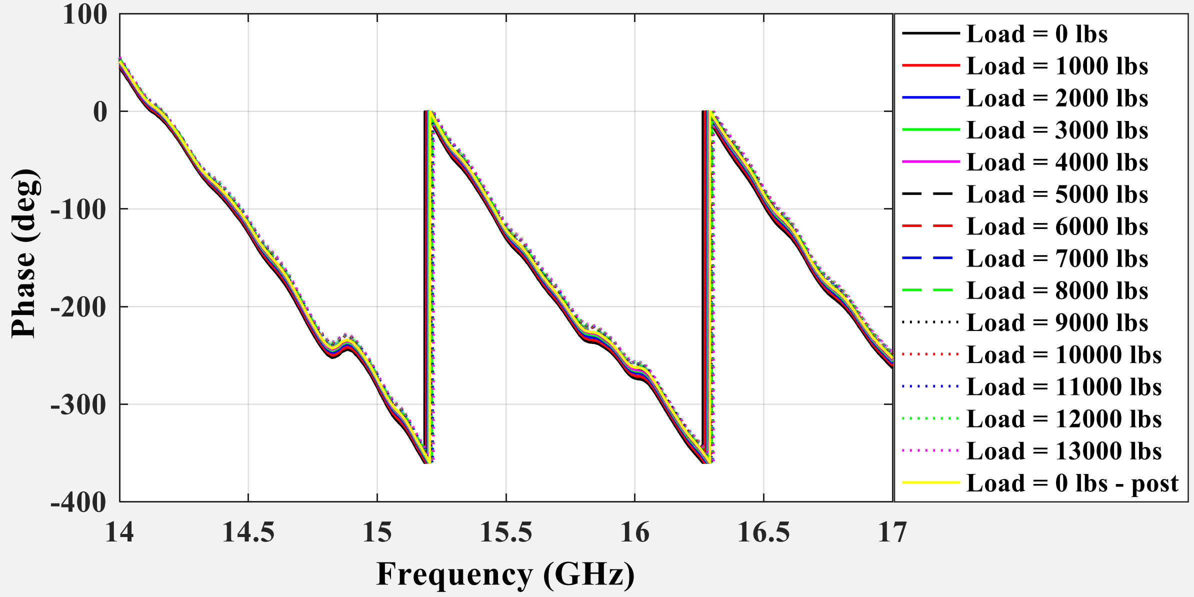
Background Subtracted



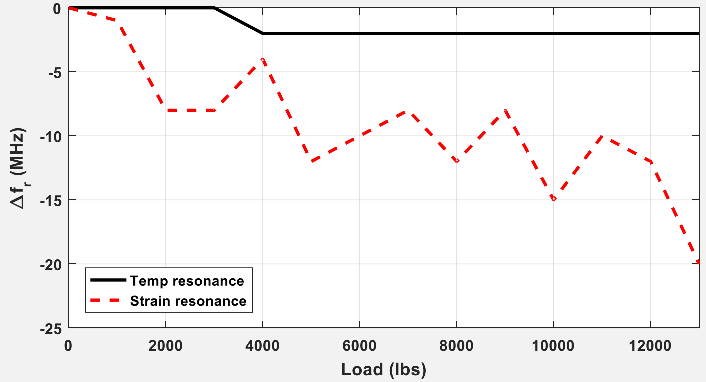


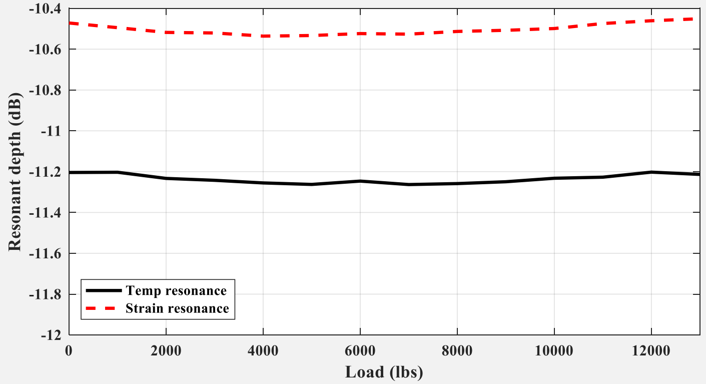
FSS Measurement Under Load

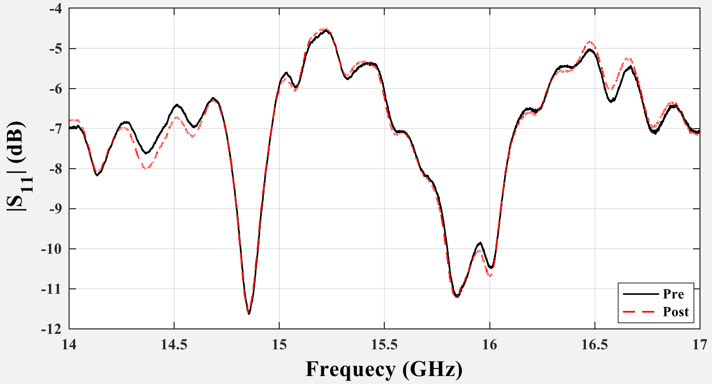




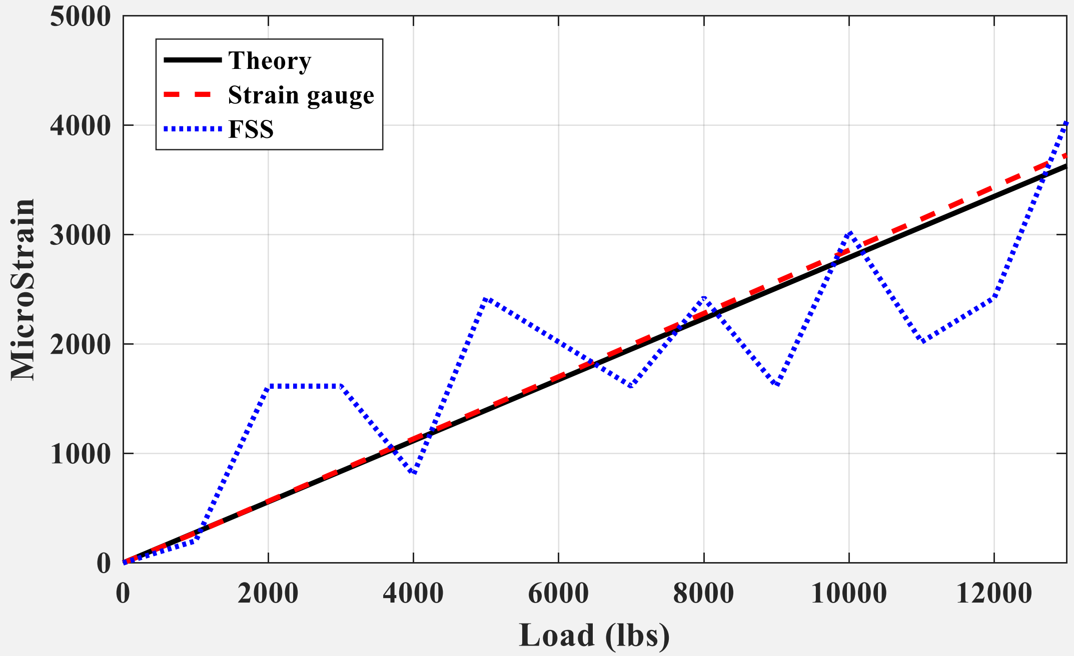
FSS Sensor Response Under Load







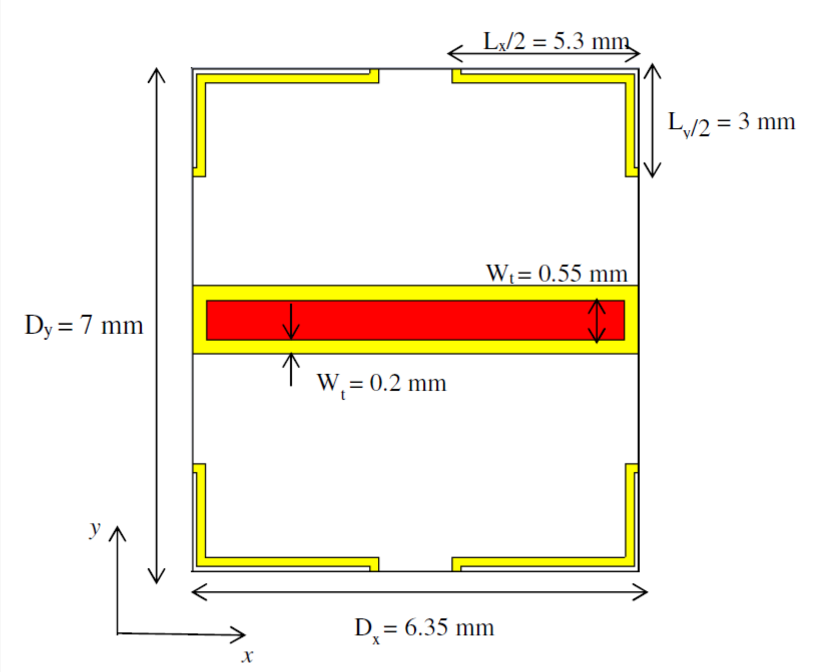
Calculated strain from frequency shift in (second) strain-sensing resonance vs. strain gauge measurement and theory.

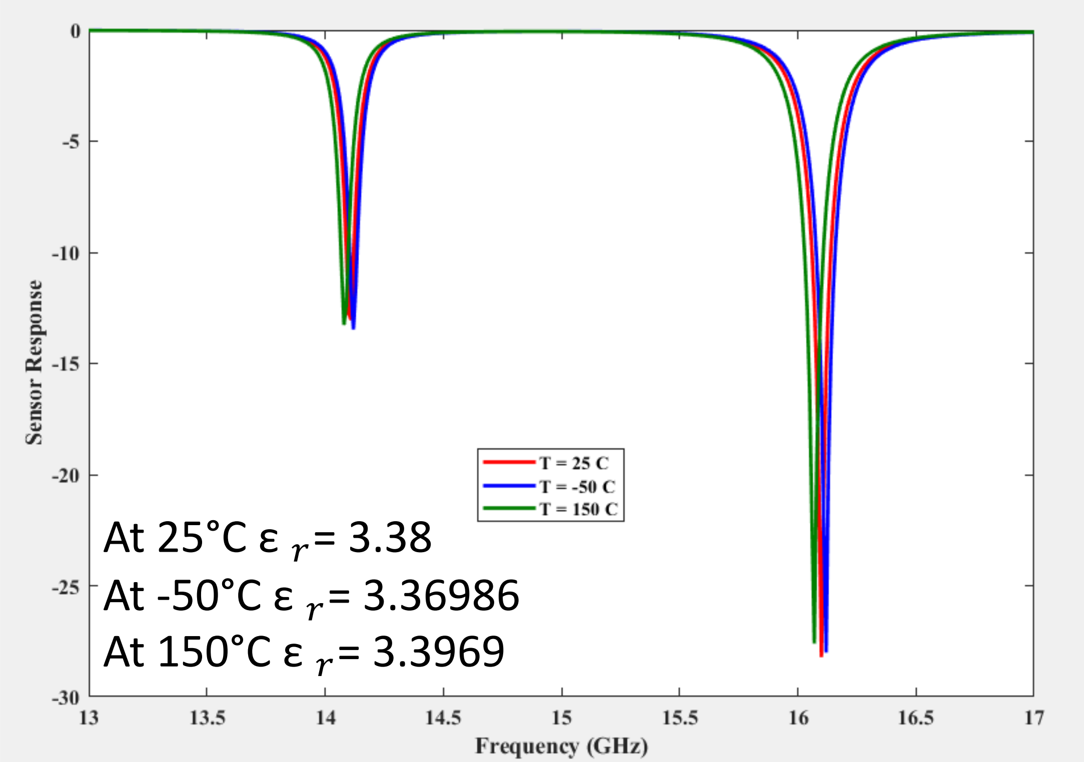


Other Practical Considerations

- Delamination of the sensor from the test structure is an ongoing concern.
  - ➢Currently investigating adjusting the shape of the sensor to reduce the chances of a lamination failure (particularly at the sensor corners).
- High (extreme) temperature applications will also be challenging due to thermal concerns related to bonding material, temperature-sensitive dielectric, etc.
- Cross sensitivity to other environmental parameters such as humidity, substrate effects (primarily thermal properties), dust contaminants….
- Substrate effects (thermal properties): *temperature dependence of permittivity* (ε_r) and *coefficient of thermal expansion* (α)

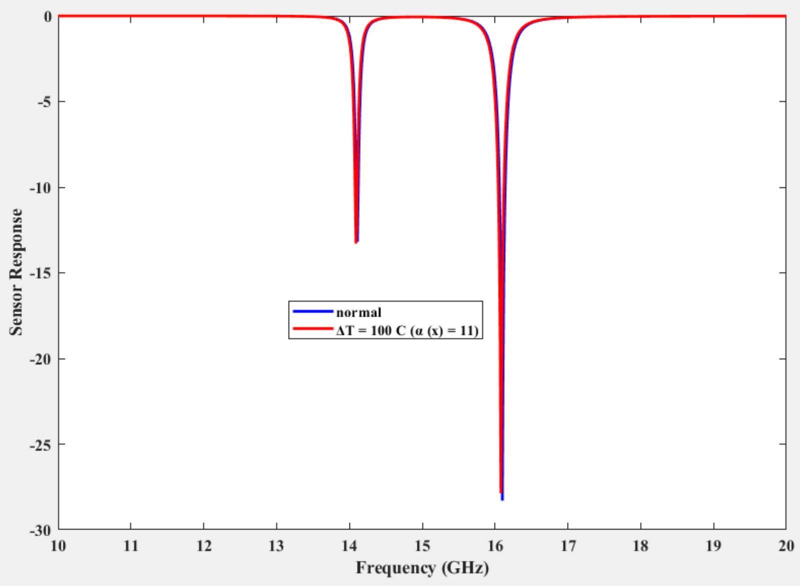
Temperature Dependence due to ε_r

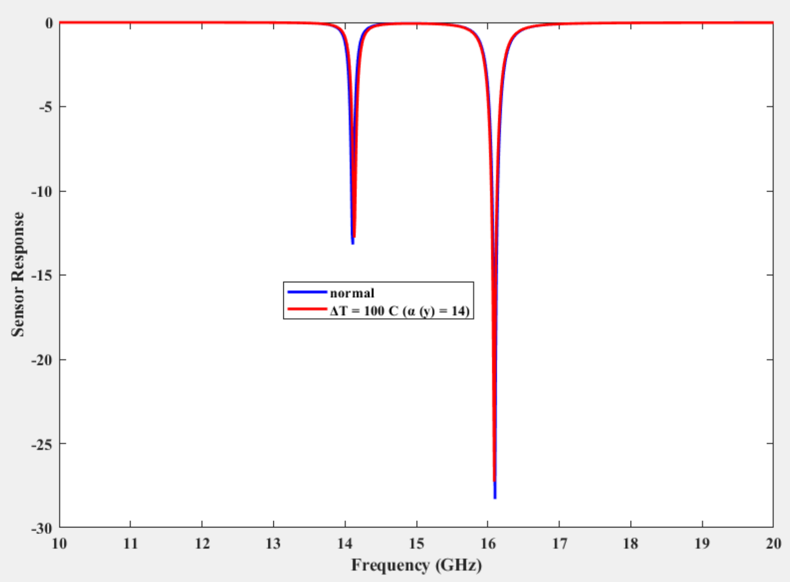


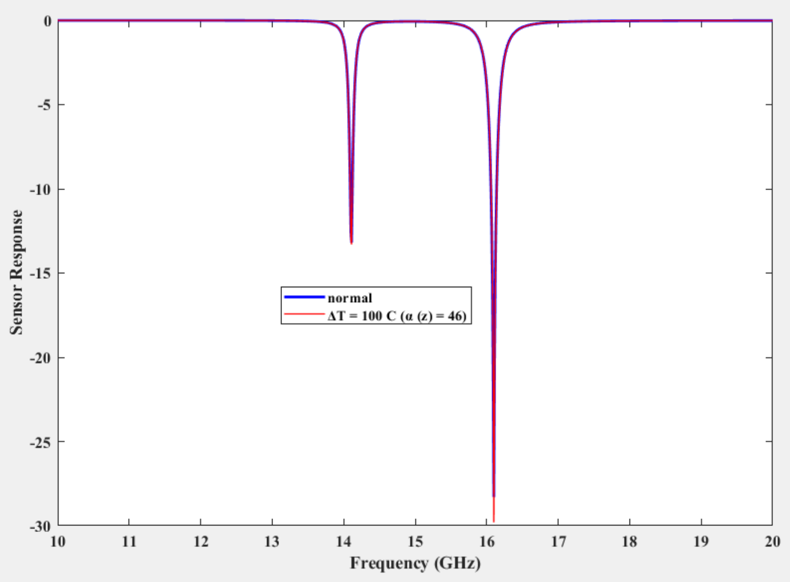


Temperature (°C)	First resonant frequency (GHz)	Frequency Shift (GHz)	Second resonant frequency (GHz)	Frequency Shift (GHz)
25	14.11	-	16.1	-
-50	14.12	0.01	16.12	0.02
150	14.08	-0.03	16.07	-0.03

Temperature Dependence due to α





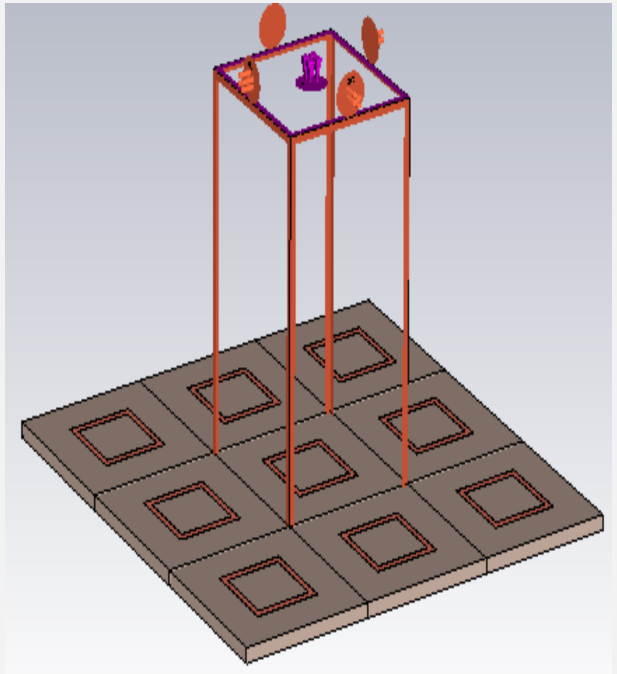


Direction of Length Change	1st Resonant Frequency (GHz)	Frequency Shift (GHz)	2nd Resonant Frequency (GHz)	Frequency Shift (GHz)
Nominal	14.11	-	16.1	-
X	14.09	-0.02	16.08	-0.02
Y	14.13	0.02	16.09	-0.01
Z	14.11	0	16.1	0

FSS Sensing Challenges - Infinite to Finite

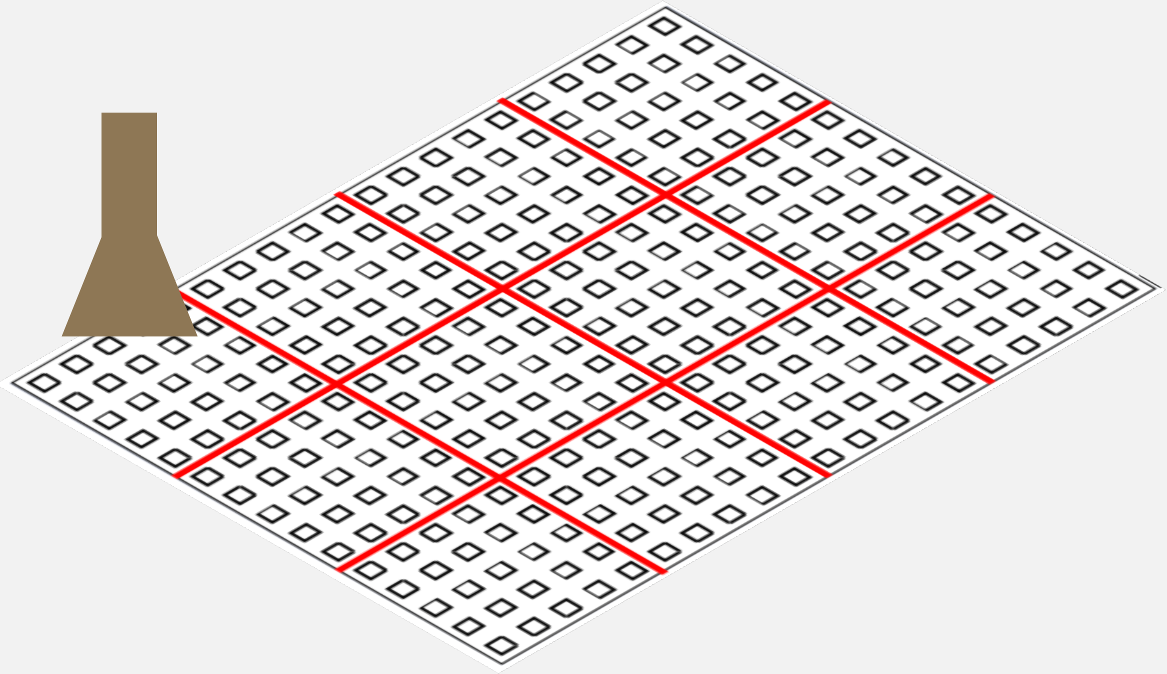
Infinite FSS

- Infinite array of elements
- Uniform excitation
- Comprehensive frequency response (low resolution)



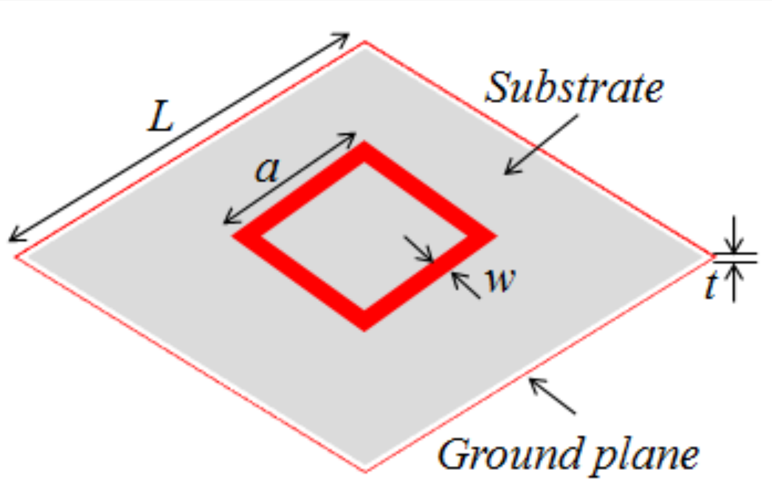
Finite FSS

- Finite array of elements
- Non-uniform excitation
- Edge effect on frequency response
- Importance of number of unit cells
- Comprehensive vs. localized illumination – resolution!!!



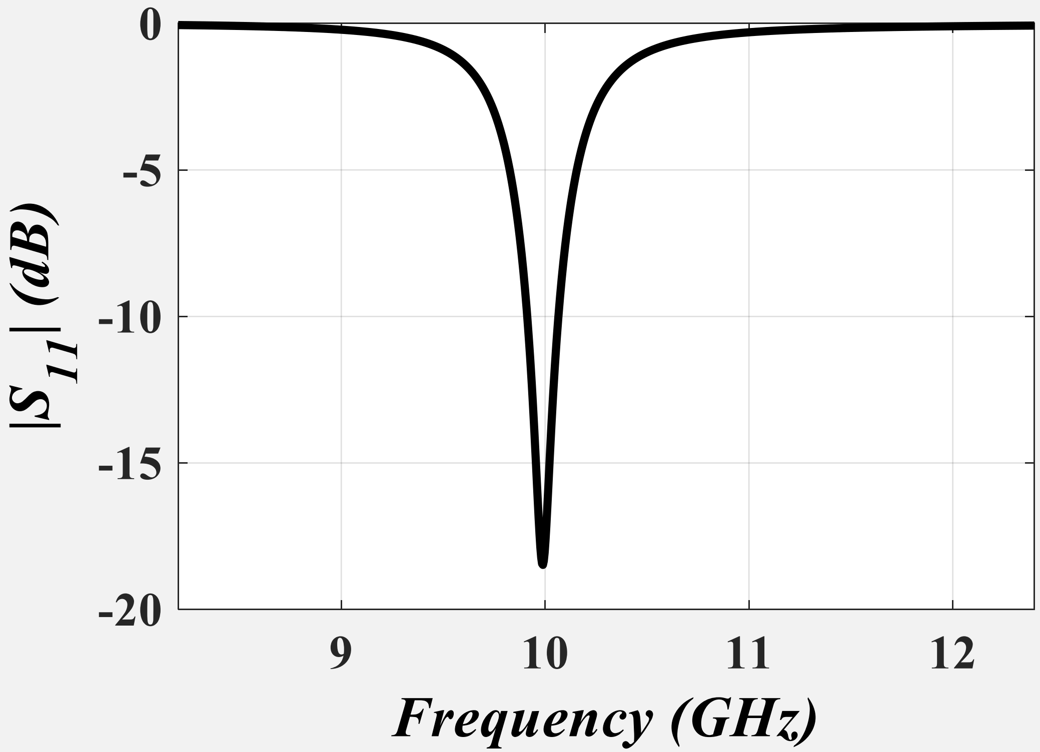
Ideal FSS Response

Loop unit cell



Substrate: FR-4, $\mathcal{E}_r = 4.3$, $tan\delta = 0.023$
L = 10 mm, *a* = 4.95 mm, *w* = 0.4 mm, *t* = 32 mils

Infinite FSS response



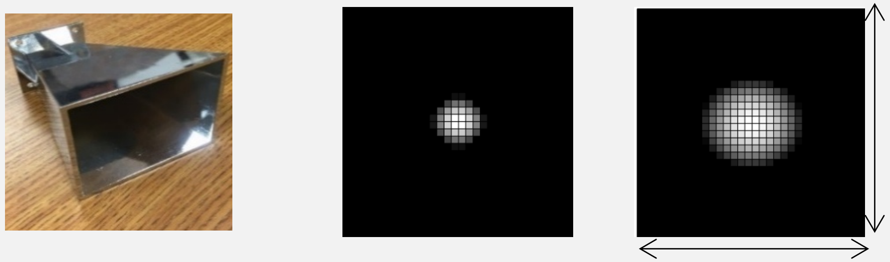
Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Effect of illumination pattern on FSS-based sensor resolution," 2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC). IEEE, 2018.

Sensing Resolution

- Parameters that affect sensor resolution:
  - Illumination footprint (size) on the sensor.
  - Sensor cell size.
  - Number of elements within a sensor cell.

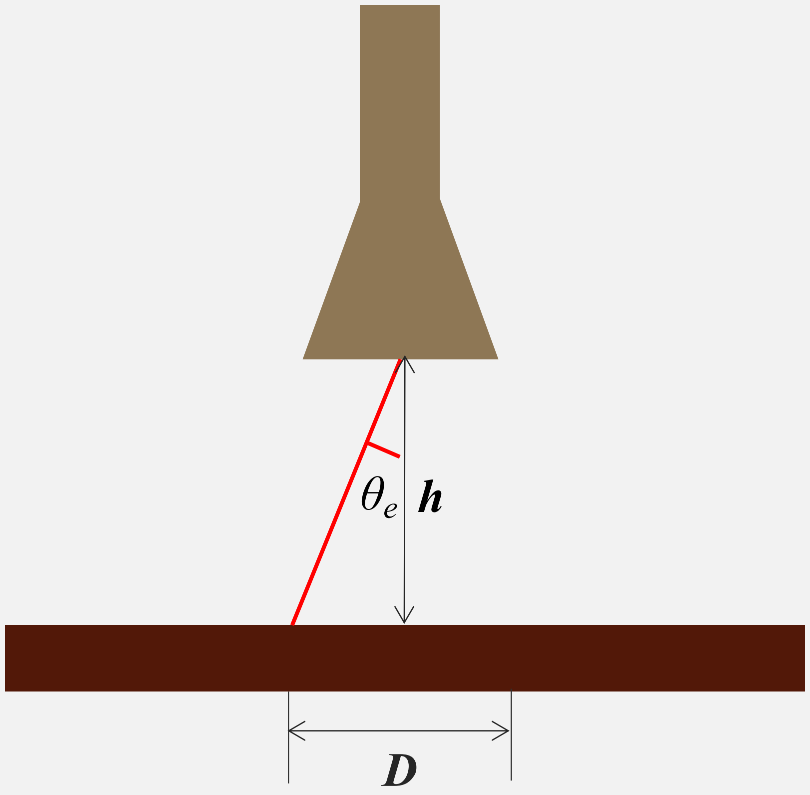
Horn

Standoff (h): $2\lambda_0$ (6 cm) $5\lambda_0$ (15 cm)



20 cm

20 cm

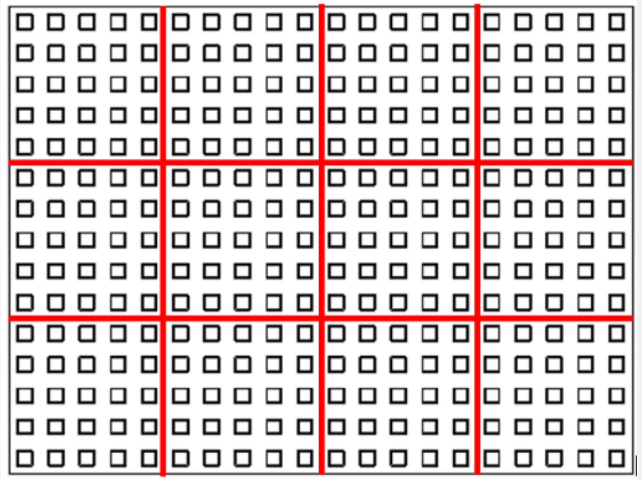


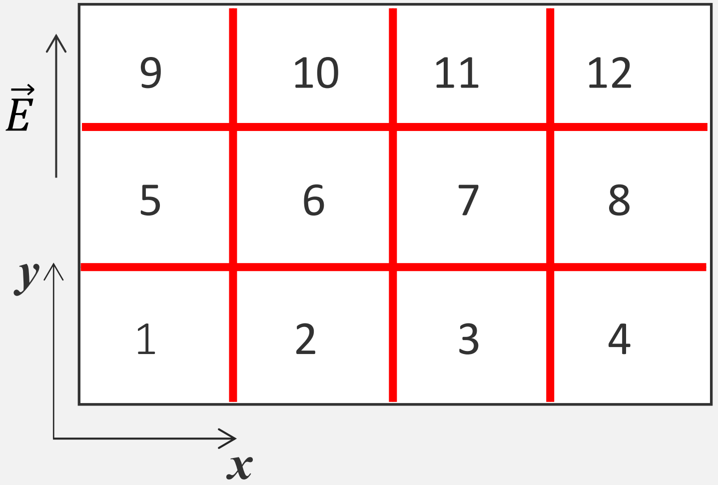
$$tan\theta e = \frac{D}{2h}$$

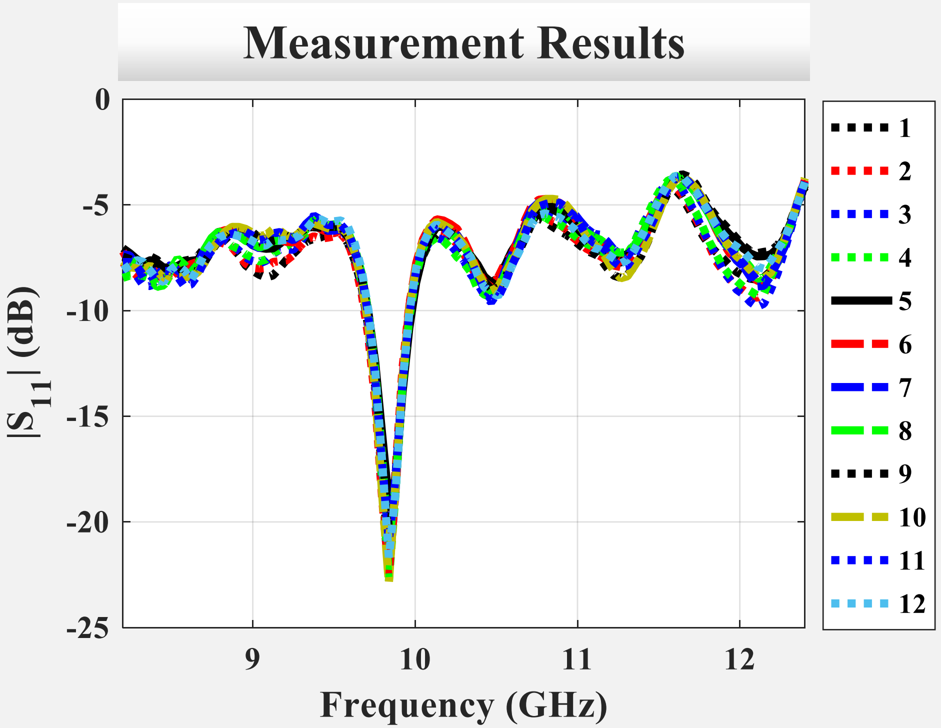
D: sensor cell size;
h: illumination distance from sensor.

Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Effect of illumination pattern on FSS-based sensor resolution," 2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC). IEEE, 2018.

Localized Sensing Measurements

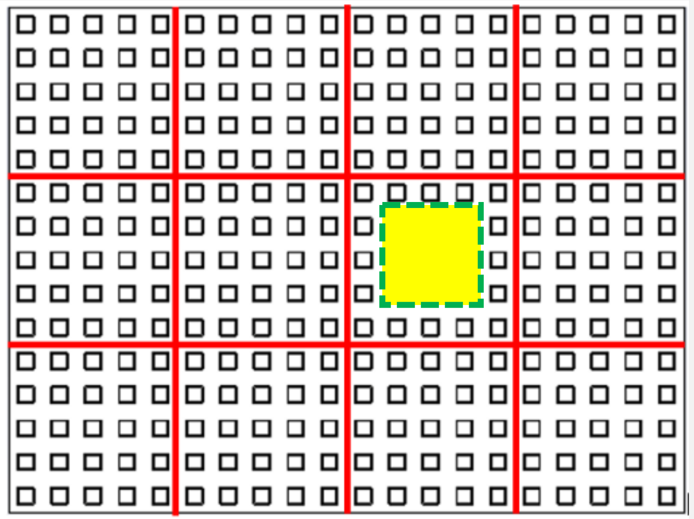




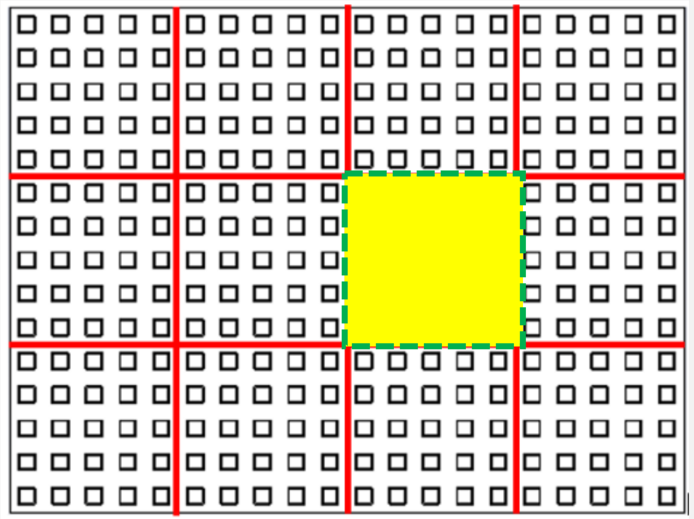


Localized Sensing – Simulated Strain

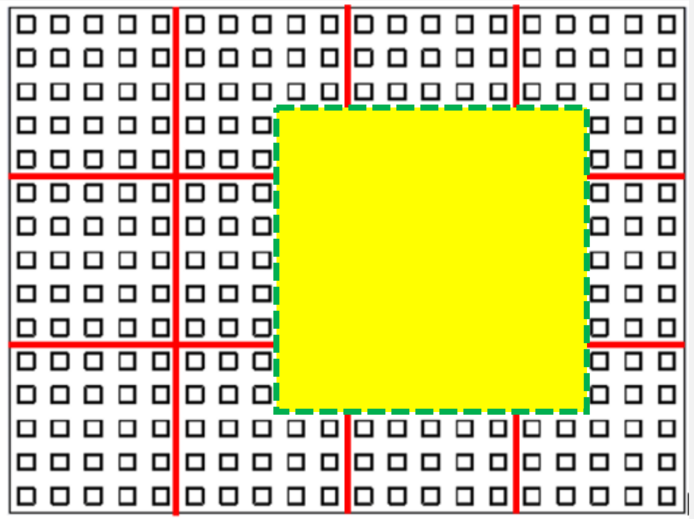
Sensor A

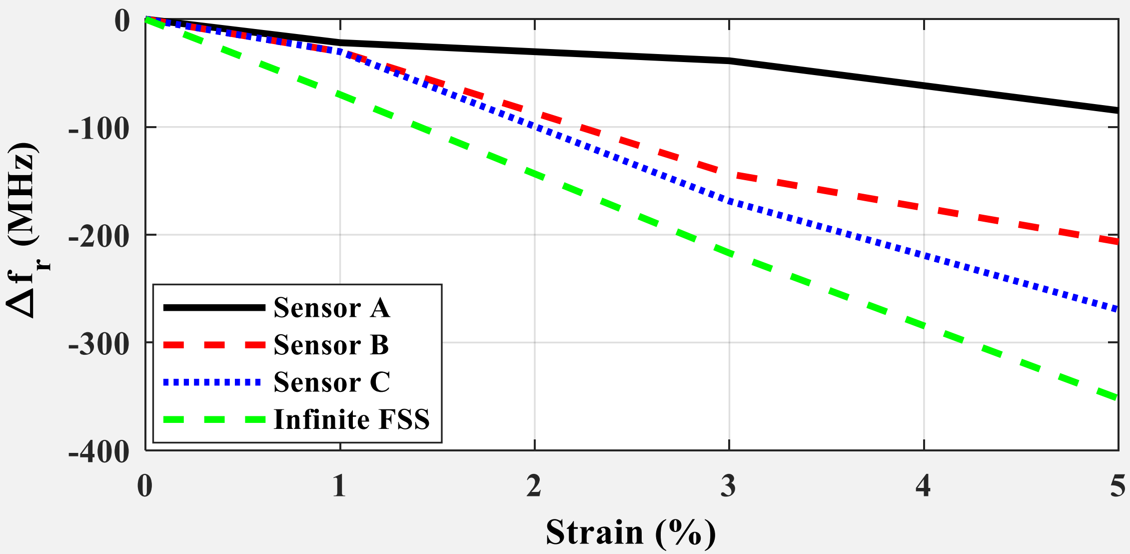


Sensor B



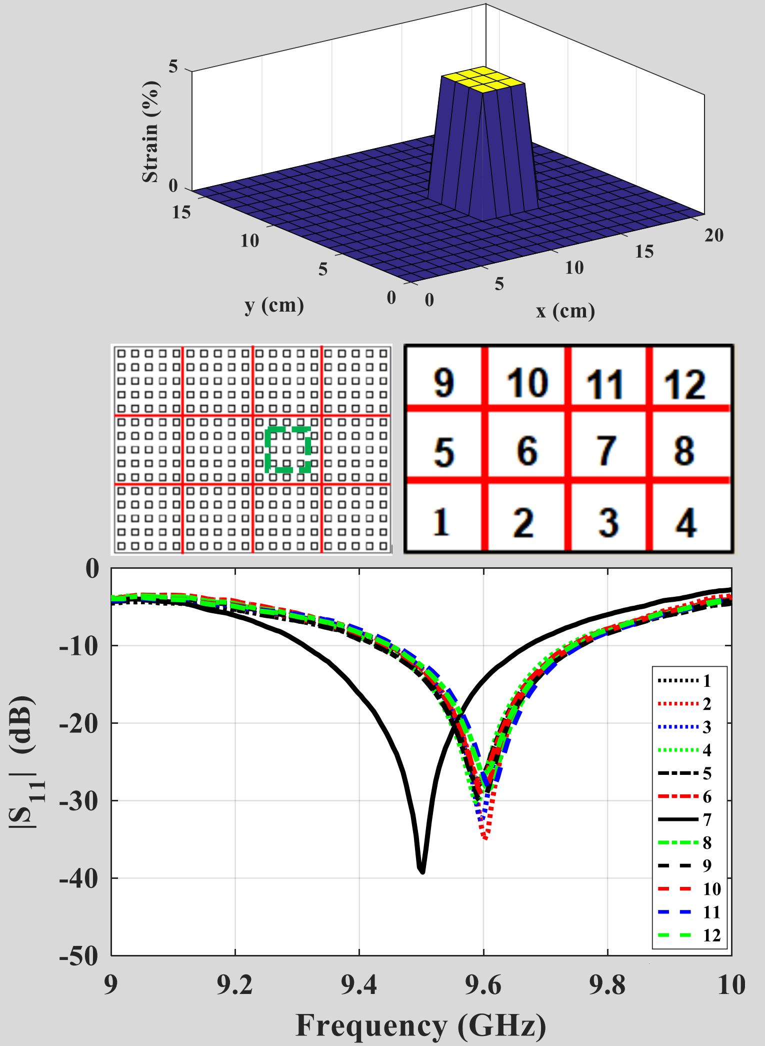
Sensor C



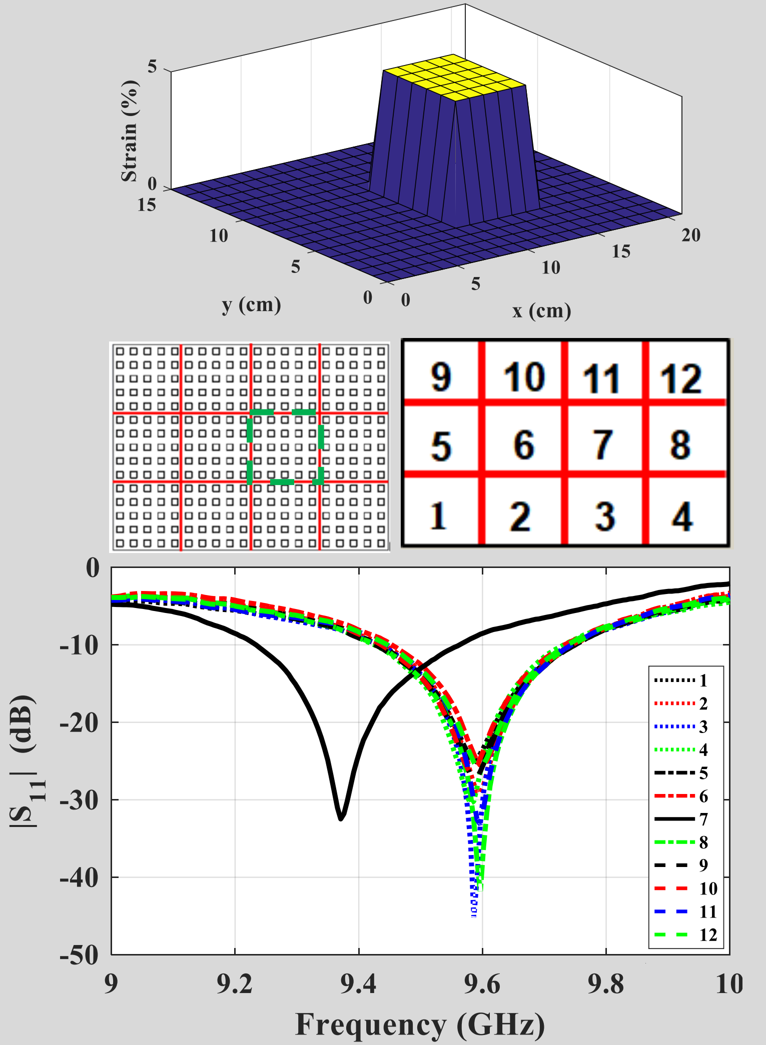


Localized Sensing - Measurements

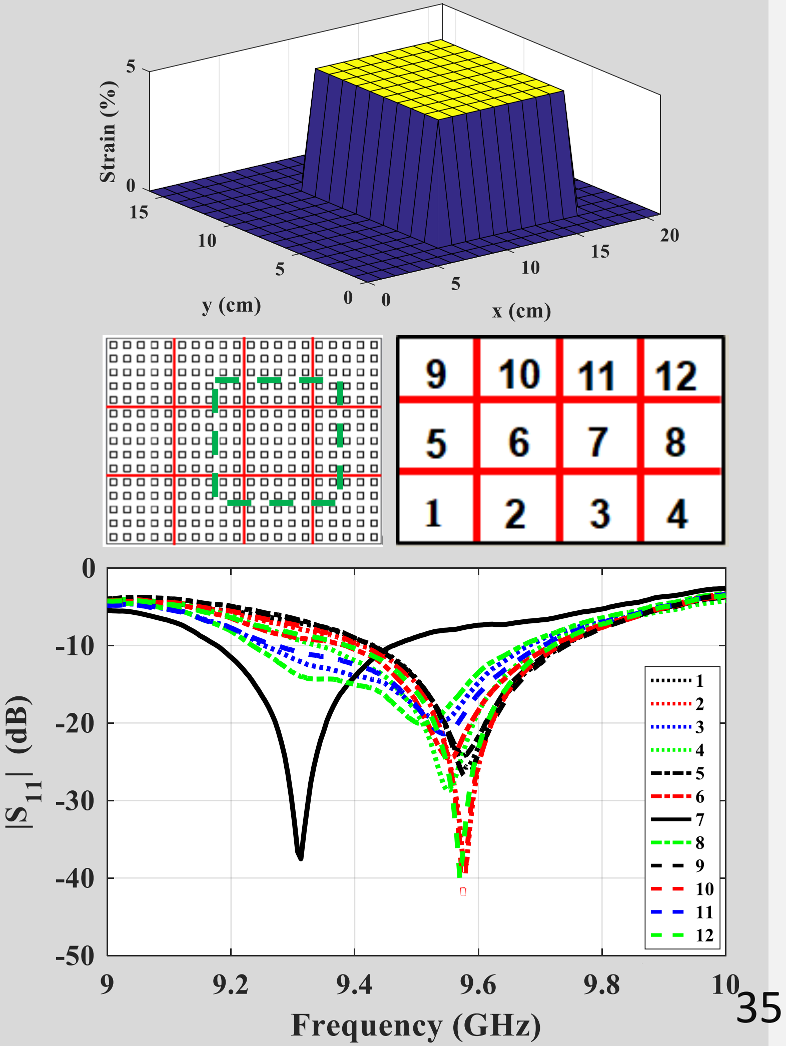
3×3 Elements
Strained area < Sensor cell area



5×5 Elements
Strained area = Sensor cell area

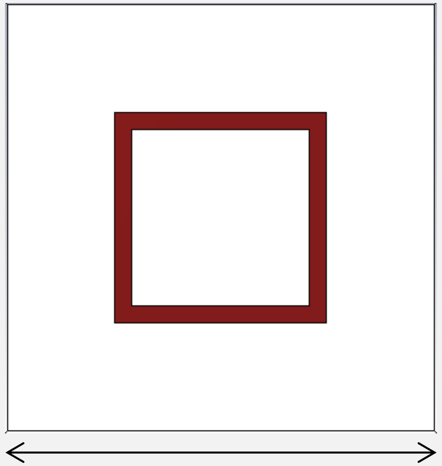


9×9 Elements
Strained area > Sensor cell area



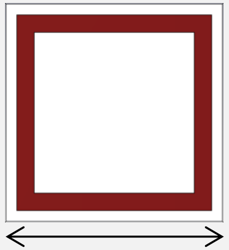
Sensor Improvement by Miniaturization

Original FSS



$D = 10$ mm $= \lambda_0/3$

Miniaturized FSS

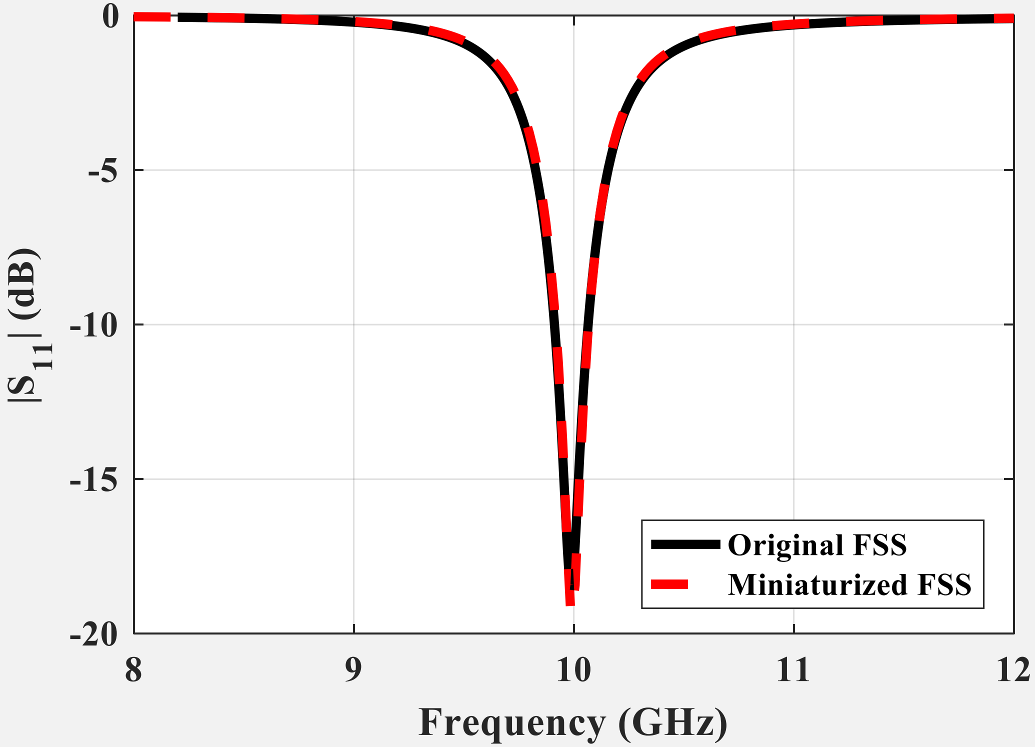


$D = 5$ mm $= \lambda_0/6$

FR-4 Substrate: $t = 32$ mils

$t = 15$ mils

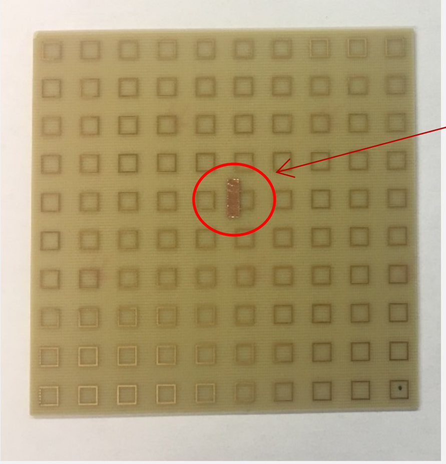
Ideal FSS Response (Simulation)



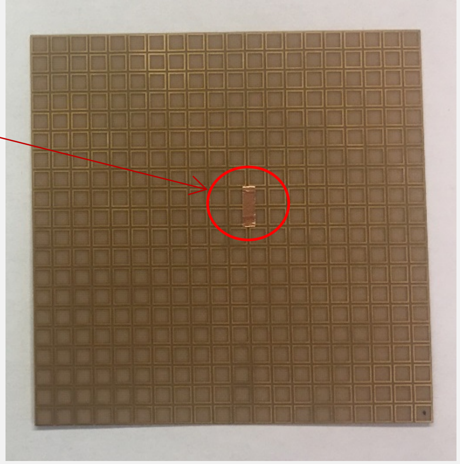
Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Improvement in FSS-Based Sensor Sensitivity by Miniaturization," Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2019 IEEE International Symposium on. IEEE, 2019.

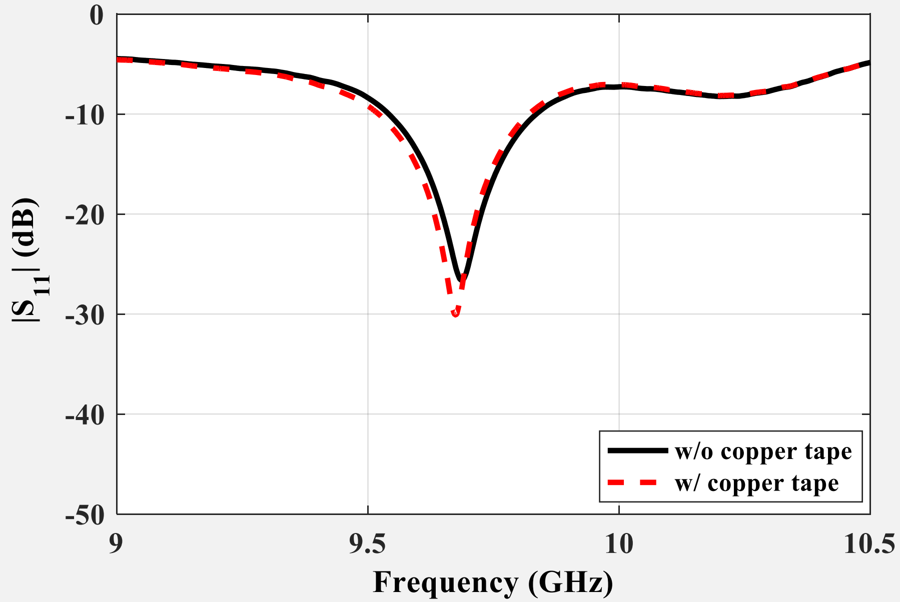
Effect of Anomaly on the Sensor Response

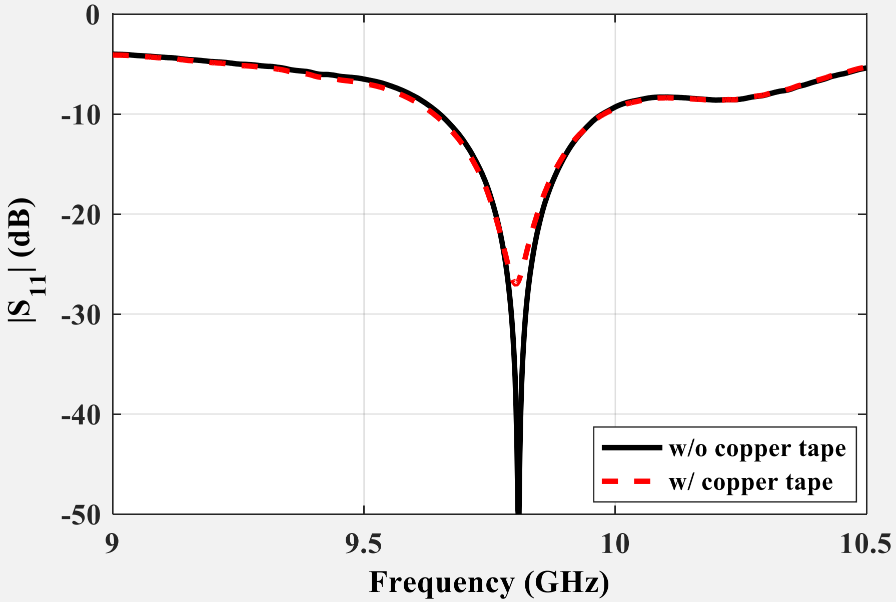
$\vec{E}$



Copper Tape





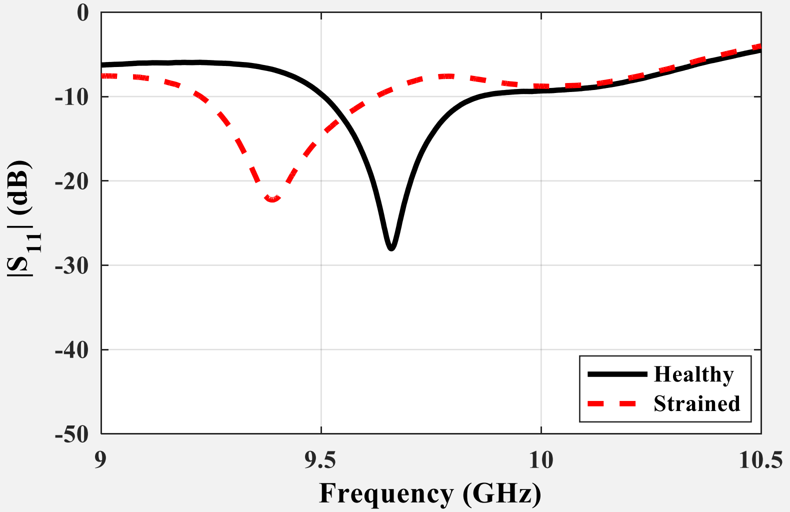


Mahmoodi, Mahboobeh, and Kristen M. Donnell, "Improvement in FSS-Based Sensor Sensitivity by Miniaturization," Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2019 IEEE International Symposium on. IEEE, 2019.

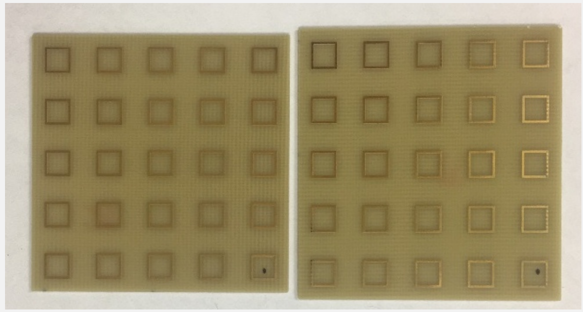
Practical Example – Sensor Miniaturization

- Effect of strain is modeled by increasing sensor dimensions by 5% in strained direction.
- Interrogating polarization is parallel to direction of strain.
- Similar frequency shift since element dimensions of both sensors are similar.

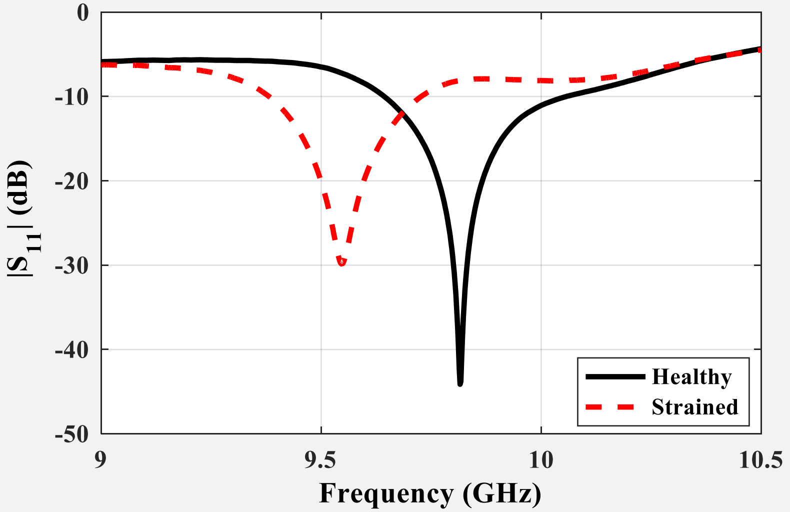
Original FSS

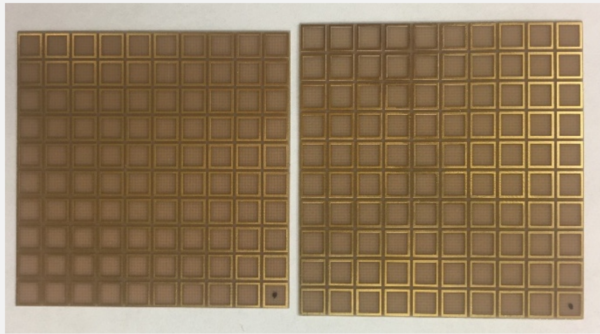


unstrained strained



Miniaturized FSS





Concluding Remarks

- FSS-based sensors have strong potential as a solution for numerous sensing needs
  - Wireless interrogation and flexible resolution provides unique capabilities
- Extreme design flexibility
- Highlighted a number of successful applications including multi-parameter (temperature and strain) sensing
- Some practical challenges remain, but the future for FSS-based sensing continues to progress and expand…...

Acknowledgment

- This work was primarily supported by a National Aeronautics and Space Administration STTR Phase I (T12.01 Advanced Structural Health Monitoring) award (Contract #NNX17CL92P).

Thank You