Printed Wireless Sensors for Structural Health Monitoring

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Wireless Crack and Strain Sensors for Structural Health Monitoring

Problem:

- Wireless detection of crack and strain in critical safety items is of interest for numerous applications
- There is a need for sensors that can be interrogated in the absence of a clear line-of-sight that are passive or energy harvesting

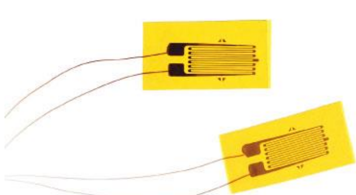
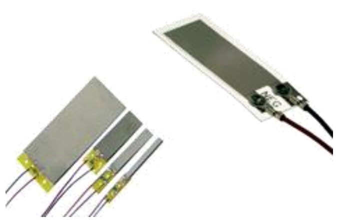
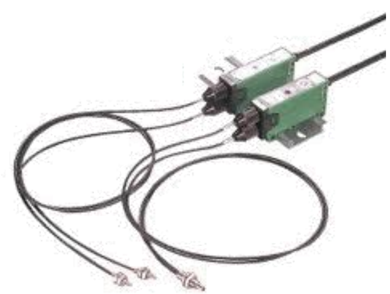
Opportunity: Ability to detect & monitor cracks/strains remotely can

✓ help minimize/prevent catastrophic failure

✓ predict/prevent failure and prolong useful life of structural components (by avoiding unnecessary replacement)

Problems with Conventional Sensors

- Installation and measurement challenges
  - ✓ Physical connectivity requirements between the sensing element and the interrogation system
  - ✓ Power requirement: Need for replacement of batteries or the sensor itself on a regular basis
- Drifts of the sensors
- Installation, maintenance, monitoring and overall cost


Comparison of current technologies

	Technology	Detection limits	Advantage/ Disadvantage
Crack Sensors	Radiography	30 – 50 microns	High resolution, far field detection; bulky, high cost
	Embedded distributed fiber-optic, electric and acoustic sensors	Crack Resolution ~ 5 micron	Cannot be interrogated without connection
	Radio frequency based passive sensors	**~ 5 micron**	**Wireless interrogation, no line of sight required**
Strain Sensors	Resistive strain gauge with RF link	Sensor dependent	Active sensors, installation issues, require power
	LCR and Capacitive	Gauge factor ~ 5	Wireless interrogation, complex fabrication, element deformed (stability?)
	Printed wireless strain sensor	**Gauge factor ~ 10**	**Passive, Wireless, sensing element is not deformed**

Key Requirements and Our Approach

Requirements

- Passive crack sensors that can be interrogated wirelessly by tracking changes in substrates and providing reliable response
- Passive wireless strain sensors with good gauge factors
- New chemistries and printable metallic ink formulations are necessary for high quality factor

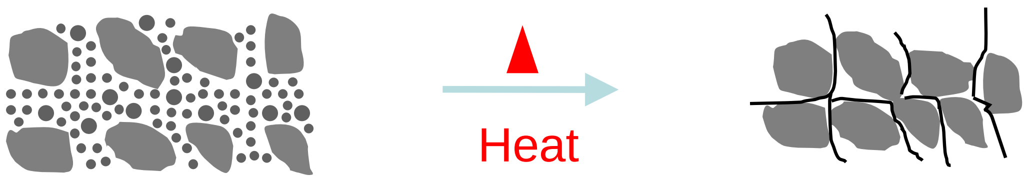
Our Approach

- Metal flake based conformal sensors: LC circuits (inductor-inter-digitated capacitor) printed on substrates using a new class of printable inks
- Cracks on substrates disrupt conductive patterns leading to a detectable change in RF response
- RF responsive multilayer strain sensor

Printing of Wireless Crack Sensors

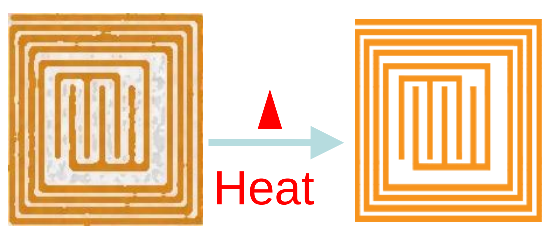
- Silver flakes (< 10 µm) and silver powder (2-3 µm) constitute the predominant functional particles
- Organic precursor of silver helps in the chemical welding

UML Silver Inks



Silver flakes; nanoparticles + silver salts

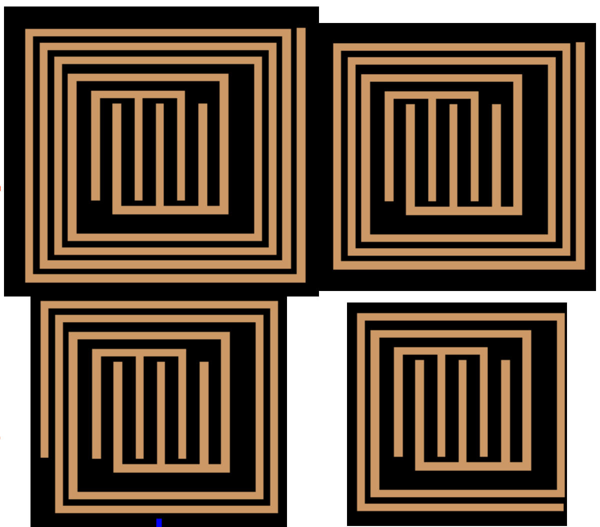
Silver flakes chemically welded by metal-organic decomposition

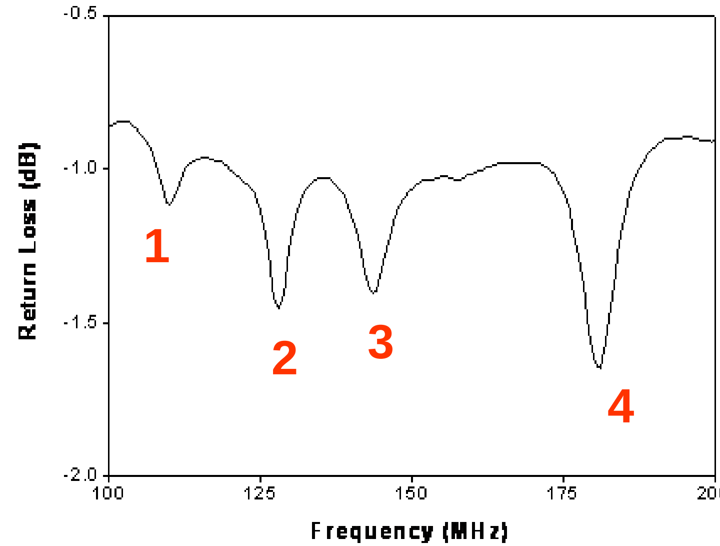


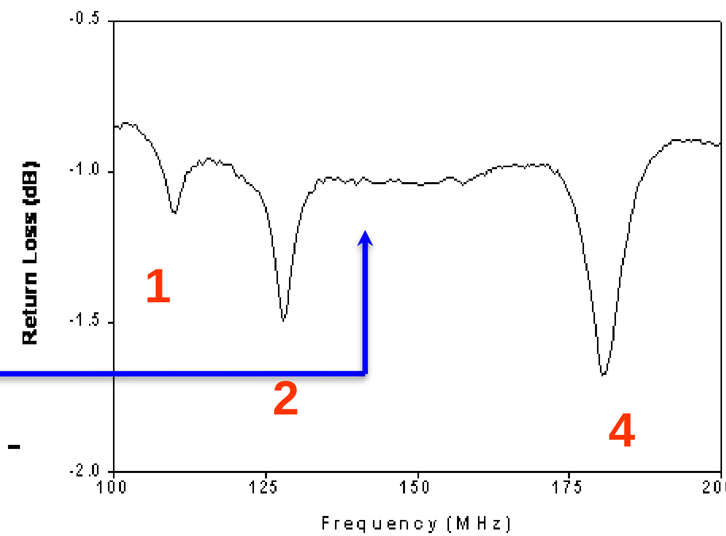
“Conductive formulations for deposition of binder-free metallic elements suitable for use in electrical, electronic and RF applications” (Ramaswamy Nagarajan, Sharavanan Balasubramanian, Joey Mead and Julie Chen), U.S. Patent 8,999,431B2, April 7, 2015.

Wireless Detection and Location of Cracks!

- ✓ Surface of interest can be covered with multiple sensors (printed using silver inks)
- ✓ Sensors resonate at different discrete frequencies

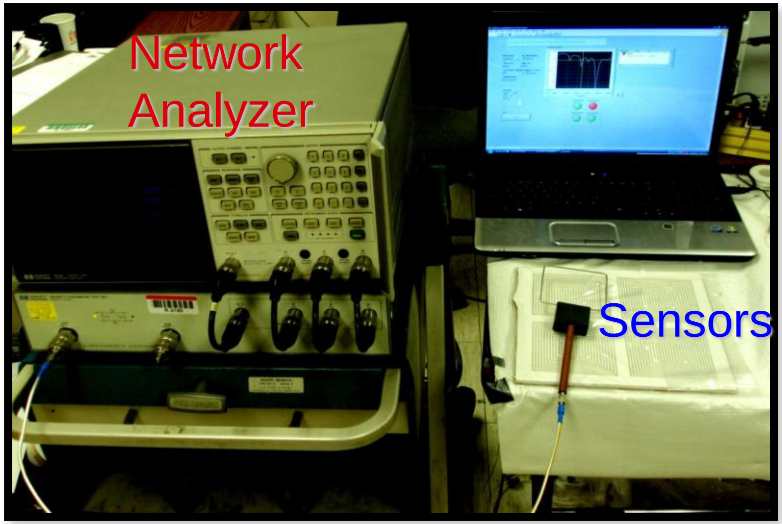




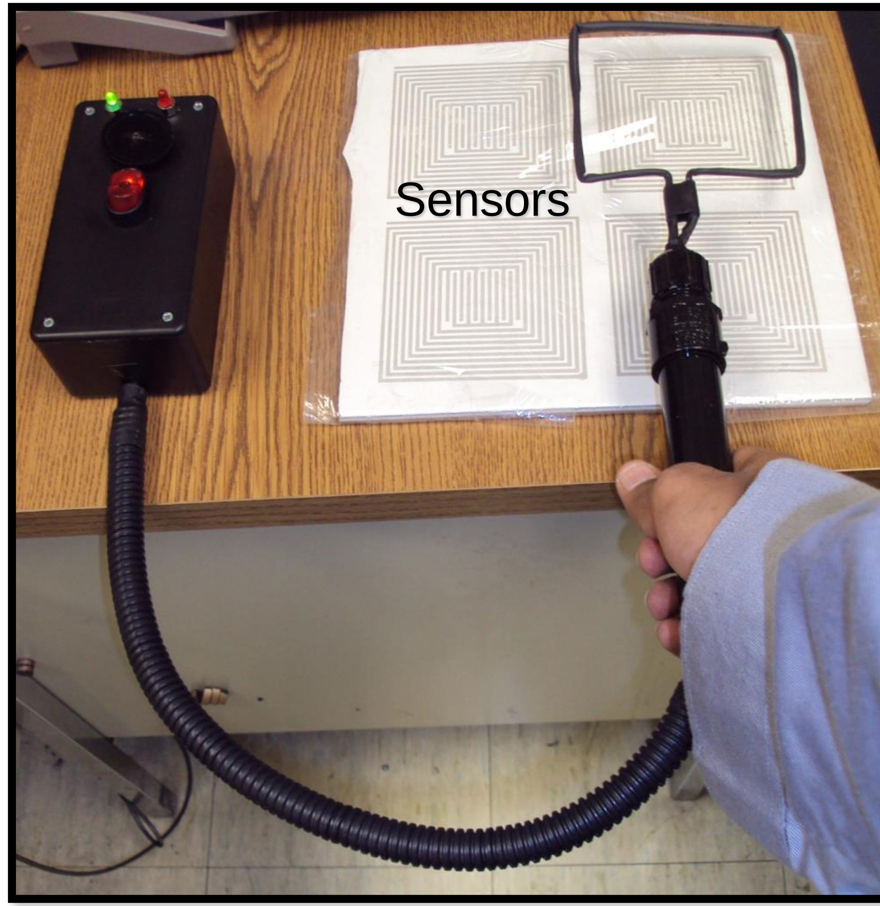


Sensor 3 was cracked - RF response missing

Miniaturizing the Interrogator



New compact portable hand-held interrogator

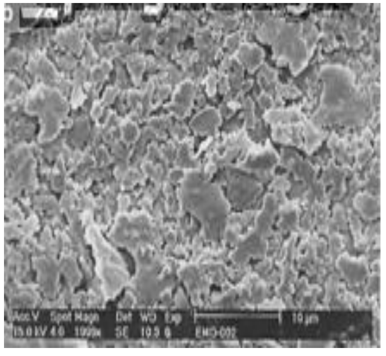


Initially the Interrogation system was base on a Network analyzer Connected to a PC
-Sensitive but bulky!

Binder-free Conductive Inks

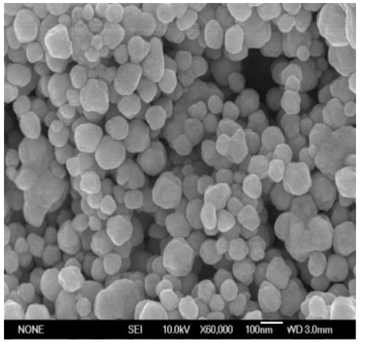
Conductive Silver Inks

Silver thick film pastes/inks



- Micron sized Silver flakes/powders
- Polymeric binders (Polyester, chlorovinyl, epoxy)
- Solvent (Butyl acetate, glycol esters)
- Additives (Rheological modifiers, adhesion promoters etc)

Silver nano inks

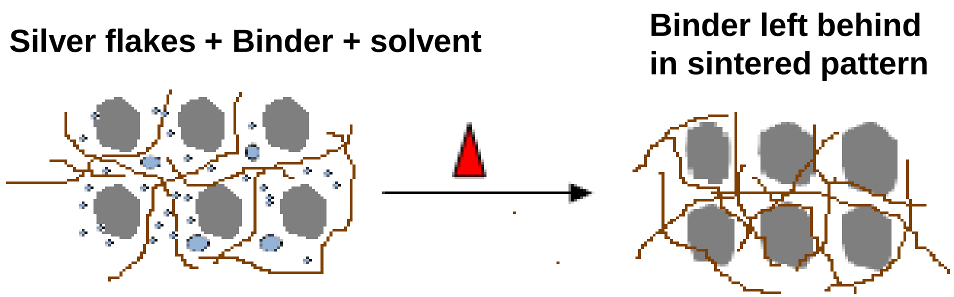


Colloidal solutions:
Silver nanoparticles with capping agents

- Capping agents – alkanethiols/ PVP /PAA
- Solvents – α-Terpineol, Toluene, Benzene

Limitations of Conventional Inks

Conventional thick film forming silver conductive Inks



- Non-conducting binder limits conductivity (Conductivity less than one or two orders of magnitude of pure silver)

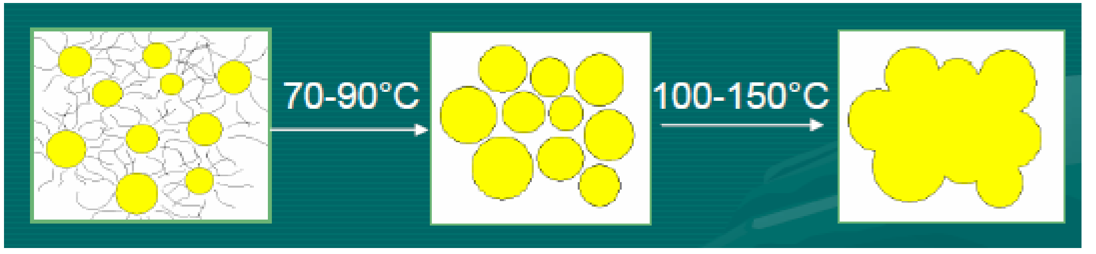
- RF performance issues!

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

- Binder leaches into the organic active layer causing long term performance and stability issues

Limitation of Nano-inks

Nanoparticle inks

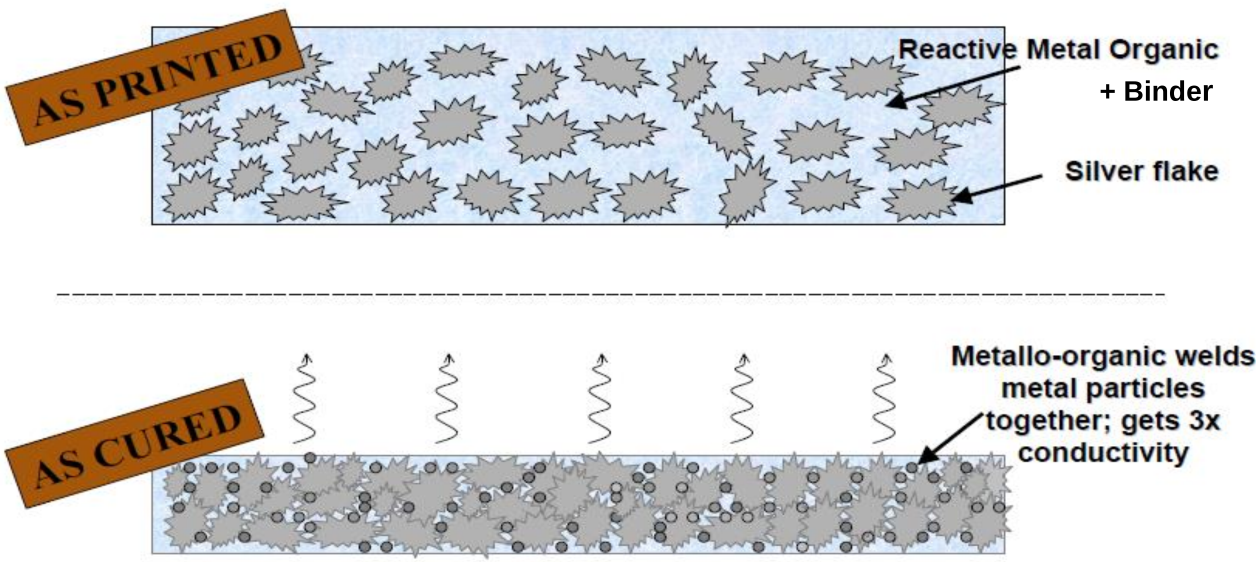


- Conductivity within an order of magnitude of silver at sintering temperature of 150 ° C
- Forms only thin films. Multiple passes required for films > 1 µm
- Skin depth at the frequencies of interest is > 1 µm
- High cost [1]

2. http://nanomarkets.net/articles/article/silver_conductive_inks_and_pastes

MOD / Chemically Welded Inks

Metal Organic Decomposition (MOD) Inks based on silver carboxylates



- Conductivity within two orders of magnitude of silver at sintering temperature 150 ° C - 190 ° C [1].
- Commercial products use Silver neodecanoate as the precursor

Conaghan, B. F., Jablonski, G. A., Kydd, P. H., Mendoza, I., & Richard, D. L. (2007). High Conductivity Inks with Improved Adhesion, US Patent

Wish list of Ink Characteristics for RF applications

- **High conductivity: Within one or two order of magnitude of pure silver ($\sigma_{Ag} = 6.3 \times 10^{7}$ S/m)**

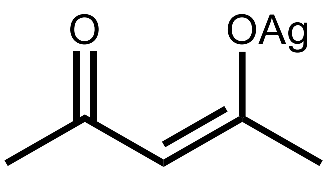
- **Strong substrate adhesion and strong particle to particle cohesion**

- **Low (preferably no) organic residue – binder free for RF applications – High quality factor**

- **Low temperature processability (< 120° C) for printing on temperature sensitive substrates like Spectra or Dyneema composites**

- **Printable using conventional (gravure, screen, inkjet methods)**

UML Innovation in Binder-free low temperature processible inks



Silver flakes + nanoparticles + Silver salt + Dispersant

Chemical welding of silver flakes

Silver salt

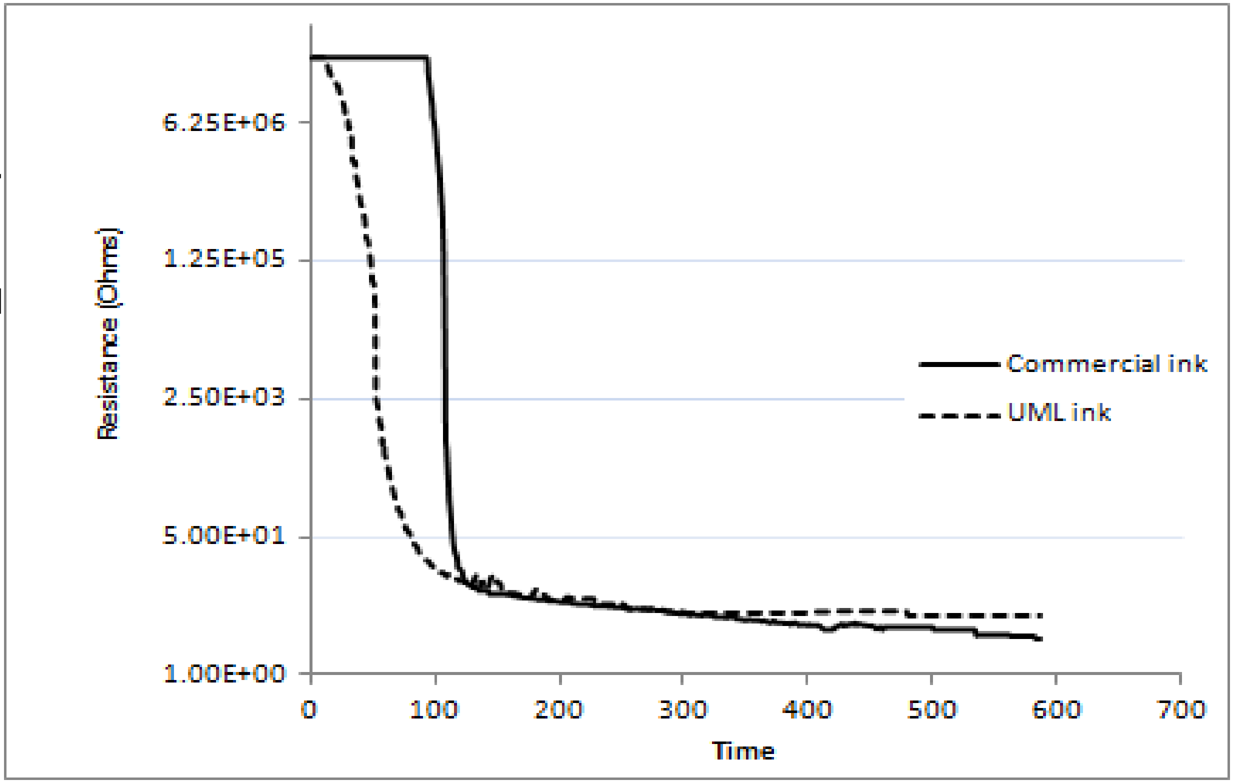
Agacac

- **Use of proprietary dispersant – eliminate the binder!**
- **Acceleration of the thermal decomposition at temperatures < 120 ° C using thermal initiators**

Kinetics of ‘Cure’
Resistance Versus Temperature

- Resistance in an oven
  at 120° C m

•UML ink Co



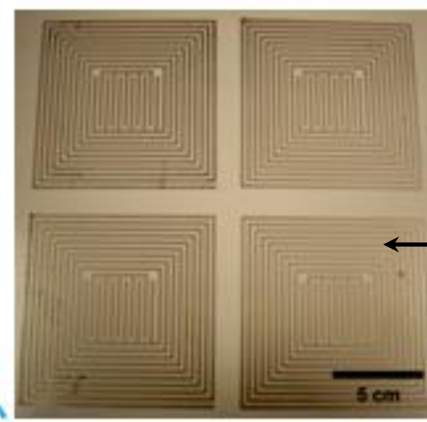
- Initially UML ink loses resistance faster than commercial inks
- Resistance of commercial ink lower than UML formulation

Wireless Crack Sensors for Trauma plates

Alumina Armor Plate

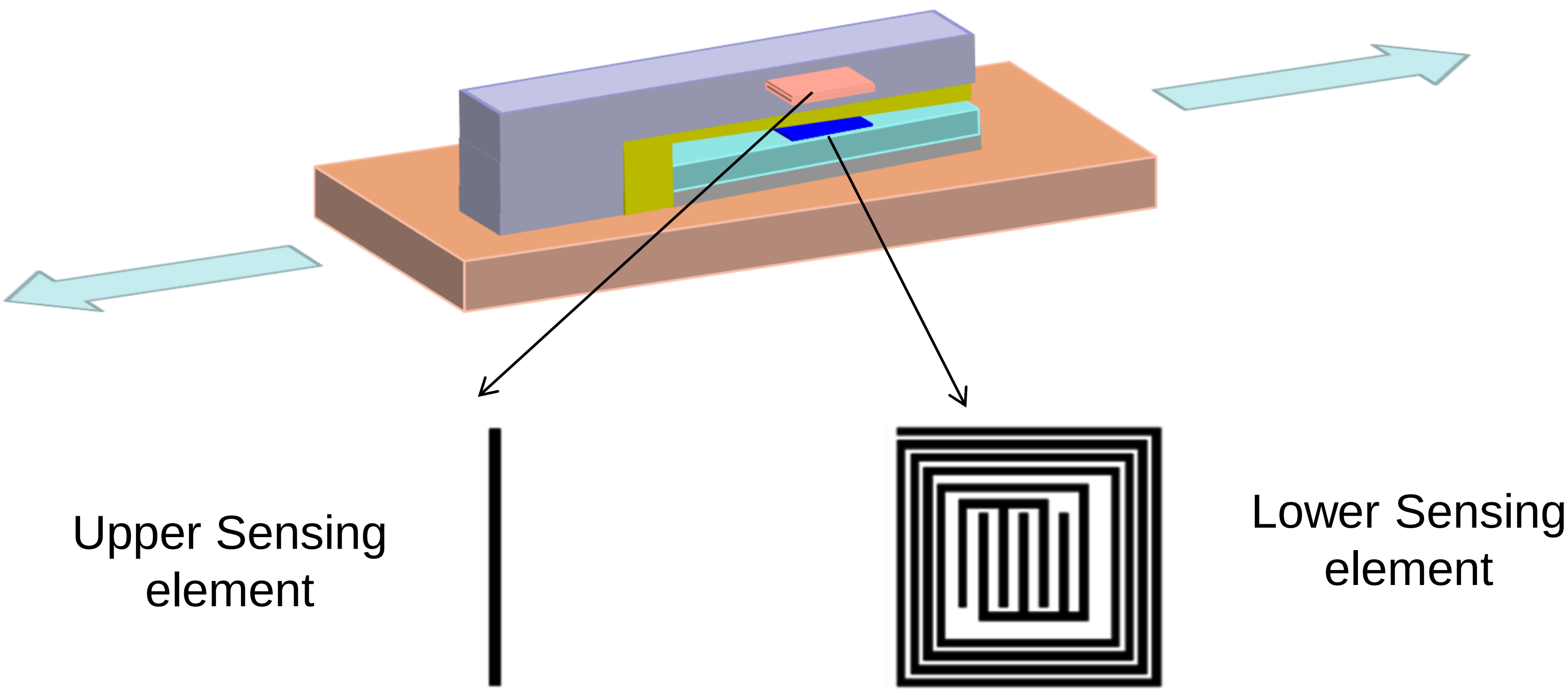
SiC
Body Armor
(Semiconductor)

Vest with trauma plate



LC sensors printed on ceramic plate (25 cm × 25 cm)

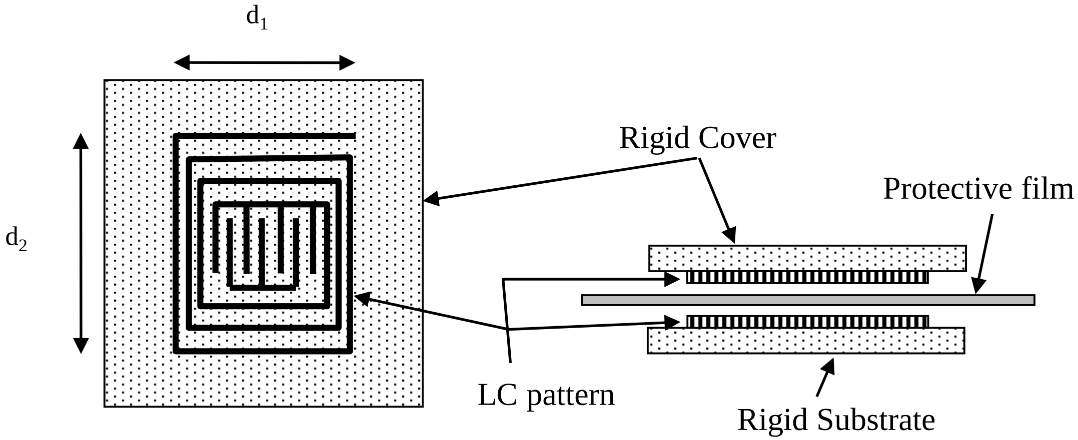
Strain Sensor in action



Wireless Passive Radio-Frequency Strain and Displacement Sensors

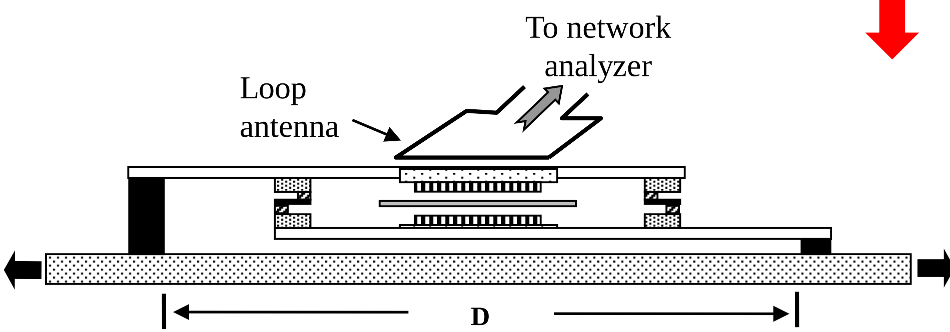
Ramaswamy Nagarajan, Jungrae Park, Sharavanan Balasubramaniam, Mario J. Cazeca, Shivshankar Sivasubramanian, Joey Mead, Julie Chen, US 9,038,483 B2., 2015.

Detailed description of the sensor

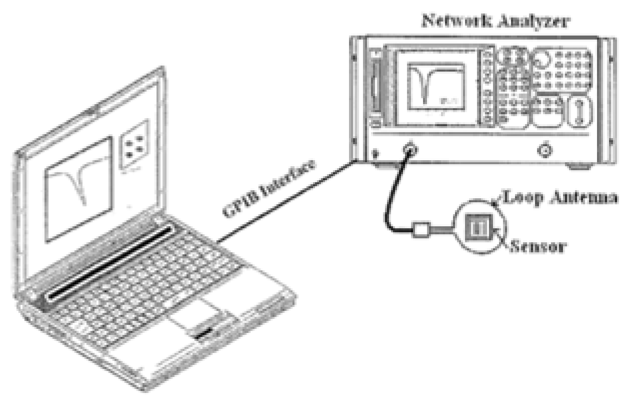


- ✓ Unlike conventional sensors, the metallic element does not deform!
- ✓ Encapsulation can provide improved durability
- ✓ Signal is generated through relative displacement!

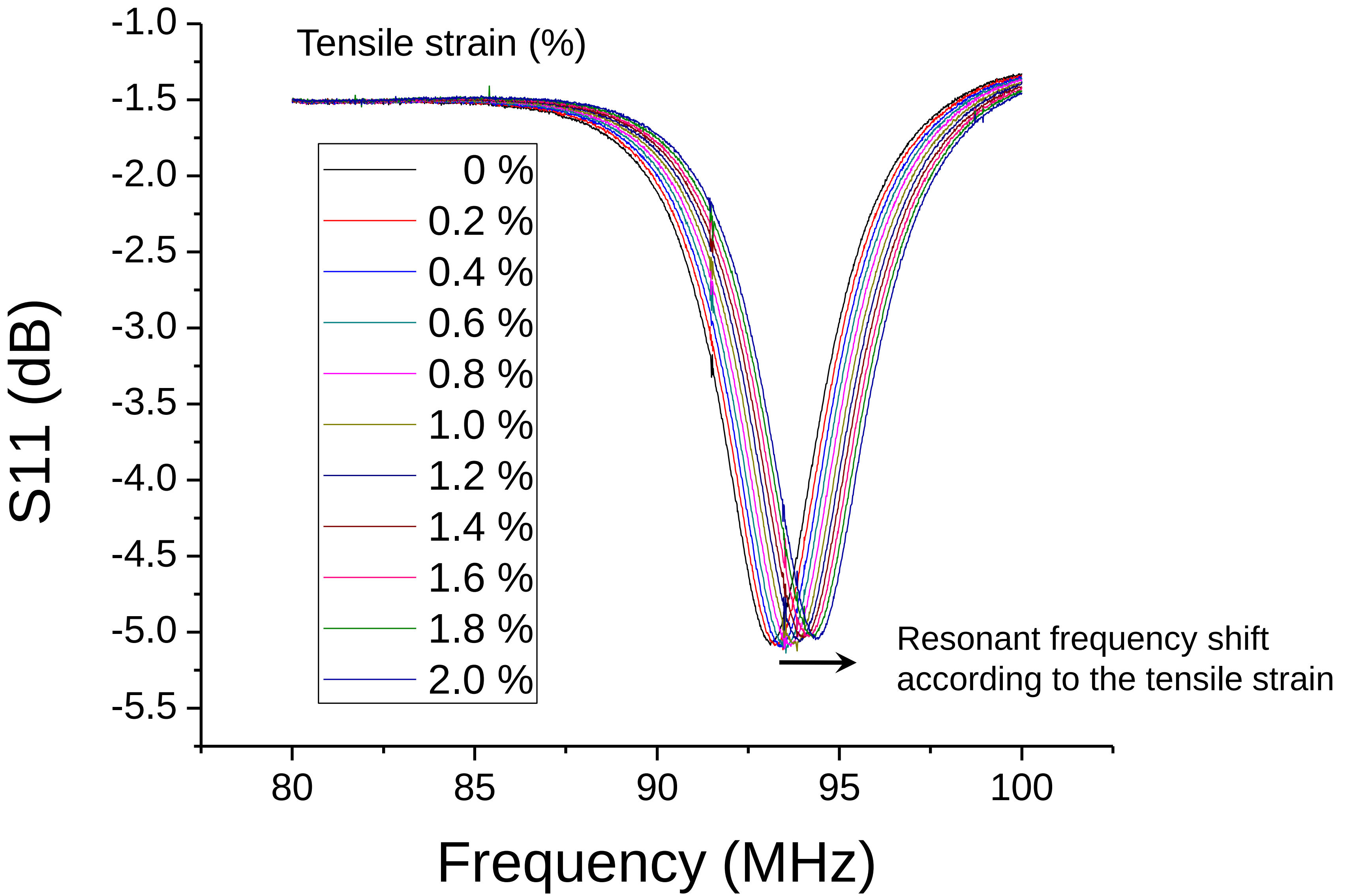
Coupled LC Patterns



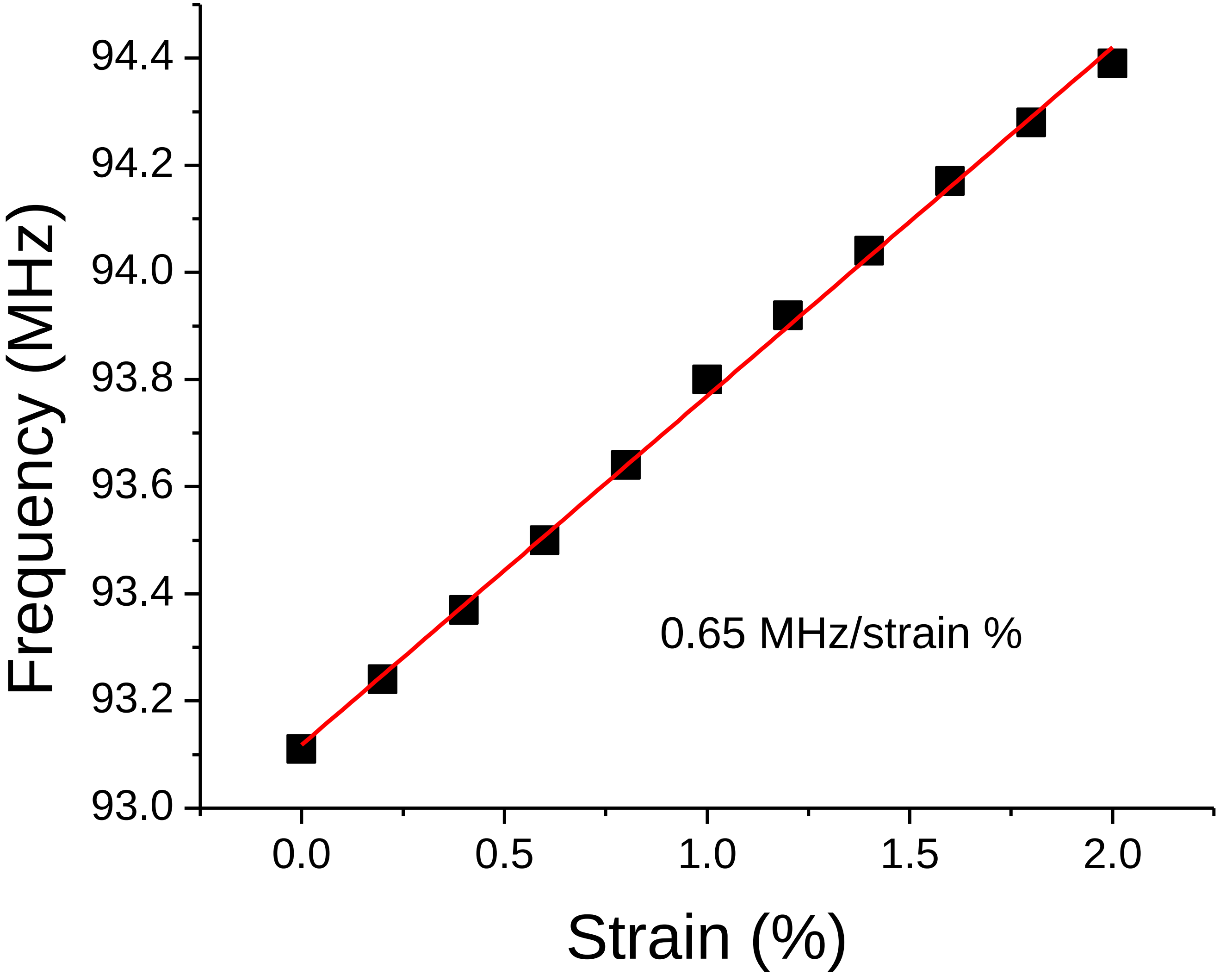
Wireless Interrogation through network analyzer



Measured RF response of the strain senor



Variation of Resonant frequency with strain



Summary and Future Directions

- Printable wireless crack and strain sensors have been developed and tested
- These sensors can be useful for structural health surveillance in numerous applications
- A new class of binder free and low temperature processable flake-based silver inks has been developed
- Optimize sensor designs and improve the lower limit of detection if cracks
- Refine the technology for increasing the range of detection
- Validate performance of the sensors on a variety of substrates and fine-tune to specific applications

Thank You!