Chipless RFID: Design Advances and Measurement Challenges in Identification and Sensing Applications

Katelyn Brinker and Reza Zoughi

Applied Microwave Nondestructive Testing Laboratory

Center for Nondestructive Evaluation

Iowa State University

Ames, Iowa USA

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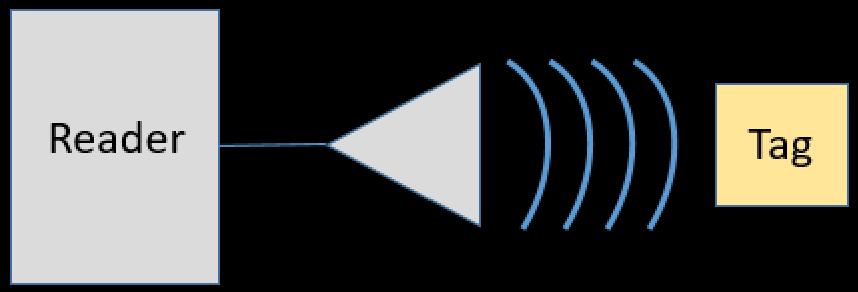
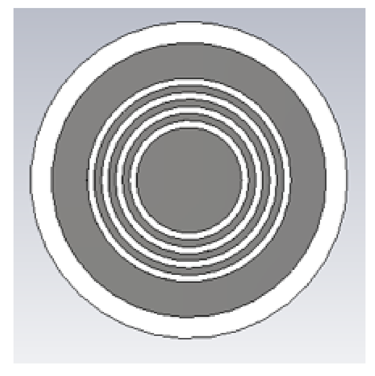
Radio Frequency Identification (RFID)

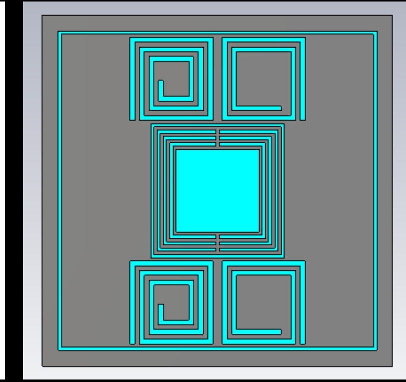
- System consists of a reader and a tag
- The reader interrogates tags with an EM wave and receives the tag response
- The tag can be active, semi-active, passive, or chipless
  - Active and semi-active tags require a battery or another power source
  - Passive tags are the most common and harvest power from the interrogating wave
  - Active and passive tags modulate their scattered waves
  - Chipless is the newest and least explored type of tag

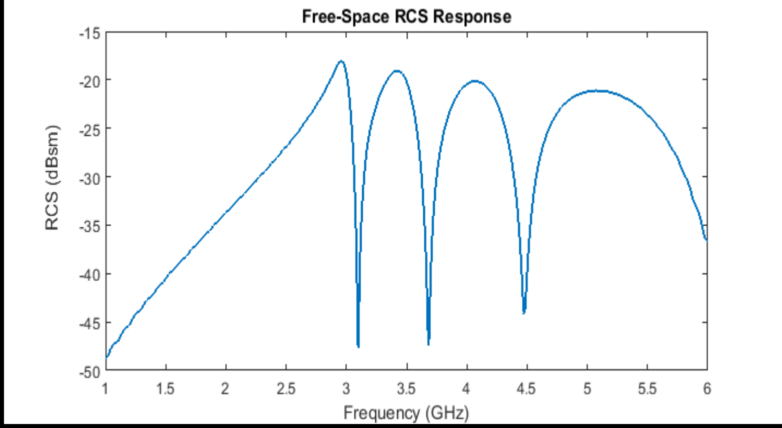


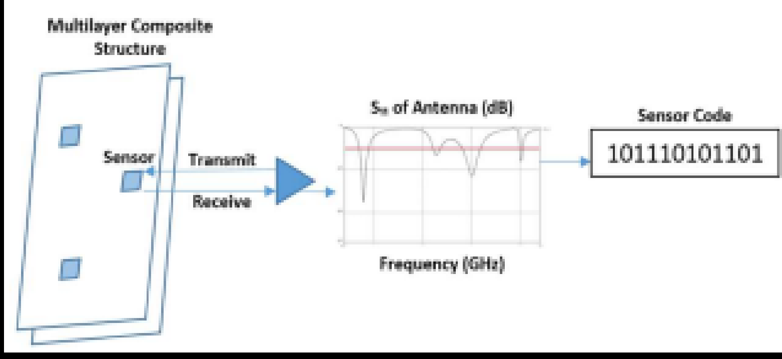
Chipless RFID Background and Applications

- Chipless RFID is a sub-set of RFID Technology
- Tags have no power source and no IC
  - Information is “stored” in the structure of the tag
- Tags are interrogated by an electromagnetic wave to produce a response (e.g., radar cross-section (RCS) or Complex Reflection Coefficient (S_{11}) vs. frequency)
- A binary code can be assigned to the response
  - Changing the response changes the code
- Tags can be used for ID or sensing applications
  - Changing the environment changes the response for sensing tags





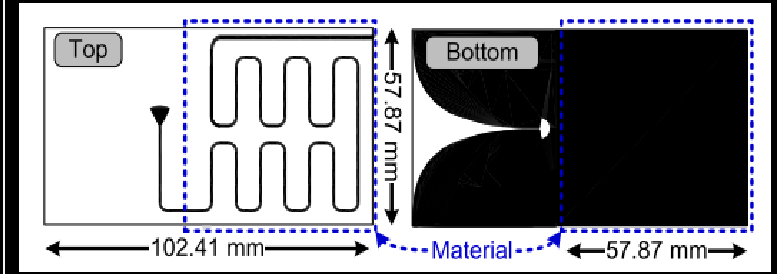




Chipless Tag Architectures

Time – Domain

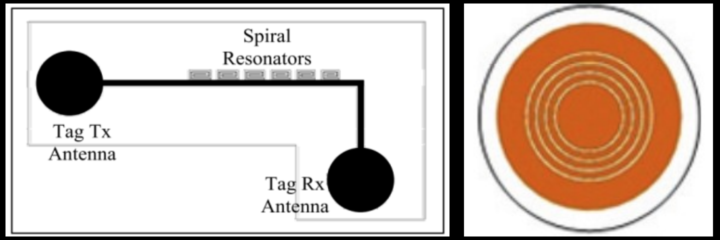
- Works based on Time Domain Reflectometry (TDR) principles
- Often incorporates meander lines
- Response can be transformed to the frequency domain for additional analysis



Time-domain tag for dielectric property sensing [1]

Frequency-Domain

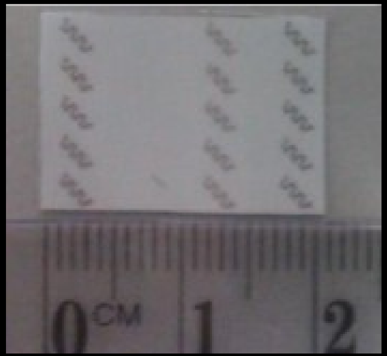
- Most common tag architecture
- Two Types: Tx/Rx and Backscatter
  - Tx/Rx tags have 2 cross-polarized antennas connected with a loaded microstrip line
  - Backscatter tags use different types of resonators to produce a desired response



Tx/Rx tag and backscatter tag [2-3]

Spatial-Domain

- Least common architecture
- Uses microwave imaging and creates a code from the generated image's features
- Easier to use at higher frequencies
- Requires a specialized reader system to make images quickly



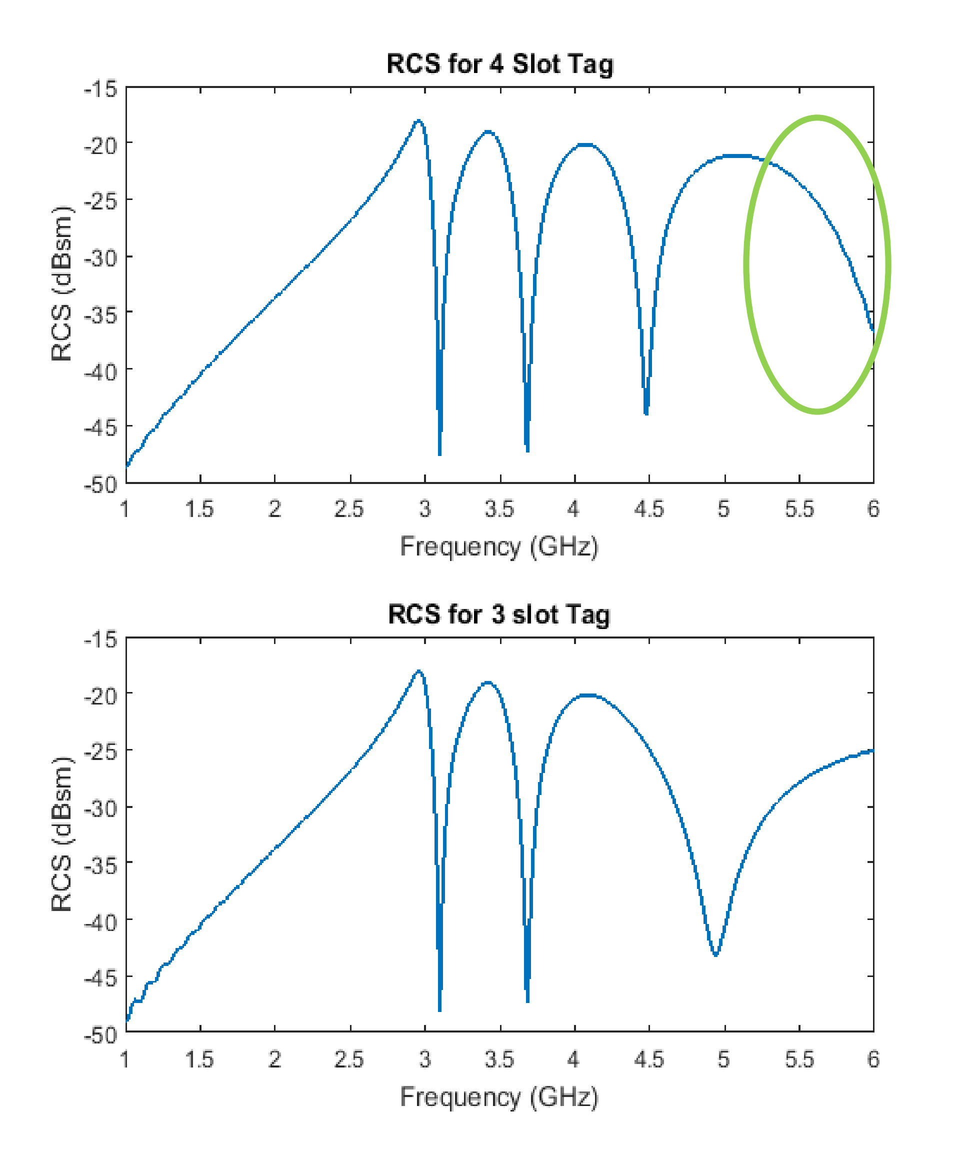
Spatial-domain depolarizing tag [4]

Encoding Methods

Coding Method Examples for 4 to 3 Slot Tag:

- Method 1: Notches are 1's, removing a notch shortens the code [5]
  - [1111]->[111]
- Method 2: Notches are 1's, removing a notch adds a 0 to the code [3]
  - [1111]->[1110]
- Method 3: Notches are 1's, elsewhere are 0's [6]
  - [01010101]->[01010100]

Methods are designed for ID based tags where the response is very predictable



Tag Metrics

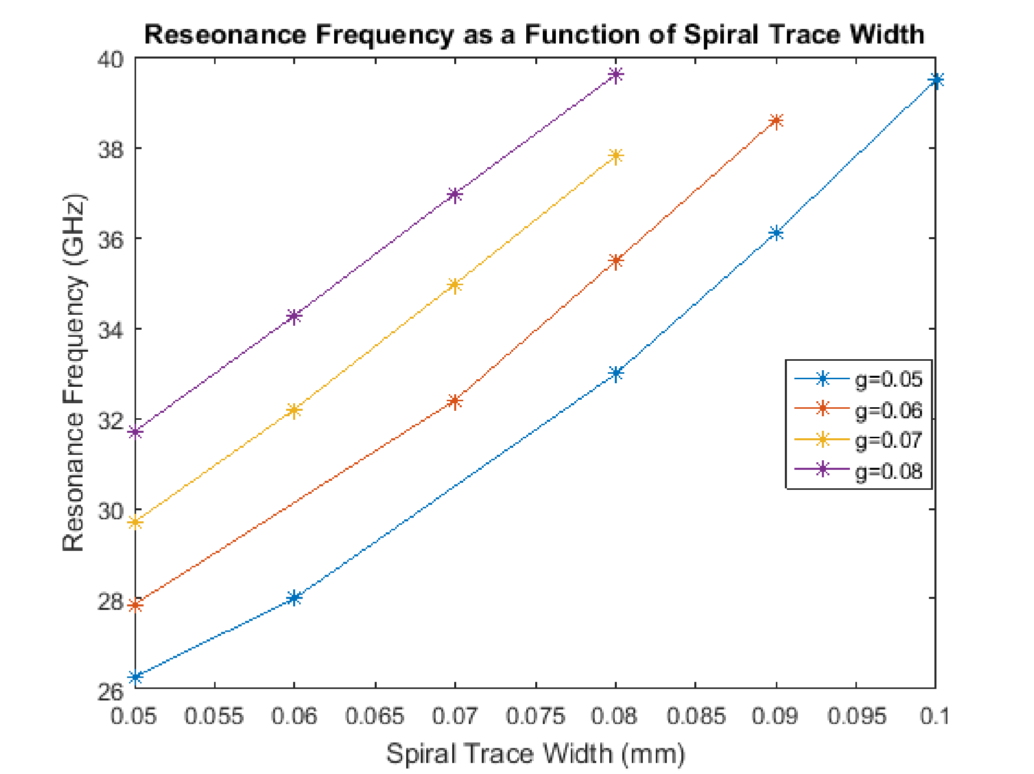
<u>Metrics for ID application tags:</u>

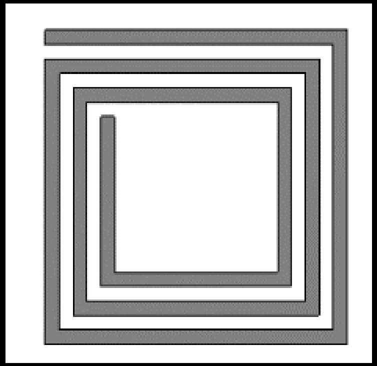
- Bit Density: number of bits in the code per square cm of tag area
- Data Density: number of bits in the code
- Spectral Density: number of bits in the code per bandwidth required for encoding
- Coding Capacity: multiple definitions, can refer to the number of possible unique codes

All of these metrics are highly dependent on the coding method used!

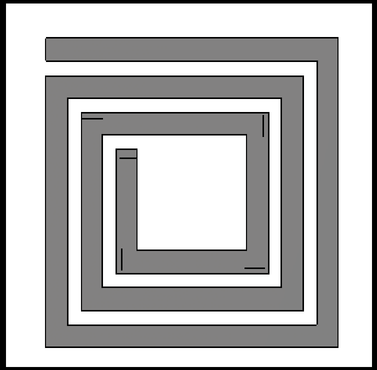
Tag Design Methodology

- Desire the ability to control the tag response so that tags can be engineered rather than designed through trial and error
- The following need to be taken into account :
  - The environment the tag will be in
  - Manufacturing options
  - Required tag metrics
- Combining multiple types of resonators can allow a greater variety of tag responses to be realized
  - Interactions between resonators can make it more challenging to discern what response characteristics are associated with what tag features
- Able to utilize design guidelines (design curves, equivalent circuits, and equations) to make purposeful changes to tag geometry



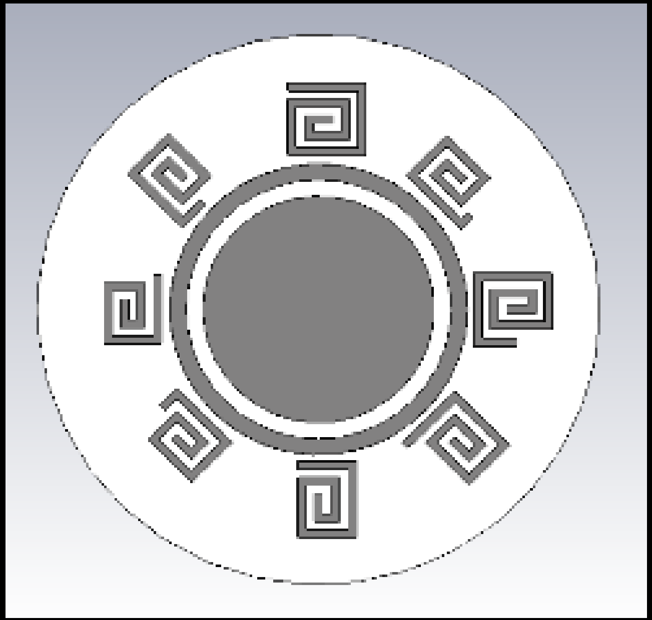


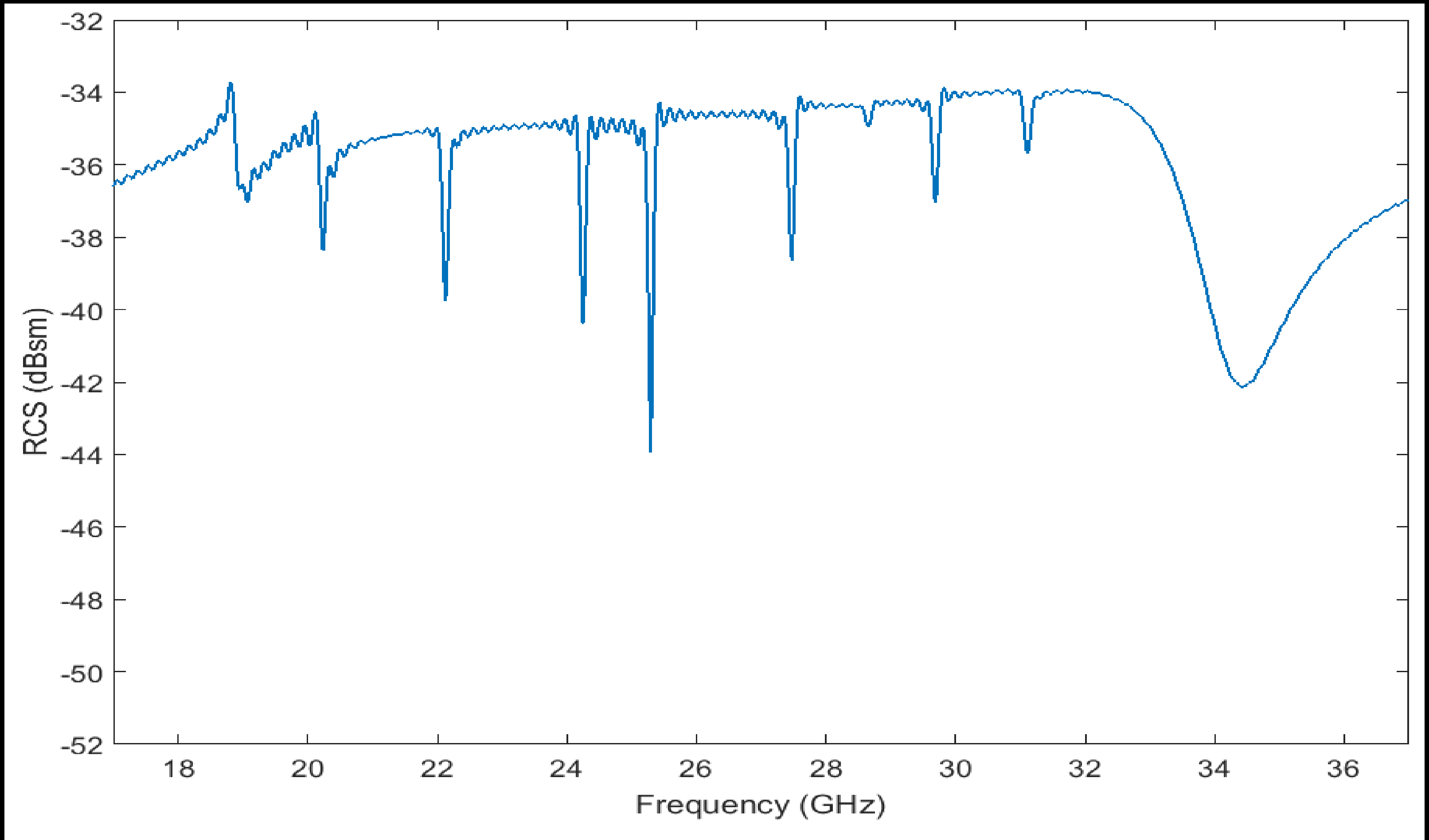
g=0.05 mm, w=0.05 mm



g=0.05 mm, w=0.08 mm

8-Spiral Tag

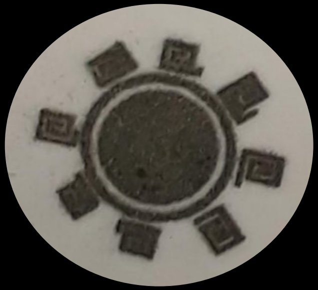


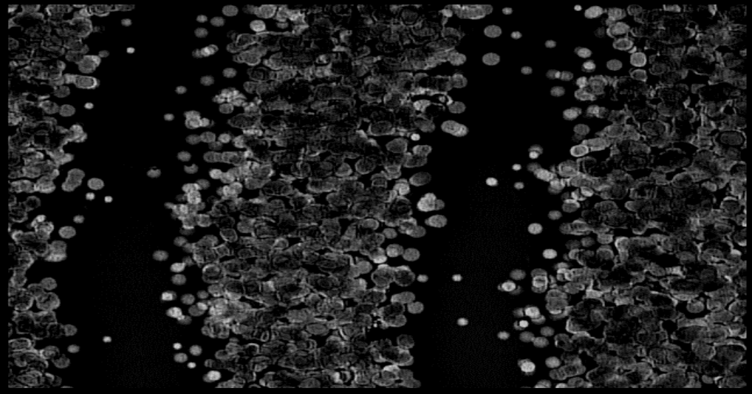


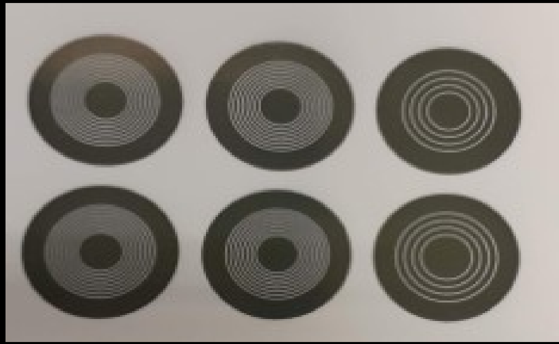
Method	Bit Density (bits/cm^2)	Coding Capacity
1	27.54	1024
2	27.54	1024
3	55.07	1048576

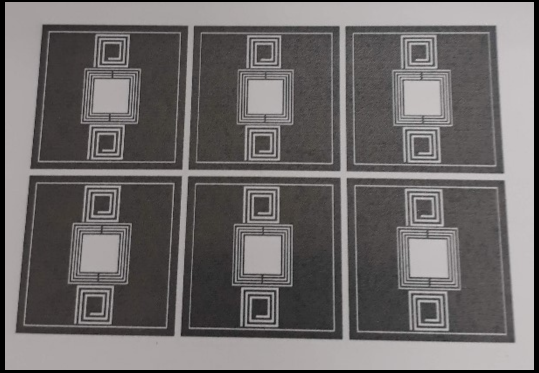
Tag Manufacturing

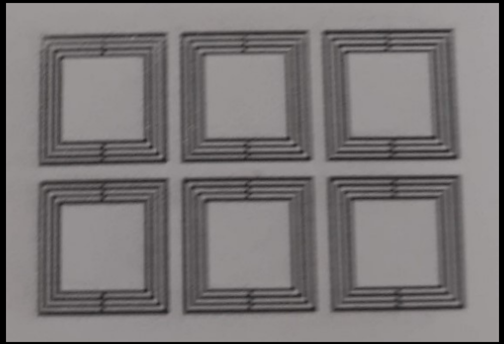
- In order for chipless RFID tags to become ubiquitous, they need to be able to be manufactured in an inexpensive and quick way
- Two Common manufacturing methods:
  - PCBs
    - Advantages: high conductivity of metallic features, capable of realizing small features
    - Disadvantages: Can be expensive
  - Ink-jet Printing
    - Advantages: Inexpensive and quick manufacturing process.
    - Disadvantages: Difficult to integrate a ground plane or use thick substrates. Prints can have low conductivity.







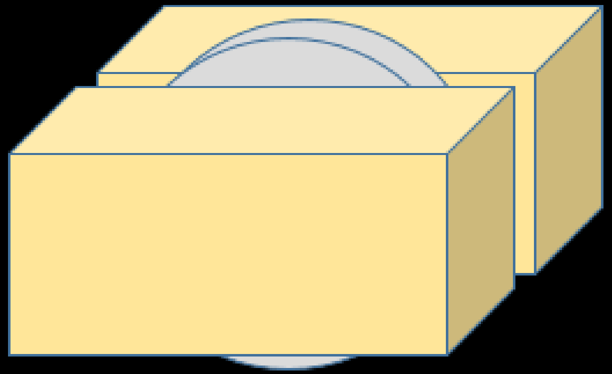




Measurement Methods

- Tag responses need to be measured accurately so that the code is properly assigned

- Common measurement methods include:
  - S-parameters – distance dependent
    - Monostatic with standoff distance
    - Monostatic loaded waveguide
    - Bistatic with standoff distance
    - Bistatic transmission measurement
  - RCS – distance independent
    - Monostatic
    - Bistatic



RCS Measurement

- Method 1: Using the Radar Range Equation [7]

$$P_r = \frac{P_t G_t G_r \sigma_{target} \lambda^2}{(4\pi)^3 R^4}$$

- Method 2: Using S11 measurements without calibration targets [8]

$$\sigma = |S'_{11}|^2 \frac{(4\pi)^3 R^4}{G_t^2 \lambda^2}$$

- Method 3: Combining S11 measurements with the Radar Range Equation [9]

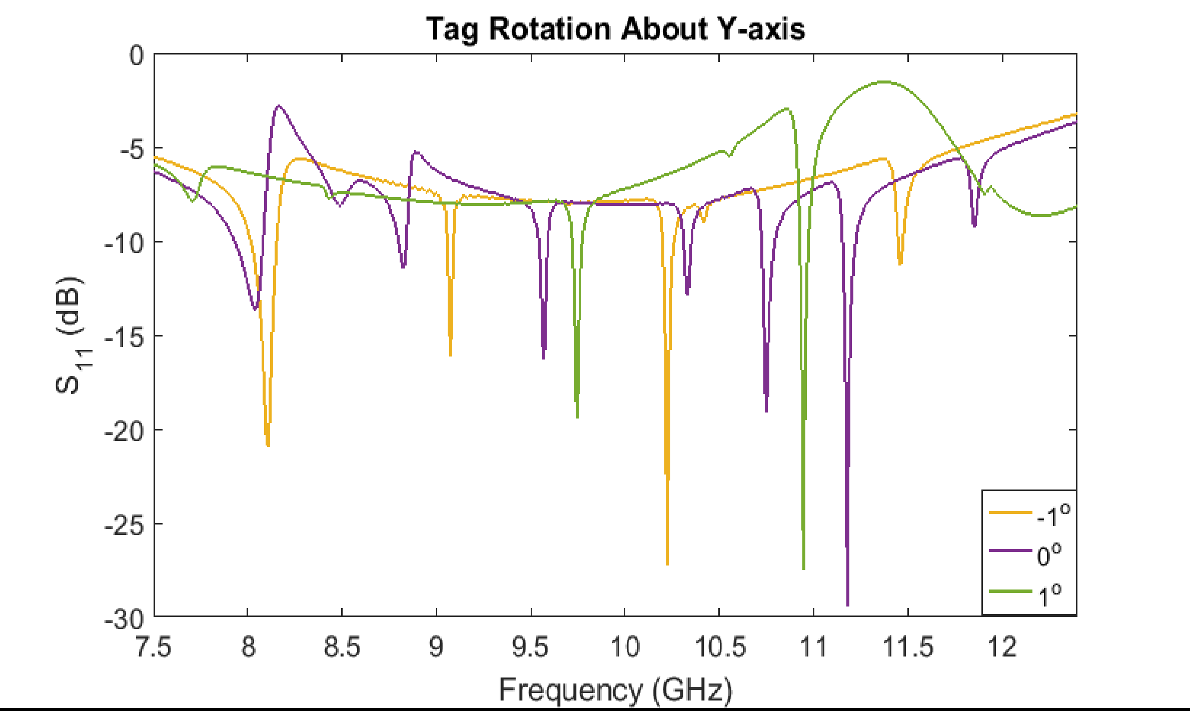
$$\sigma = \left|S_{11}^{target} - S_{11}^{mount}\right|^2 \frac{(4\pi)^3 R^4}{G^2 \lambda^2 \left(1 - \left|S_{11}^{Tx/Rx}\right|^2\right)^2}$$

- Method 4: Using a reference target with S-parameter measurements [10]

$$\sigma_{tag} = \left[\frac{S_{21}^{tag} - S_{21}^{support}}{S_{21}^{ref} - S_{21}^{support}}\right]^2 \sigma_{ref}$$

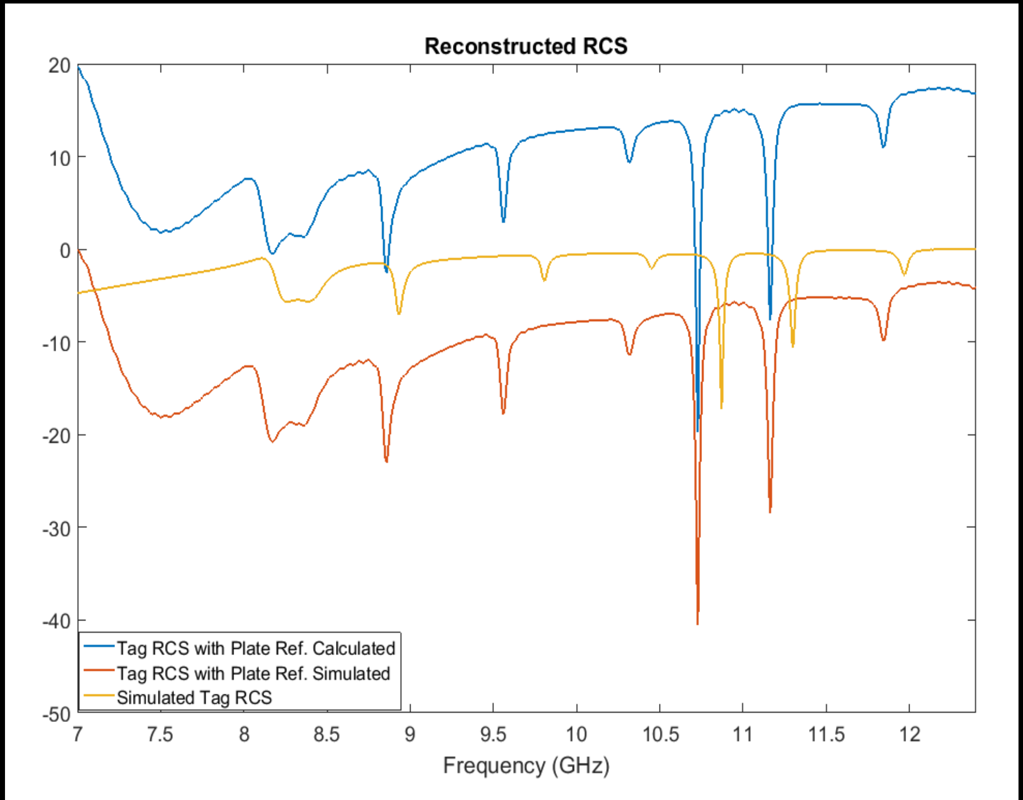
Measurement Challenges

- Distance dependency
  - Small changes in distance between tag and reader antenna cause response differences
- Orientation sensitivity
  - Small rotations of the tag with respect to the reader antenna can cause large response differences
- Small read range
  - Ability to discern the tag response diminishes as the distance between the tag and reader antenna increases



Measurement Challenges

- Need for calibration targets
  - Makes it difficult to measure RCS outside of a laboratory environment
- Tag localization
  - Responses from tags close to each other can interfere with each other
- Environmental effects
  - Reflections from the tag background can interfere with the tag response
  - Ex. superposition of scattering from tag and from what the tag is attached to

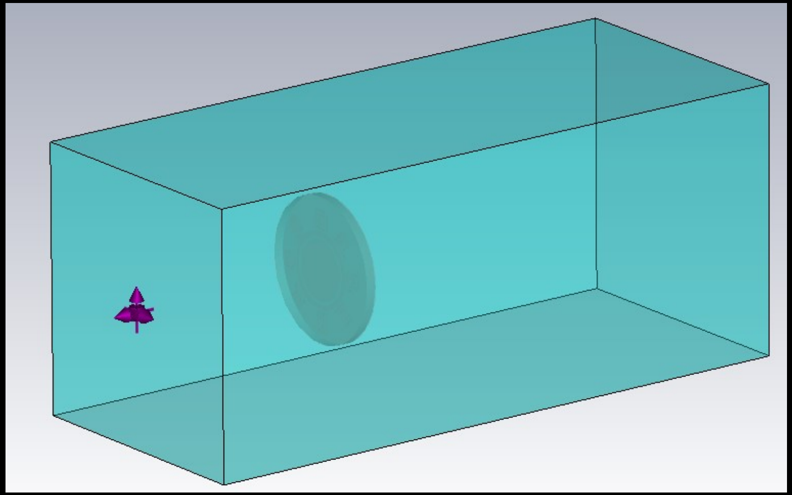


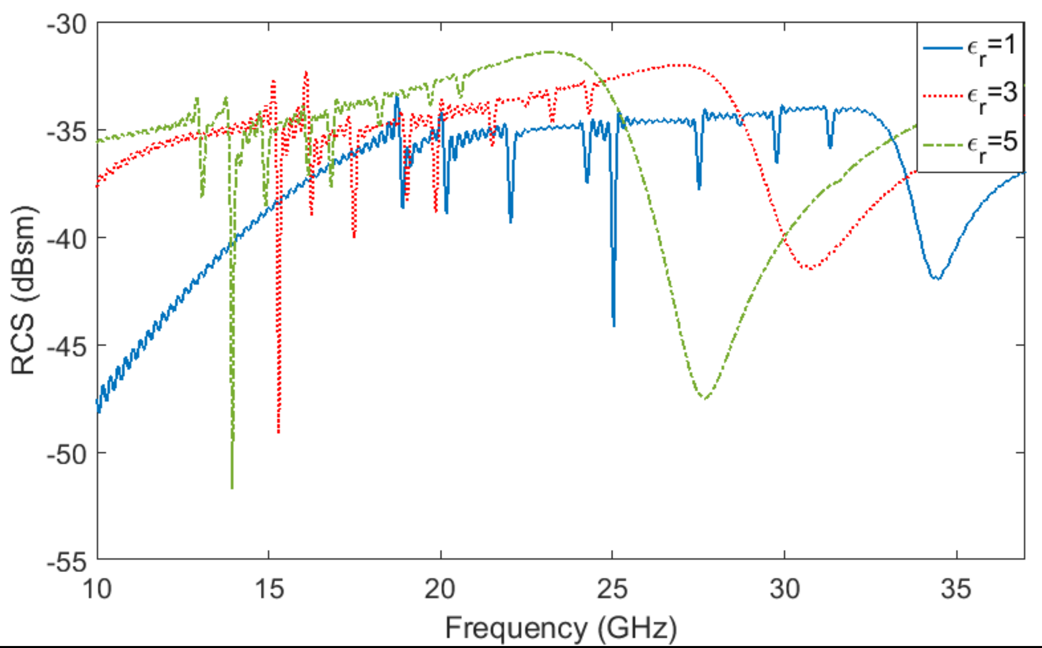
Overcoming Measurement Challenges

- Orientation independent tags
  - Mitigates z-axis rotation issues, but not x- or y-axis rotation
- Depolarizing tags
  - Isolates the response of the tag from that of the background
- Specialized reader antennas
  - Using dual or circular polarization to reduce z-axis rotation sensitivity
  - Using high gain antennas to increase the read range
  - Using antennas with narrow beams to illuminate single tags

Chipless RFID for Sensing

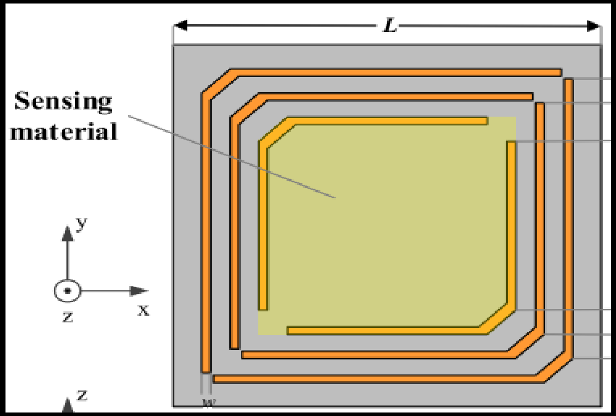
- Tags can be designed so that changes in the environment result in changes of the tag's code
- Sensing parameter examples: dielectric constant, humidity, temperature, strain, corrosion, displacement, light intensity, etc.
- Binary codes often are not assigned to sensing tag responses, but they can be
  - Typically look at the shift or change in magnitude of 1 notch in the response
- Key challenge: isolating the effect of the sensing parameter from the effects of the measurement challenges



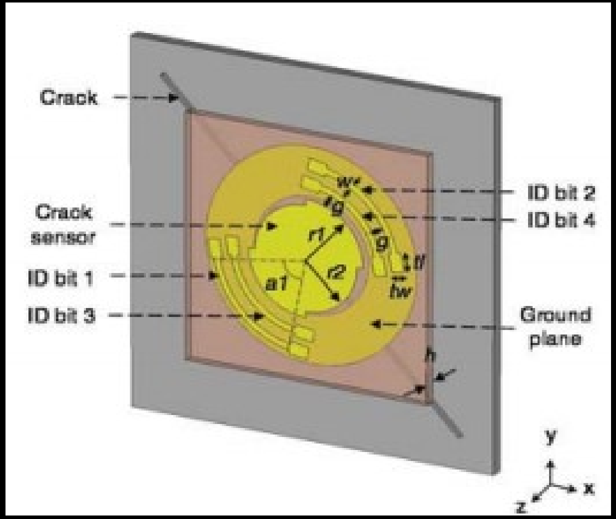


Combining Identification and Sensing

- Can have tag features in a sensing tag (code bits) that are not sensitive to the sensing parameter
  - Act as ID bits
- Can have a sensing feature (bit) that is sensitive to an environmental factor
  - Ex. Sensing the effect of the material the tag is attached to on the response for correction purposes
- Key challenge: isolating the effect of the sensing parameter from the effects of the measurement challenges



Humidity sensor with ID bits [11]



Crack sensor with ID bits [12]

Conclusions

- Chipless RFID has the potential to provide inexpensive, passive, and wireless identification and sensing capabilities

- There are still many challenges, some significant, to be overcome in the chipless RFID field, especially for bringing chipless RFID out of the lab. and into the practical applications realm

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