UCR:
An Unclonable Chipless RFID Tag

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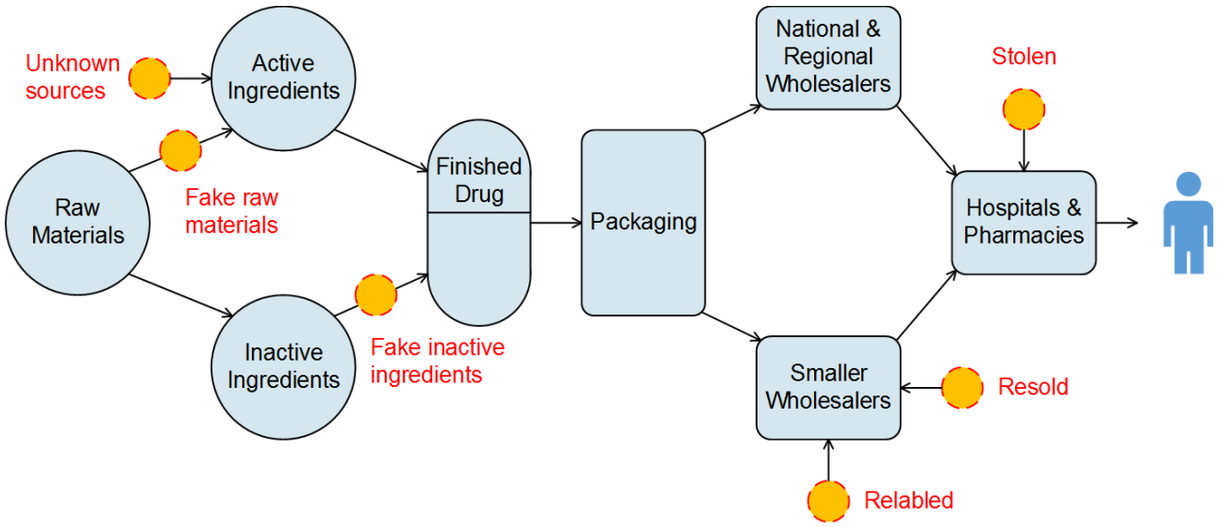
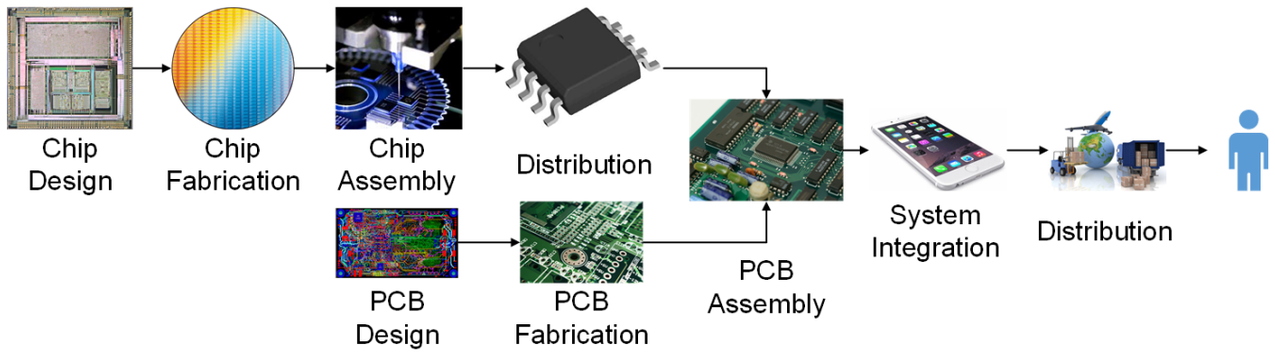
Supply Chain Risks

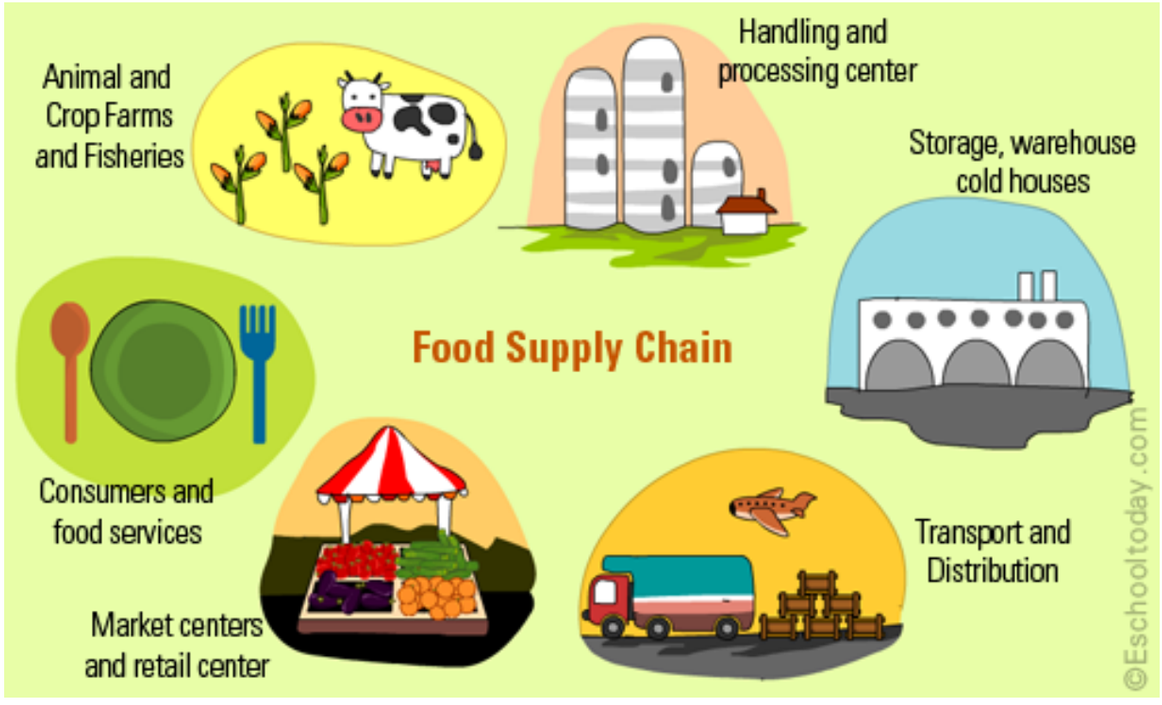
- **Counterfeiting**
  - Over 20,000 IPR infringing seizures with a total value of $1.22 billion in 2014
- **Theft**
  - 794 cargo thefts throughout the US in 2014, with the average loss of $232,924 per incident
- **Impact**
  - About 1 minion deaths a year in Africa are linked to the counterfeit drug trade
  - Globally, 7 minion deaths a year are caused by fake malaria and tuberculosis drugs



Pharmaceutical supply chain



Electronic supply chain



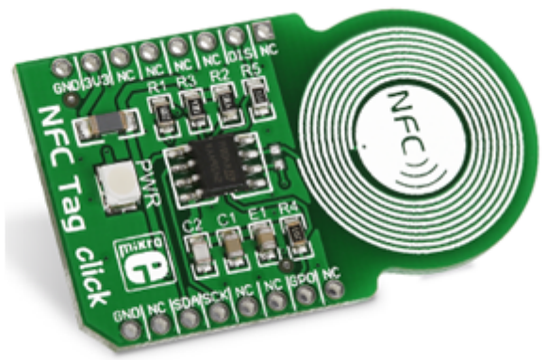
Food supply chain

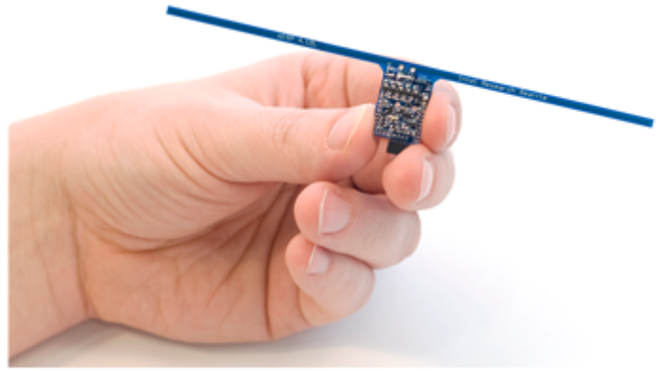
Conventional Solutions

- **Barcodes and QR codes**
  - Easy to duplicate
  - Require individual scanning
  - Need direct line-of-sight and close proximity to reader
- **IC based RFID tags**
  - Price is high (as high as 1 dollar) !!!
  - Tag information is possible to be overwritten by attacker

Barcode

QR code

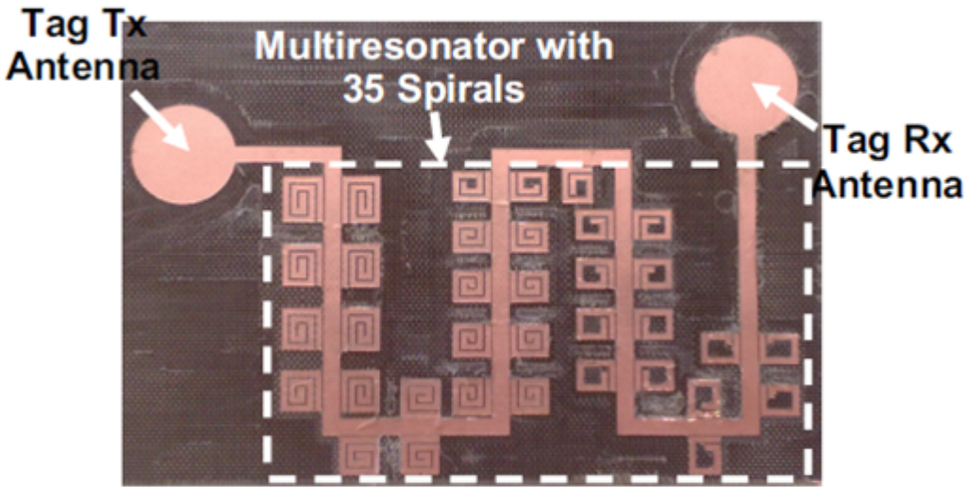




IC based RFID tag

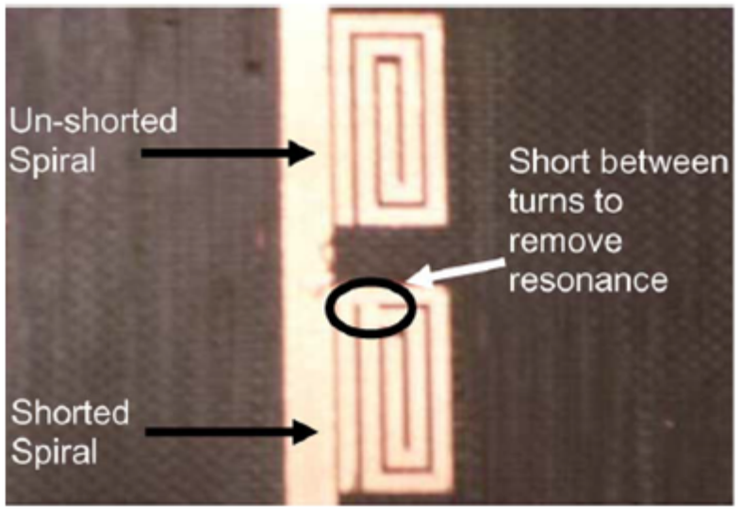
Existing Chipless RFID Tags

- **Merits of chipless RFID tags**
  - Extremely low price (as low as 0.1 cents)
  - Elimination of tag memory
  - Can be placed inside the package
  - Can be directly printed on the products or their packages with conductive ink
- **Shortcomings of existing chipless RFID tags**
  - Require either removing or shorting some resonators to encode data
  - Increase the manufacturing time/cost
  - Easy to clone
  - Small ID size
  - Large tag area



Credit: *Stevan Preradovic*

35-bit chipless RFID tag
(length = 88 mm, width = 65 mm)



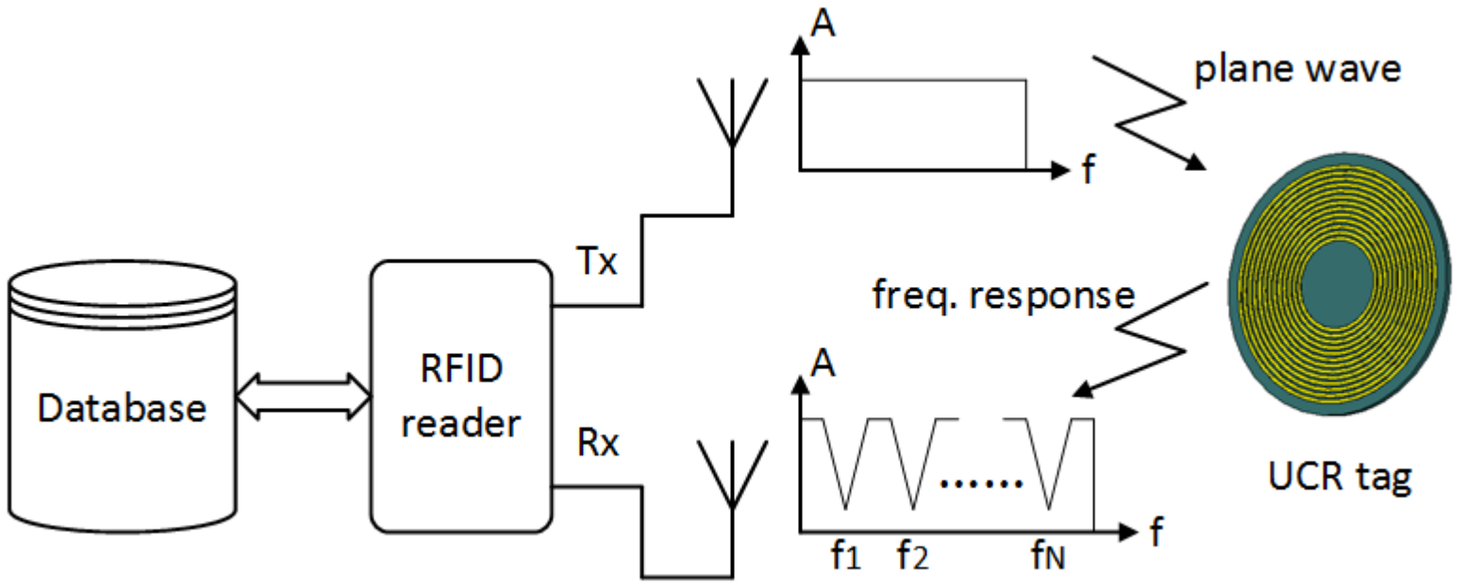
Credit: *Stevan Preradovic*

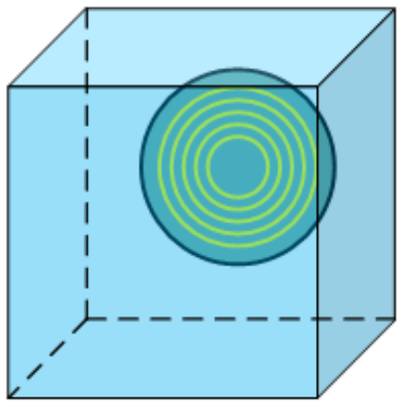
Removing spiral resonances via shorting the spiral turn

Contributions

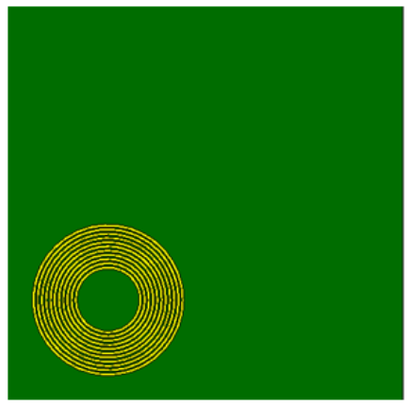
- Theoretical analysis of resonance frequency sensitivity of slot resonator
- The ***first*** chipless RFID tag that exploits process variations during tag fabrication
  - ID is unique and unclonable
  - Large ID size
  - Small tag area
- An efficient look-up method that speeds up the authentication process of UCR tags
- Performance evaluation of UCR tags under extremely adverse environmental conditions
  - Noisy environment
  - Varying angles of plane wave incidence

UCR System





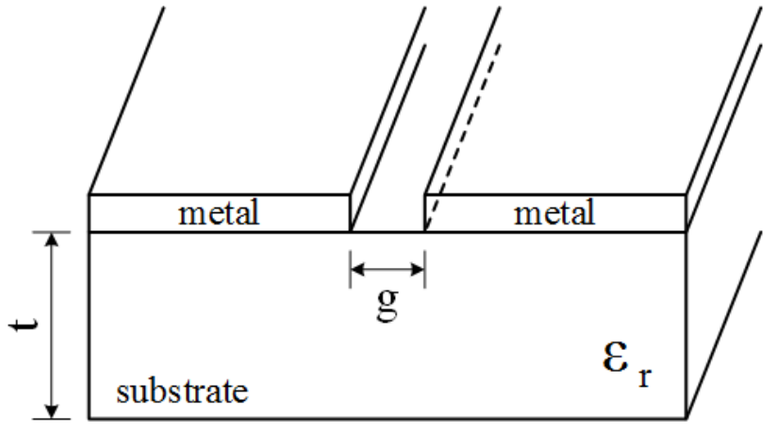
UCR inside the package



UCR on the PCB

- **UCR tag**
  - Consists of a certain number of concentric ring slot resonators placed on a certain substrate (e.g., TACONIC TLX-0)
- **RFID reader**
  - Provides the UWB plane wave and captures the frequency response spectrum
- **Excitation signal**
  - An ultra wideband (UWB) plane wave
- **ID**
  - The vector (f_1, f_2, …, f_N) composed of fundamental resonance points in the frequency response spectrum

Notch Frequency Sensitivity



Cross-section view of slot line

g : air gap

t : substrate thickness

L : slot length

ε_r : dielectric constant

c : light speed in vacuum

- The partial derivatives of notch frequency to slot parameters and relative permittivity of substrate material:

$$\frac{\partial f_s}{\partial g} = \frac{c\Phi \frac{\partial F}{\partial g}}{tG + 2L\Phi}$$

$$\frac{\partial f_s}{\partial t} = \frac{cG\Phi \frac{\partial F}{\partial t} - Gf_s}{tG + 2L\Phi}$$

$$\frac{\partial f_s}{\partial \varepsilon_r} = \frac{\Phi[cG \frac{\partial F}{\partial \varepsilon_r} + (2Lf_s - cF)\frac{\partial G}{\partial \varepsilon_r}]}{tG^2 + 2LG\Phi}$$

$$\frac{\partial F}{\partial g} = \frac{0.1503432 t \varepsilon_r^{0.945}}{(g + 2.3864t)^2}$$

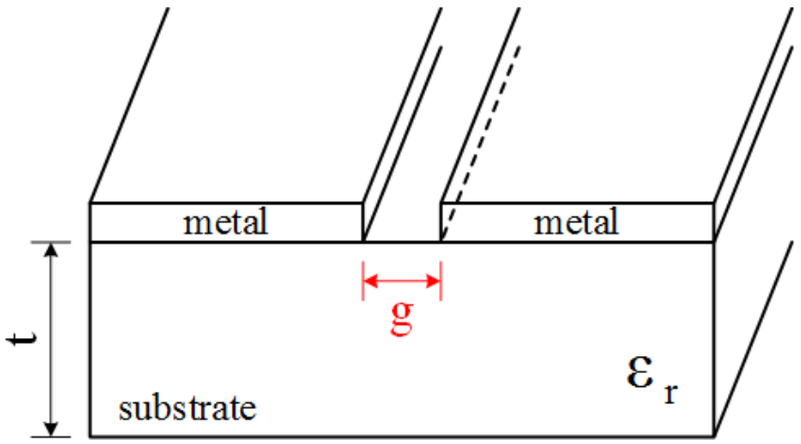
$$\frac{\partial F}{\partial t} = \frac{0.1503432 g \varepsilon_r^{0.945}}{(g + 2.3864t)^2}$$

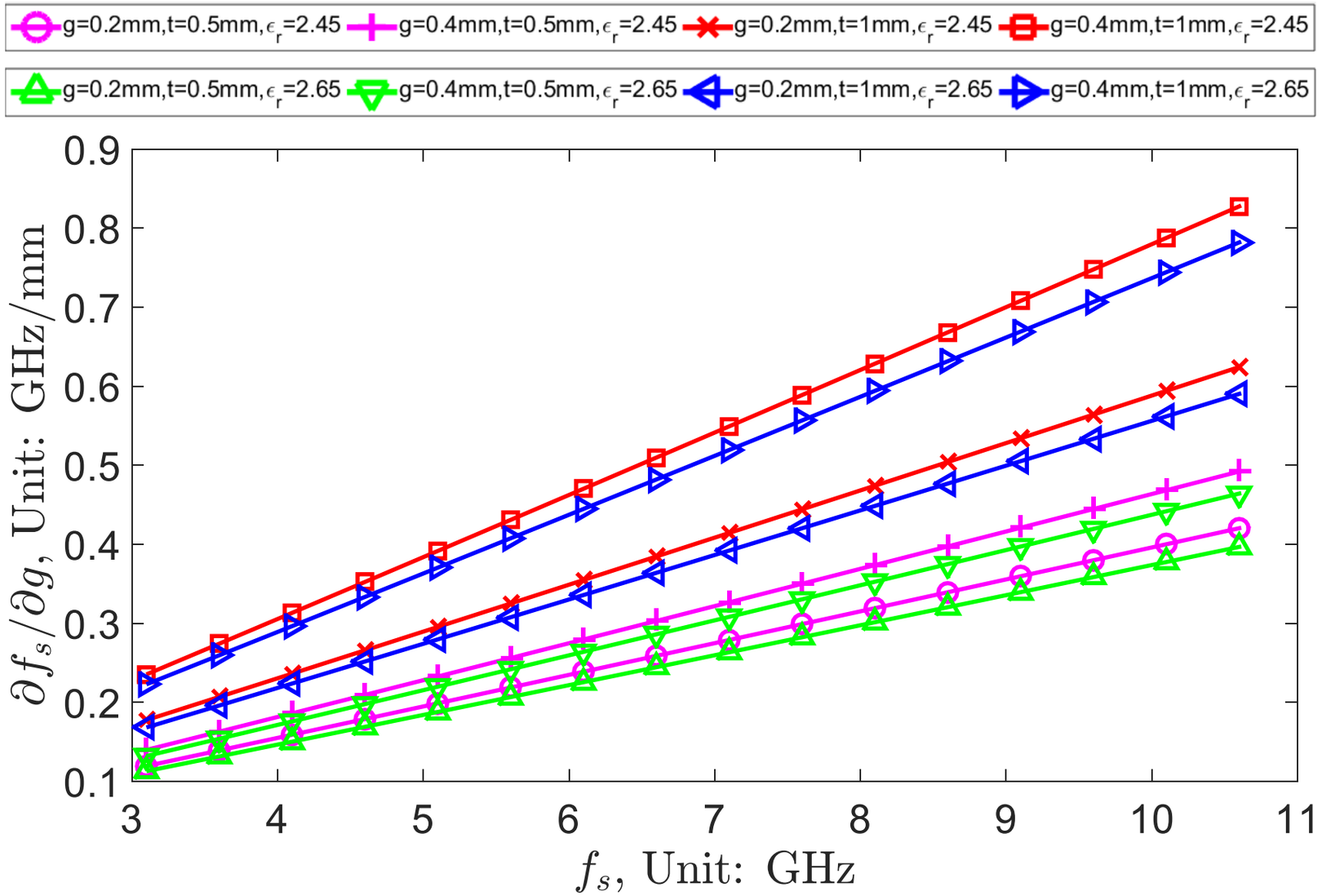
$$\frac{\partial F}{\partial \varepsilon_r} = -\frac{0.365}{\varepsilon_r} + \frac{0.059535 g \varepsilon_r^{-0.055}}{g + 2.3864t}$$

$$\frac{\partial G}{\partial \varepsilon_r} = \frac{0.083695}{\varepsilon_r^2}$$

$$\Phi = exp(\frac{cF\text{-}2Lf_s}{cG})$$

Notch Frequency Sensitivity to Air Gap

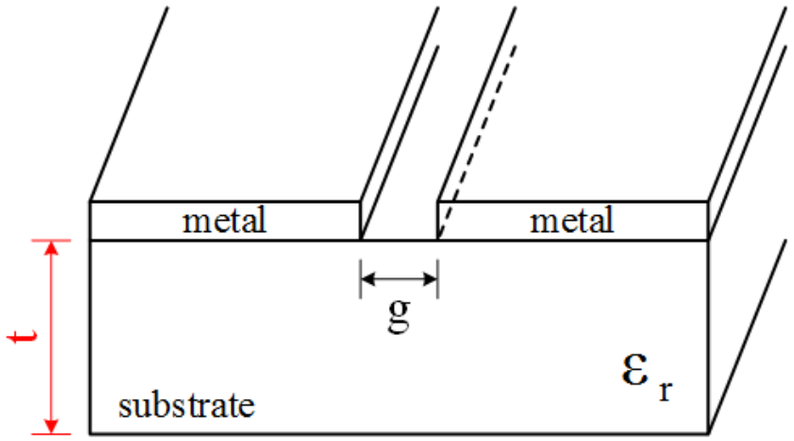


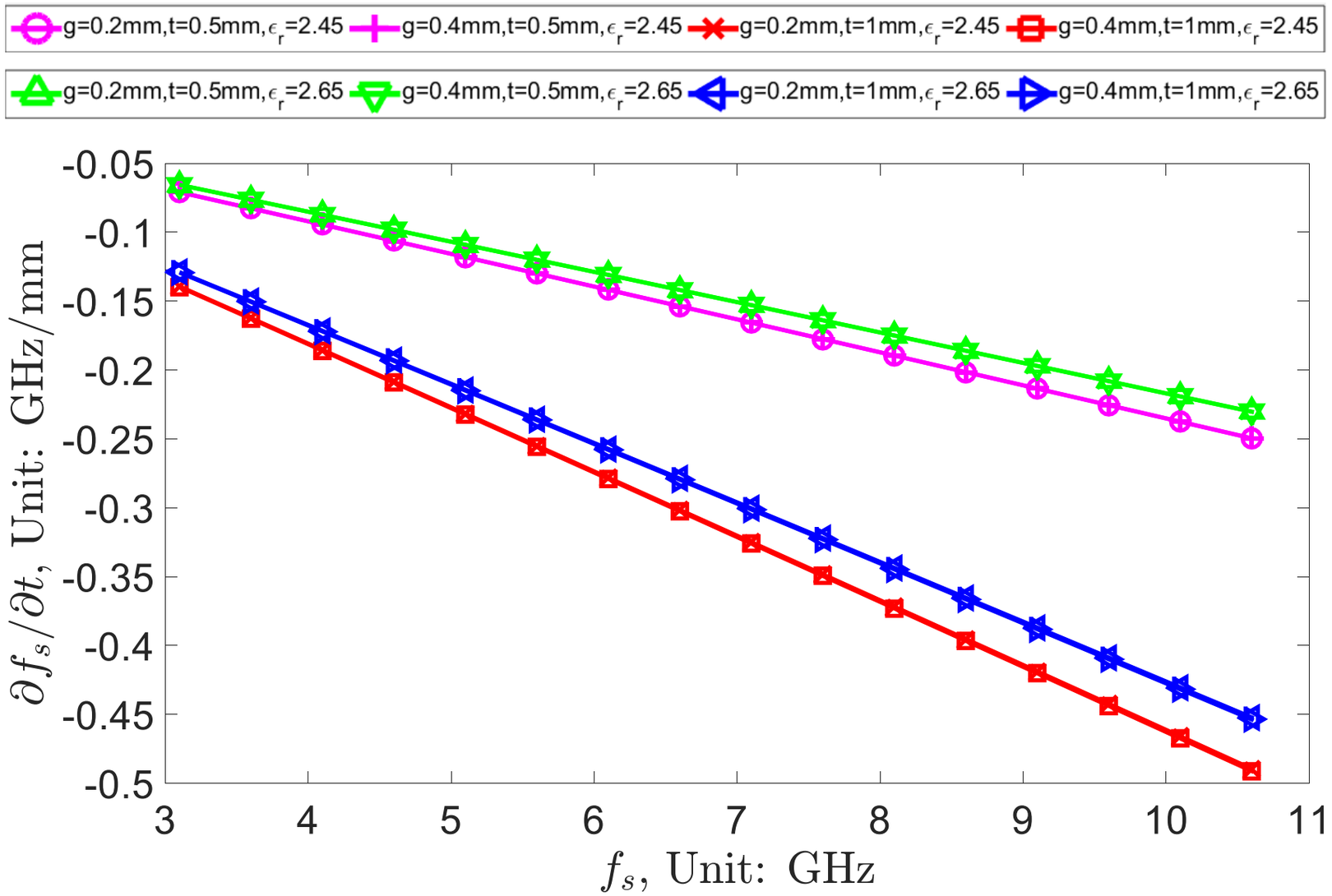


Sensitivity of notch frequency to air gap

- Notch frequency sensitivity to air gap appears linear to the variance of notch frequency in the frequency range of UWB.
- The larger the notch frequency is, the larger the notch frequency sensitivity to air gap will be.

Notch Frequency Sensitivity to Substrate Thickness

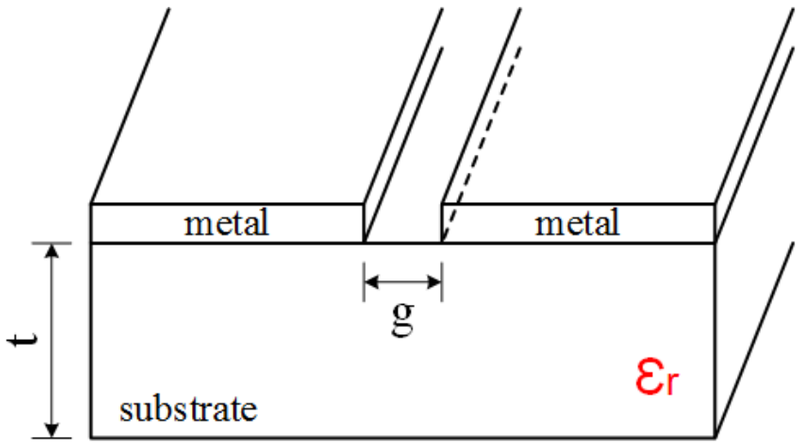


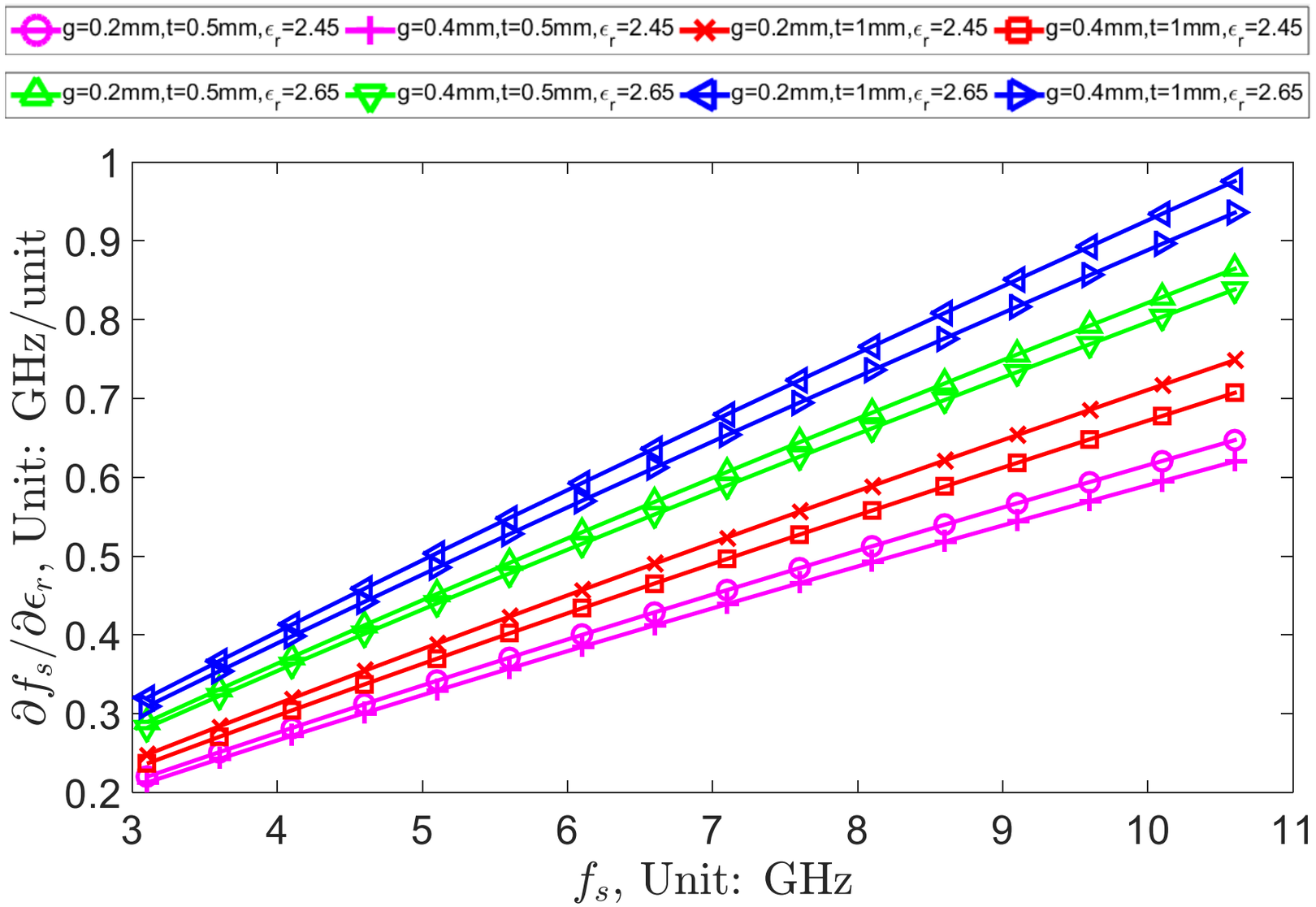


Sensitivity of notch frequency to substrate thickness

- Notch frequency sensitivity to substrate thickness appears linear to the variance of notch frequency in the frequency range of UWB.
- Air gap has little impact on the sensitivity of notch frequency to the variance of substrate thickness.

Notch Frequency Sensitivity to Relative Permittivity





Sensitivity of notch frequency to relative permittivity

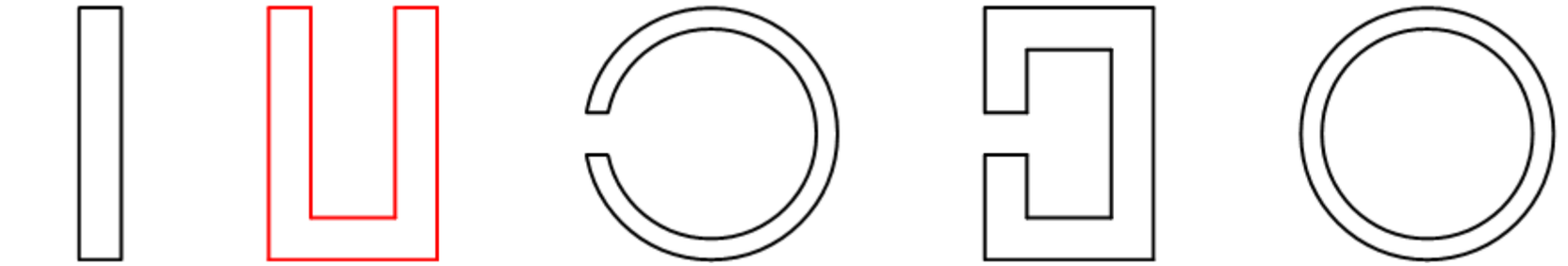
- Notch frequency sensitivity to relative permittivity appears linear to the variance of notch frequency in the frequency range of UWB.
- The larger the notch frequency is, the larger the notch frequency sensitivity to relative permittivity will be.

Polarization Angle Impact

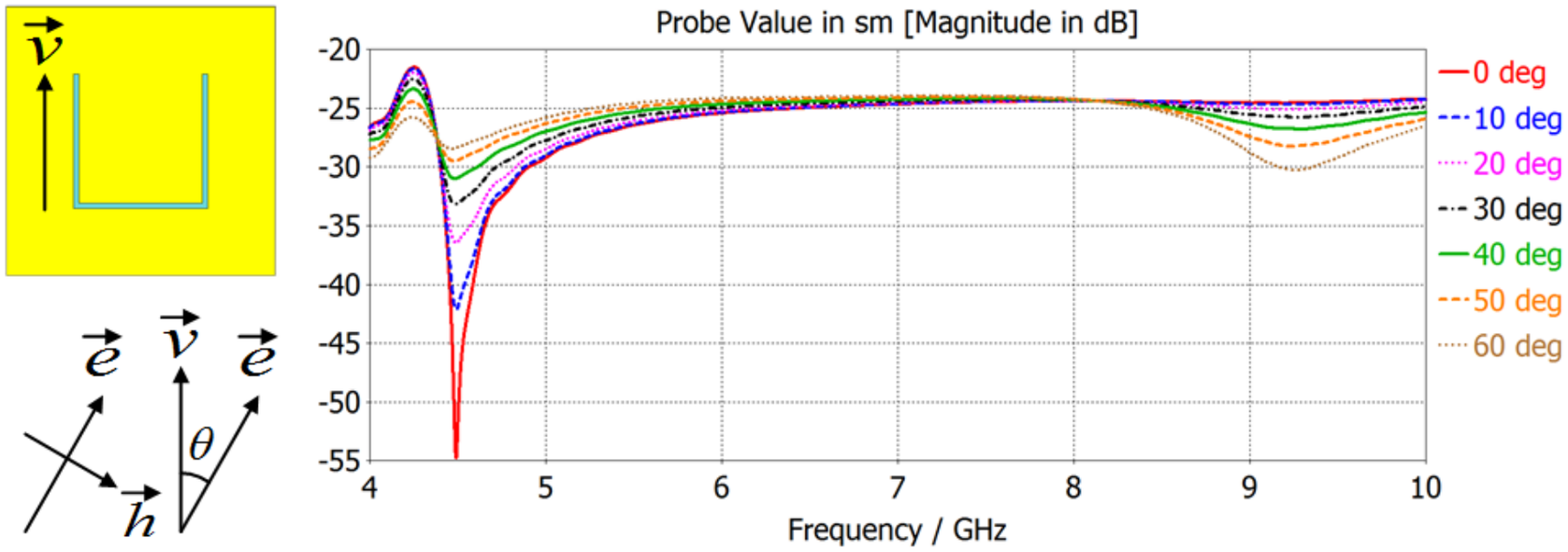
$\vec{v}$: slot direction

$\vec{e}$: linear polarization direction of incident plane wave

θ: the angle between $\vec{v}$ and $\vec{e}$



- If θ is larger than a certain limit, the backscattered response from the U-shaped slot resonator will be too weak to be captured.



Polarization angle impact on U-shaped slot resonator

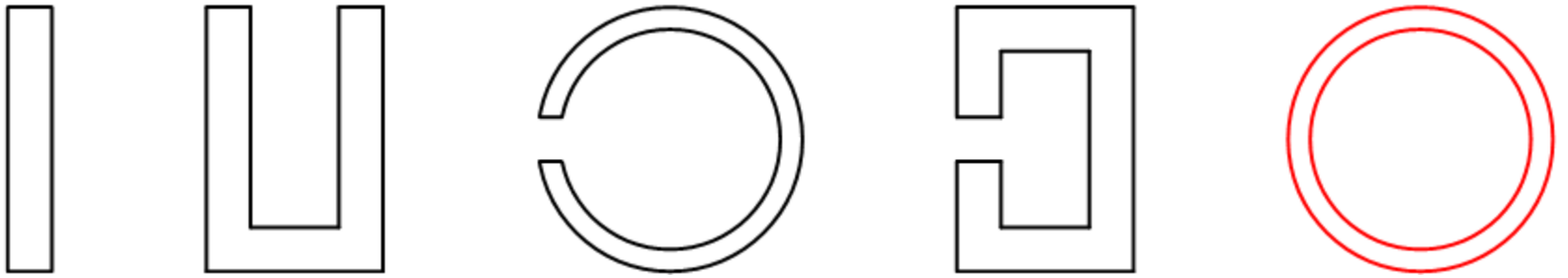
Polarization Angle Impact

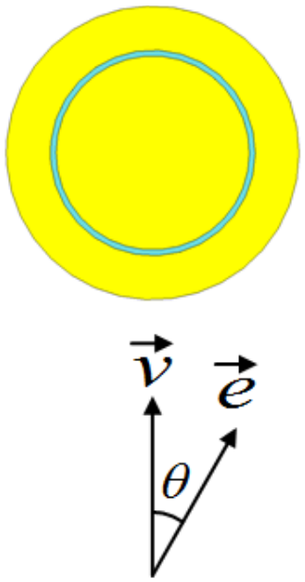
$\vec{v}$: slot direction

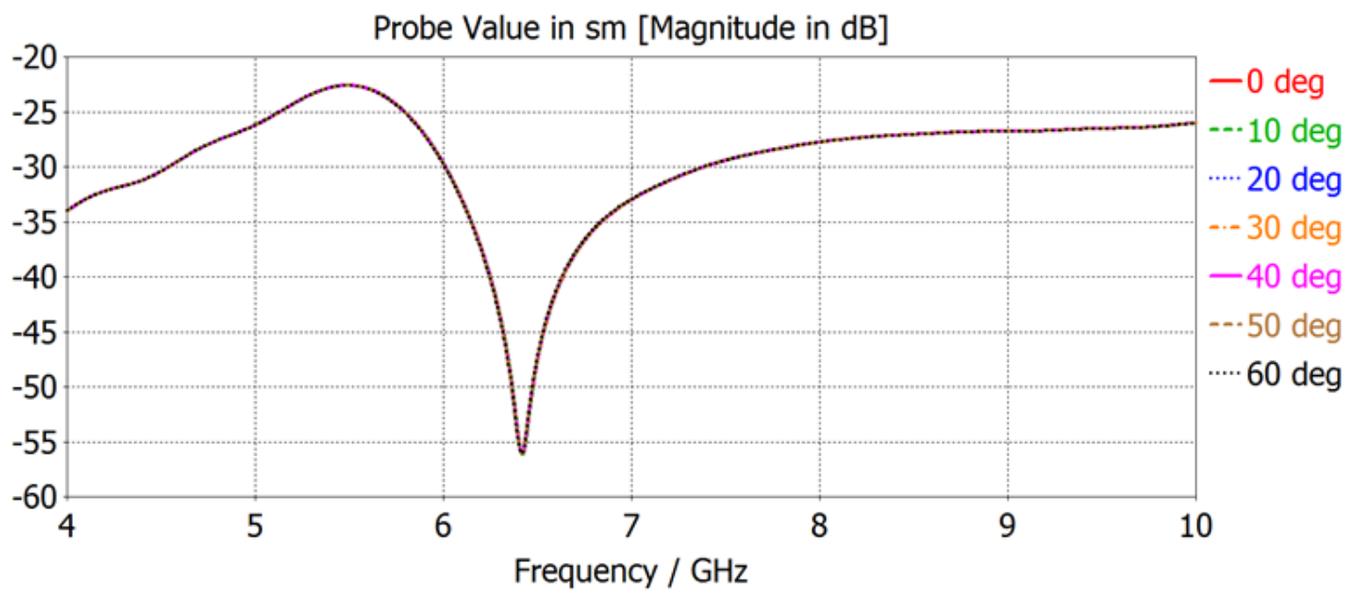
$\vec{e}$: linear polarization direction of incident plane wave

θ: the angle between $\vec{v}$ and $\vec{e}$

- Polarization angle has little impact on the backscattered response from the circular ring slot resonator.







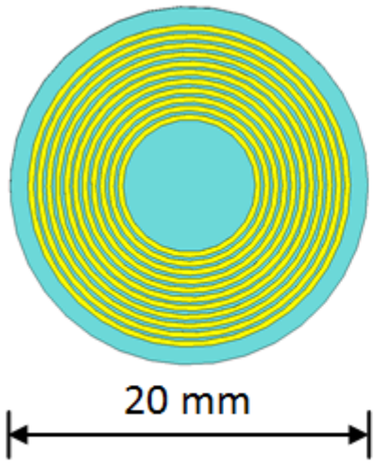
Polarization angle impact on circular ring resonator

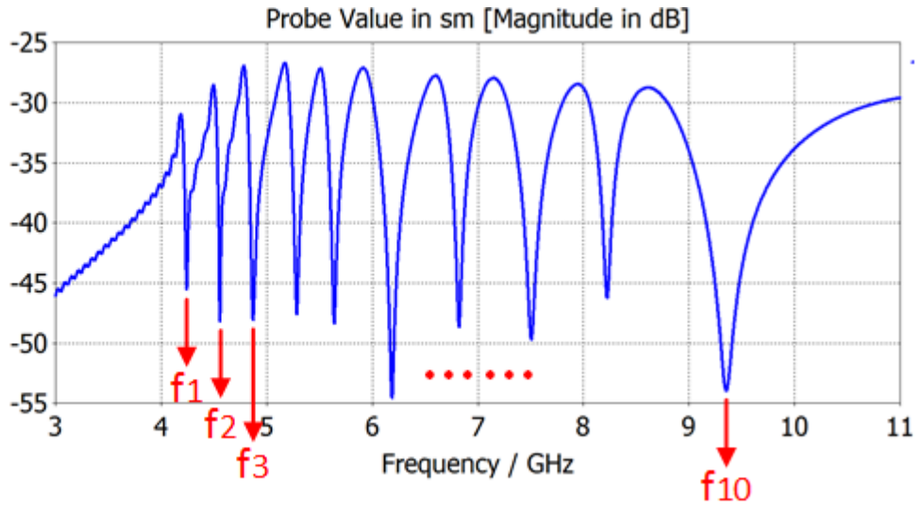
UCR Tag

The Euclidean distance (ED) between $\vec{v}_i^{\,j}$ and $\vec{v}_i^{\,k}$:

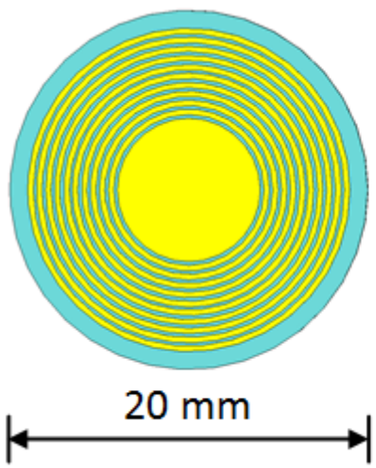
$$ED_i^{j,k} = |\vec{v}_i^{\,j} - \vec{v}_i^{\,k}| = \sqrt{\sum_{r=1}^{N} (f_r^j - f_r^k)^2}$$

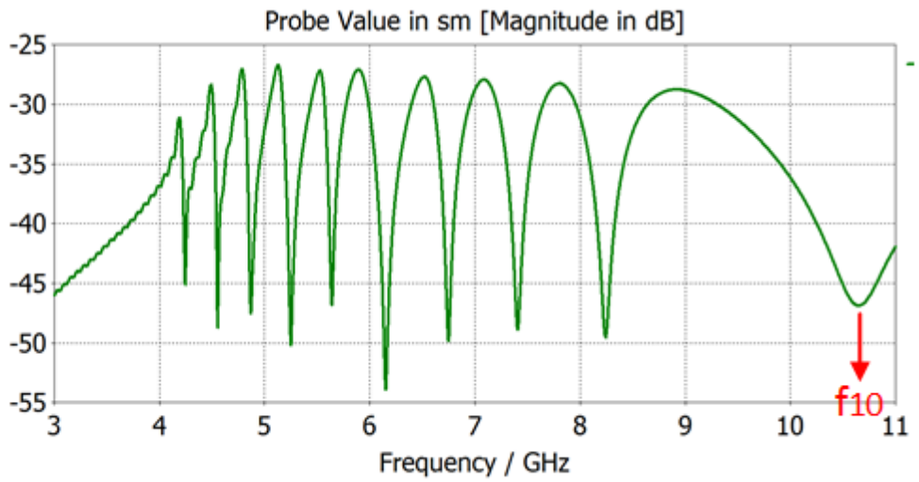
- **Unique UCR tag**
  - Random process variation
- **Unclonable UCR tag**
  - The adversaries cannot easily model the uncontrollable process variations during tag fabrication
- **Remove the central circular pad**





Central void





Central filled

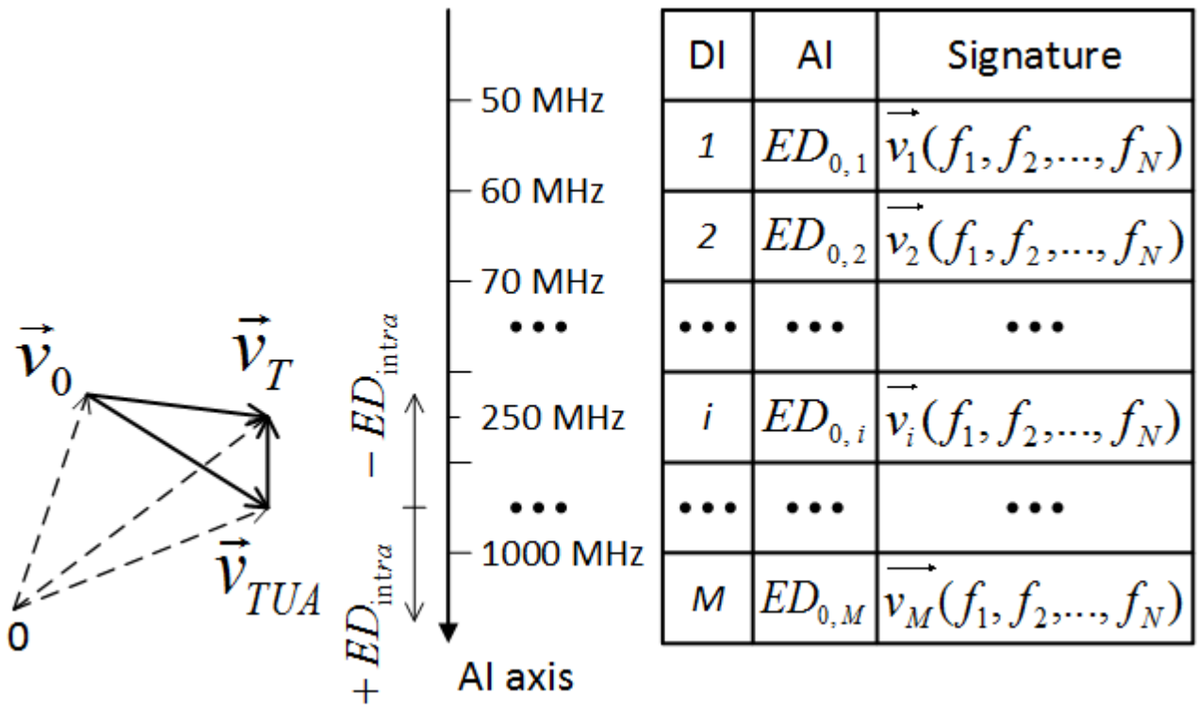
PCB Manufacturing Tolerances

Supplier	Laminate	ε_r	ε_r Tolerance
TACONIC	RF-30	3.00	+/- 0.10
TACONIC	TRF-43	4.30	+/- 0.15
TACONIC	TLX-0	2.45	+/- 0.04
ROGERS	RO3003	3.00	+/- 0.04
ROGERS	RO4350B	3.48	+/- 0.05
ROGERS	RT/Duroid 6006	6.15	+/- 0.15

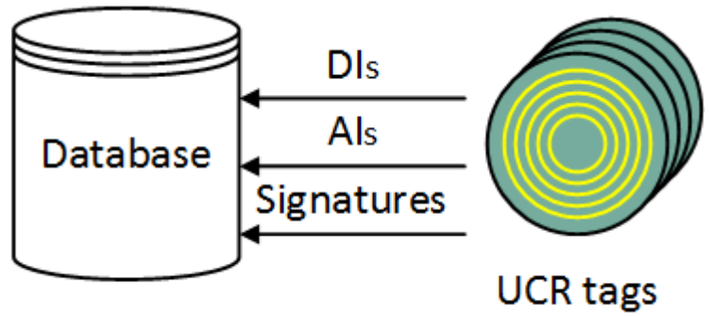
PCB Manufacturer	Trace Width / Air Gap Tolerance	PCB Thickness Tolerance
Advanced Circuits	max (+/-20%, +/-0.002”)	max (+/-10%, +/-0.005”)
Sunstone	+/- 20%	+/- 10%
Sierra Circuits	+/- 0.0001”	+/- 10%
Precision PCBS	+/- 20%	+/- 0.005”
RUSH PCB	+/- 0.005”	+/- 10%

- The dielectric constant tolerances can range from 1.33 % to 3.49 %.
- For the trace width and air gap, the maximum deviation between design value and measured value can be as large as 20 %.
- PCB thickness will typically have a tolerance of 10 %.

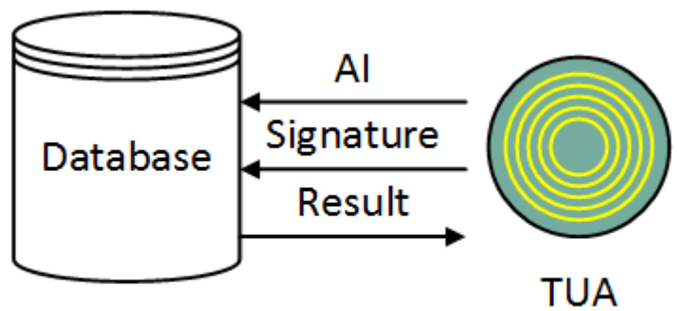
Look-up Table



DI	AI	Signature
1	$ED_{0,1}$	$\vec{v}_1(f_1, f_2, \ldots, f_N)$
2	$ED_{0,2}$	$\vec{v}_2(f_1, f_2, \ldots, f_N)$
...	...	...
i	$ED_{0,i}$	$\vec{v}_i(f_1, f_2, \ldots, f_N)$
...	...	...
M	$ED_{0,M}$	$\vec{v}_M(f_1, f_2, \ldots, f_N)$



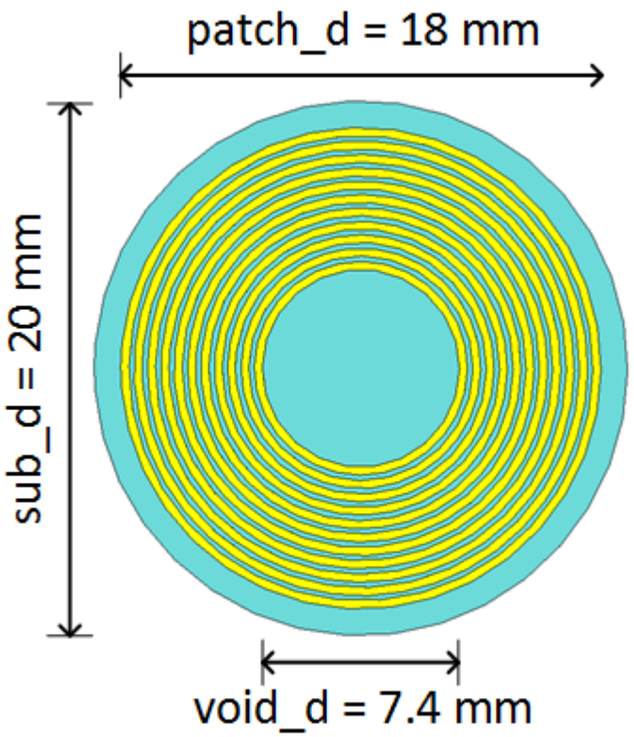
Enrollment



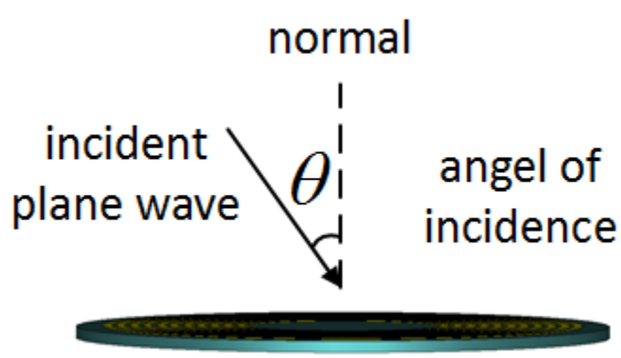
Look-up table that stores all the signatures of valid tags **Authentication**

- **Enrollment phase**
  - The signatures of all UCR tags are measured by the manufacturer
- **Authentication phase**
  I. Calculate the Euclidean distance between the signature of design value and the signature of TUA
  II. Locate TUA on the AI axis using $ED_{0,TUA}$
  III. Compare the signature of TUA with its nearest neighbor on the AI axis
  IV. Terminate if the signature of TUA matches with its k*th* nearest neighbor; otherwise we move on to its (k+1)*th* nearest neighbor

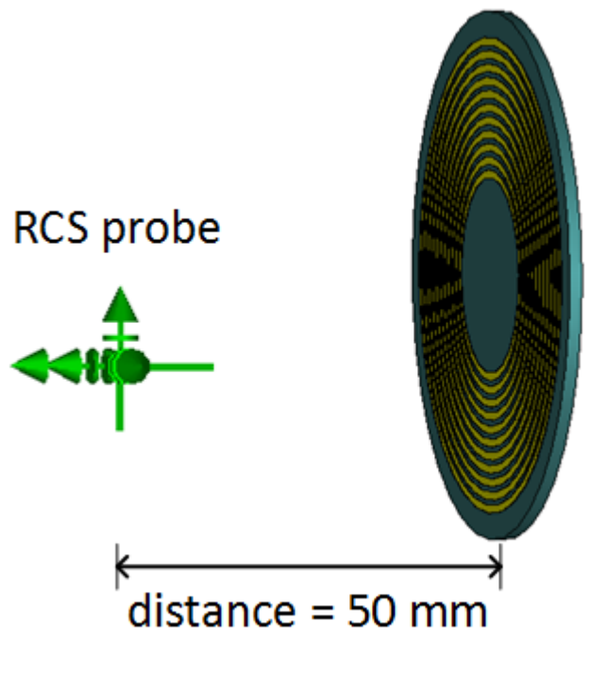
Evaluation Model



UCR tag dimensions



Angle of incidence



Distance between RCS probe and UCR tag

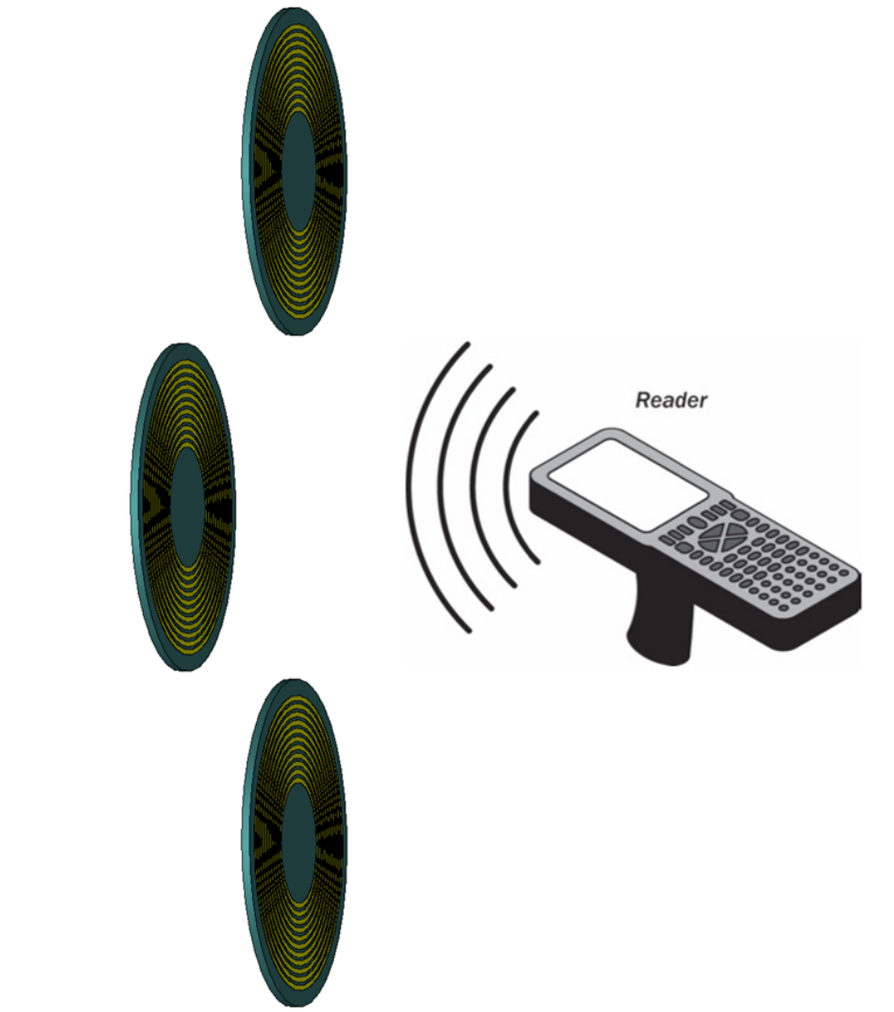
- The proposed chipless RFID tag consists of 10 concentric ring slot resonators placed on the TACONIC TLX-0 substrate.
- The metallic pattern is made of pure copper.
- Circularly polarized plane wave is used to stimulate the chipless RFID tag.
- The radio cross-section (RCS) probe is placed 50 mm away from the tag to detect the backscattered signal.

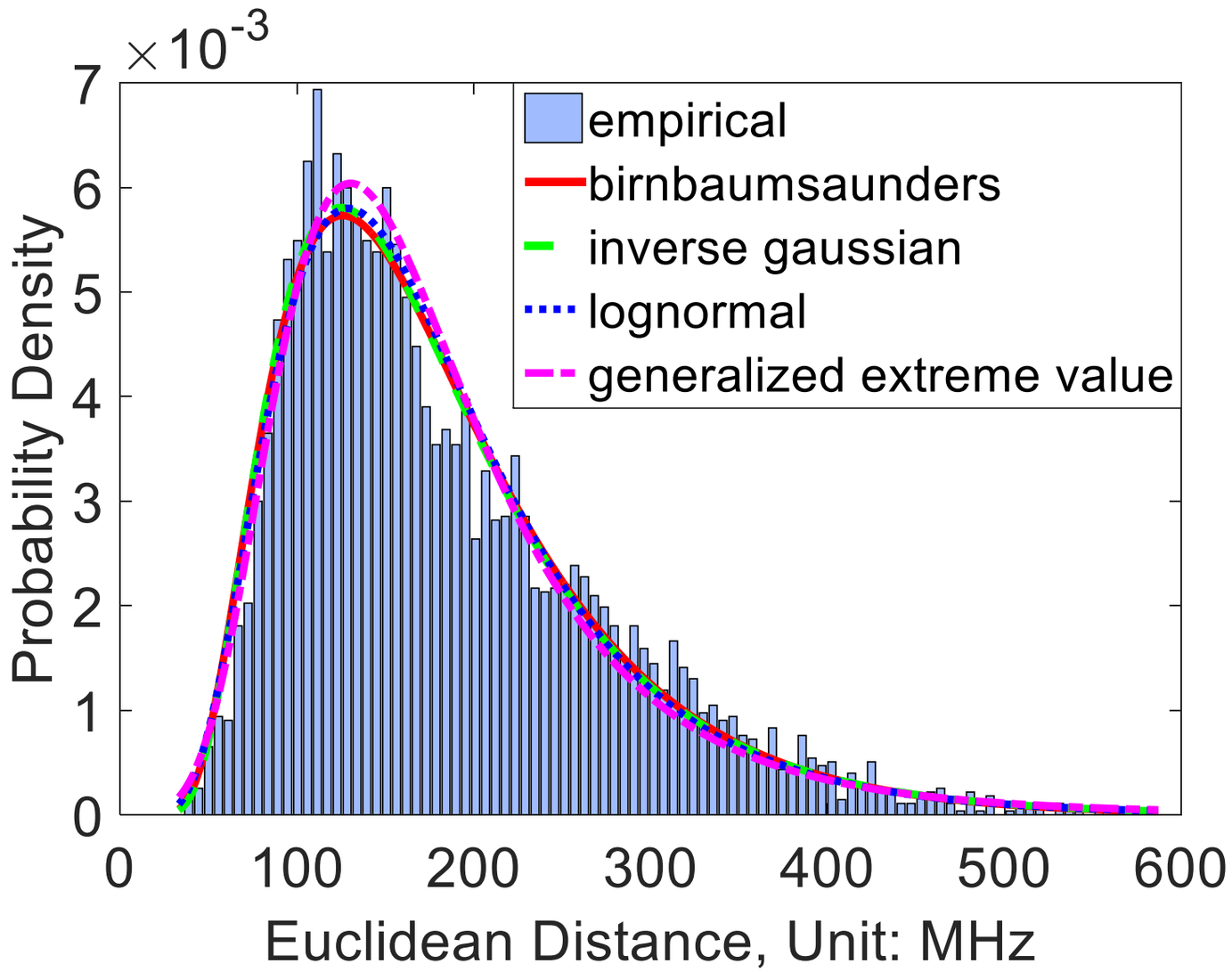
Simulation Parameters

Parameter	Value
Substrate diameter	20 mm
Substrate thickness	N (0.5mm, 0.0423mm)
Substrate dielectric constant	N (2.45, 0.0133)
Patch diameter	18 mm
Patch thickness	0.035 mm
Central void diameter	7.4 mm
Air gap i (i=1,...,10)	N (0.2mm, 0.0169mm)

- Substrate thickness and dielectric constant, and air gaps conform to normal distributions with design values as the mean values and tolerances as the triples of standard deviations.
- The frequency band used by UCR tags ranges from 4 GHz to 10 GHz.

Simulation Results

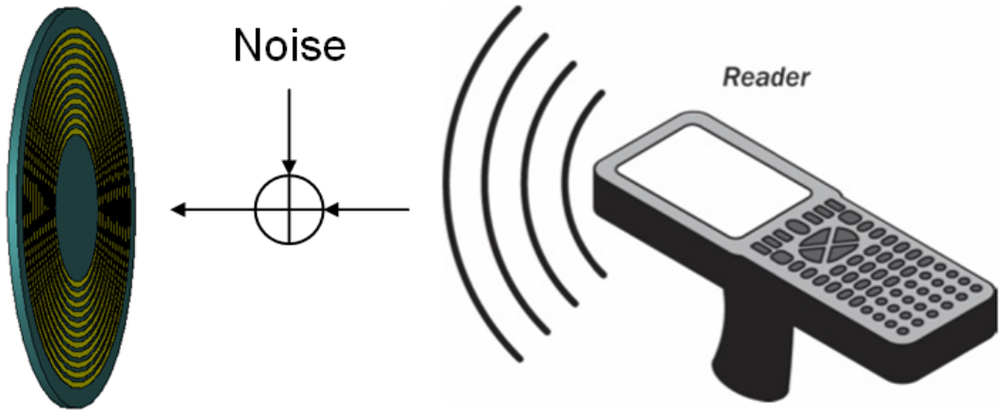


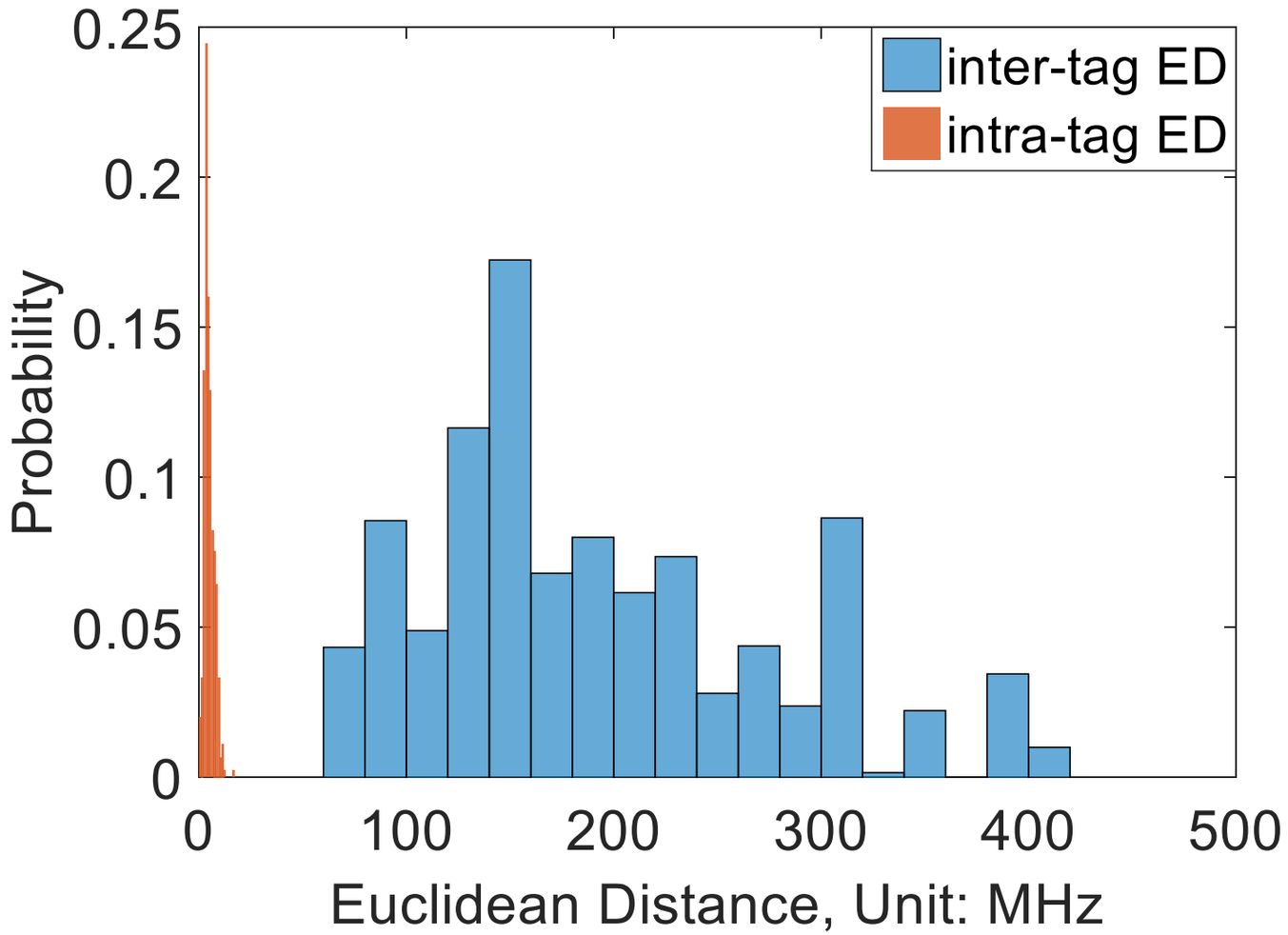


Euclidean distance distribution of UCR tags

- The minimum value, mean value, and maximum value of Euclidean distances for the 100 samples are 33.2039 MHz, 180.9612 MHz, and 587.0043 MHz respectively.
- Simulation result demonstrates that the Euclidean distances between signatures of UCR tags are effective at differentiating each other.

Simulation Results

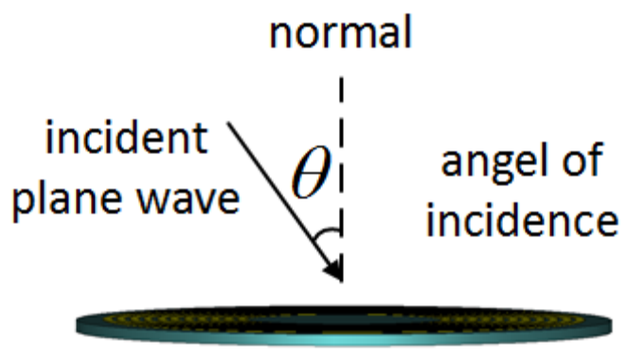




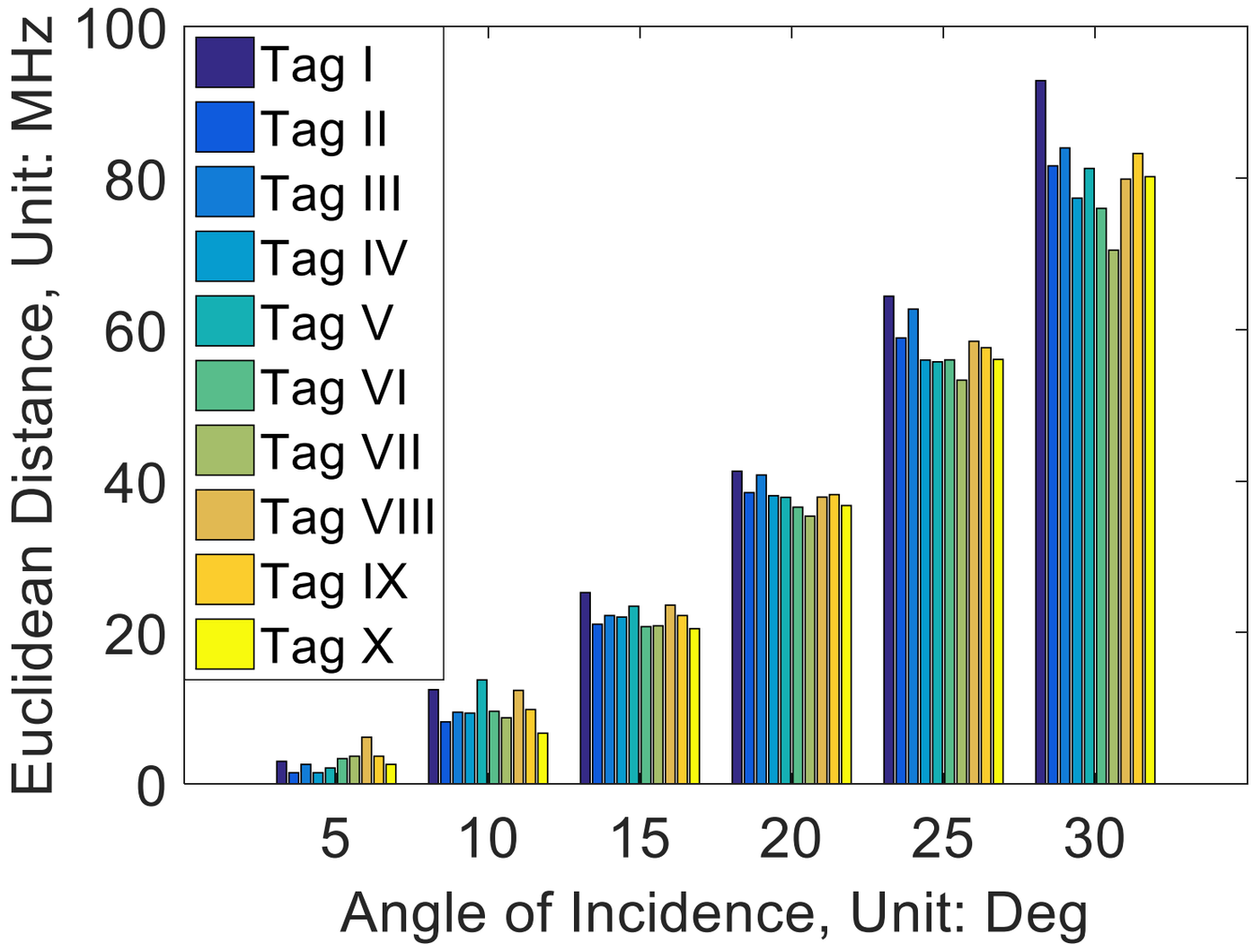
Euclidean distance distributions of UCR tags in the presence of WGN with a SNR of 10 dB

- The margin between minimum inter-tag Euclidean distance and maximum intra-tag Euclidean distance reaches approximately 50 MHz.

Simulation Results



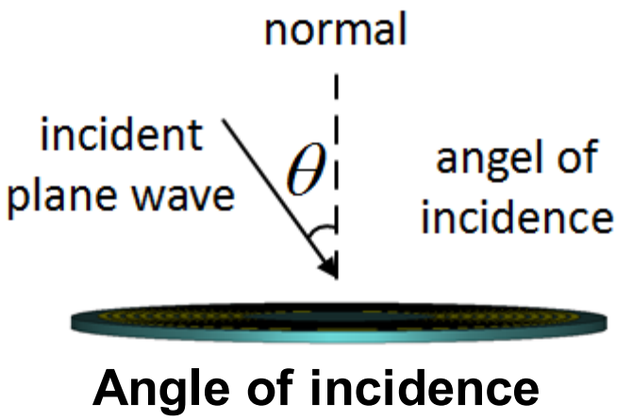
Angle of incidence



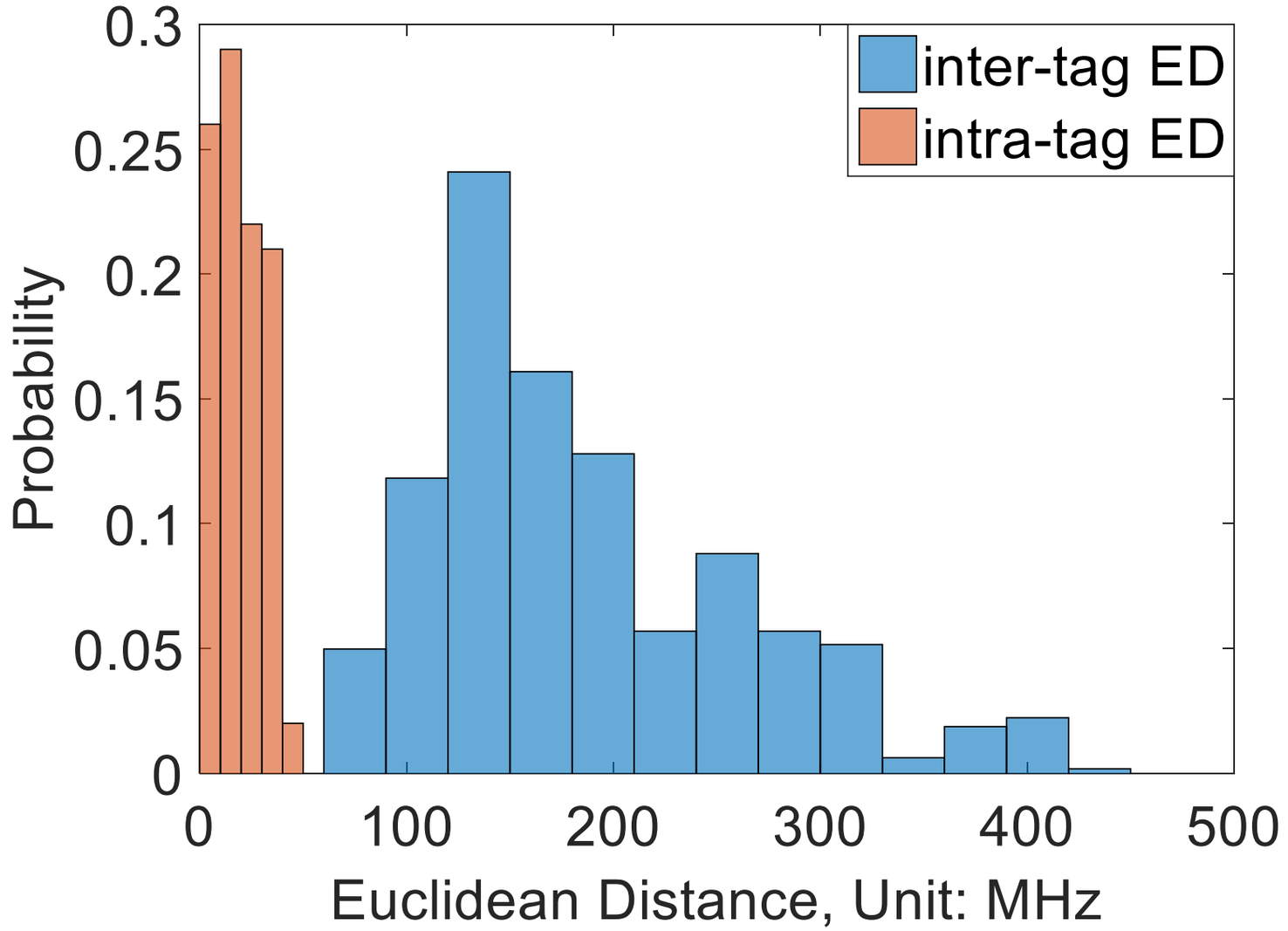
Euclidean distances relative to zero incident angle

- The larger the angle of incidence is, the larger the Euclidean distance relative to zero incident angle will be.

Simulation Results



Angle of incidence



Euclidean distance distributions of UCR tags when angle of incidence varies from 0° to 20°

- The margin between minimum inter-tag Euclidean distance and maximum intra-tag Euclidean distance reaches approximately 20 MHz.

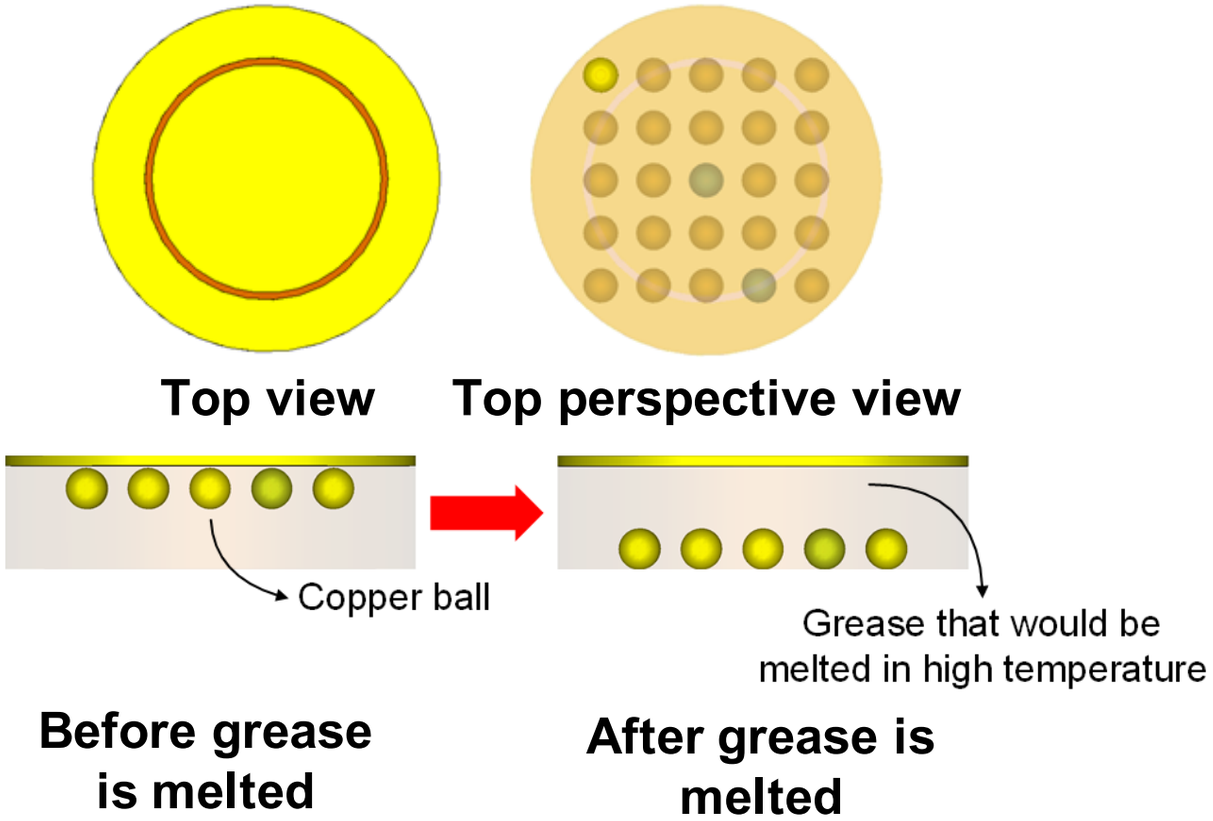
Attack Analysis

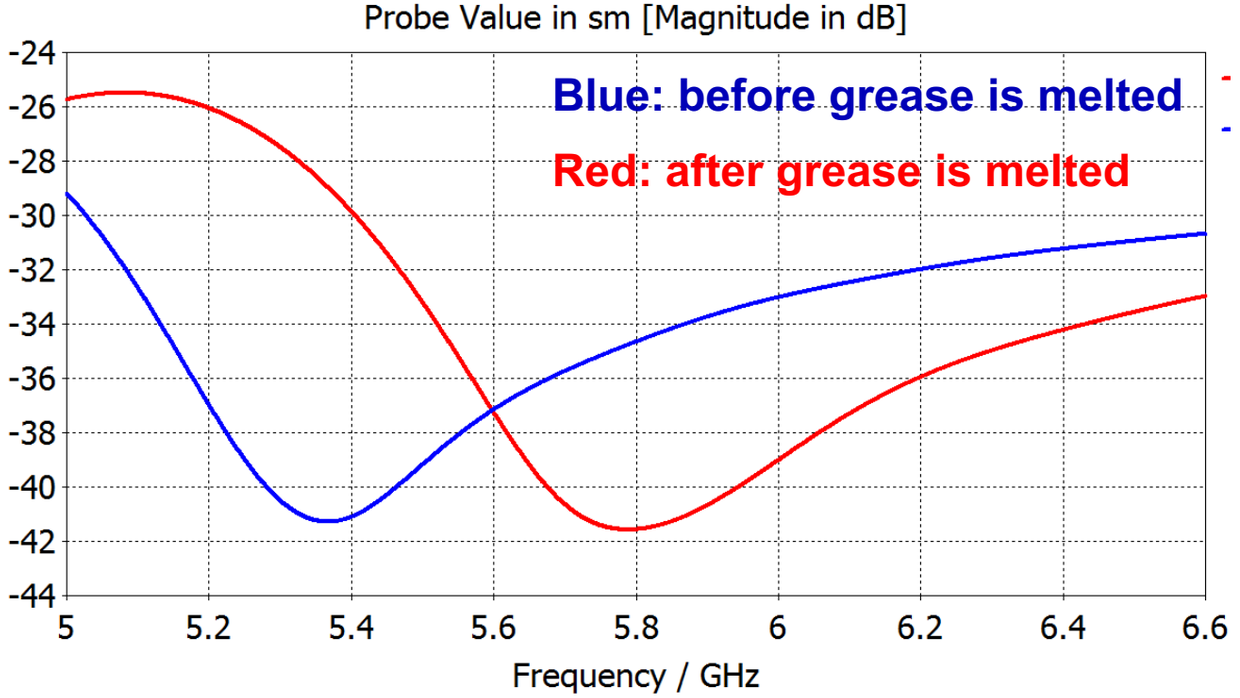
- **Cloning**
  - Process variations during tag fabrication
    - Uncontrollable
    - Cannot be easily modeled
  - Replay attack
    - Equipment to record and replay the frequency response spectrum is expensive
    - Attack equipment would be detected
- **Removal**
  - Non-electronic product
    - UCR tag can be placed inside the package
  - Electronic product
    - UCR tag can be integrated on the PCB

- **Swapping**
  - UCR tag ID could be bound with original product serial number and stored in the database

Conclusion and Future Work

- **Merits of UCR system**
  - ID is unique and unclonable
  - UCR tags can be fabricated with the same layout and do not require post-processing to encode data
  - Small tag area (20 by 20 mm²)
  - Short manufacturing time and low manufacturing cost (as low as a few cents)
  - Fast authentication process with the proposed look-up method
- **Temperature tracking**





The resonance point will shift to a higher frequency after grease is melted.