Recent Developments in Miniaturized Planar Harmonic Radar Antennas

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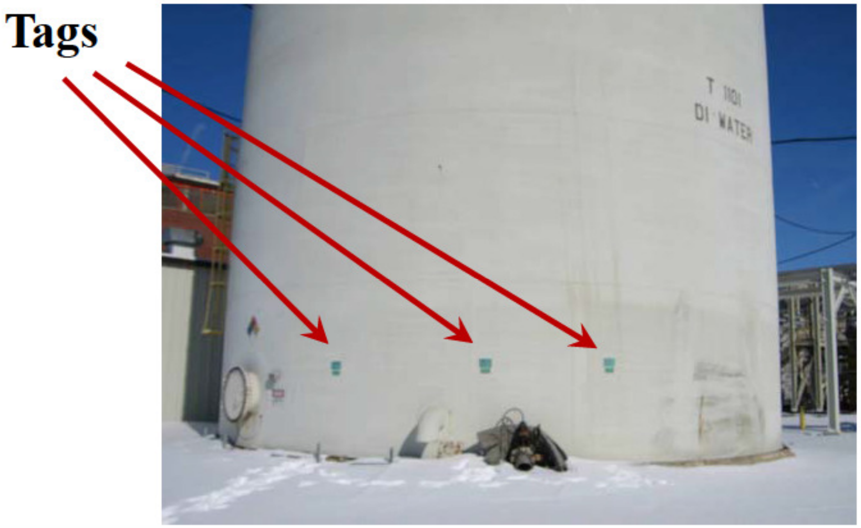
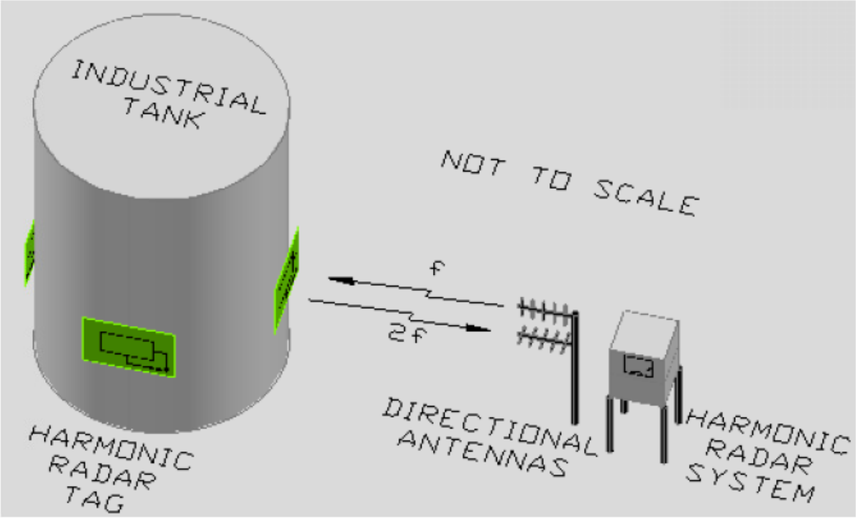
Motivation

- The Dow Chemical Co. (Midland, MI) sponsored research to develop a corrosion detecting radar system
- Goal: generate significant labor savings relative to manual inspections of insulated outdoor chemical tanks
  - The corrosion detecting “tag” would reside beneath insulation, against the metal chemical tank—need to have planar antenna with integral groundplane to avoid feedpoint impedance issues (following [8] and NEC2 simulations)

Typical chemical tank



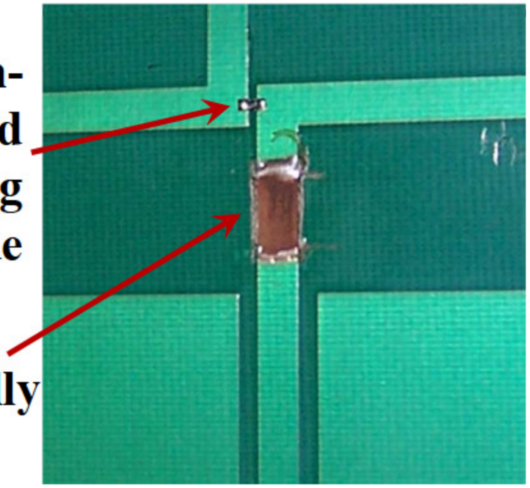
Overview of radar system use



Background

- Reactive element corrodes proportionally to chemical tank
- Tag return loss proportional to corrosion—increased tag loss is detected by the harmonic radar system

“Good” element: normal tag return signal strength

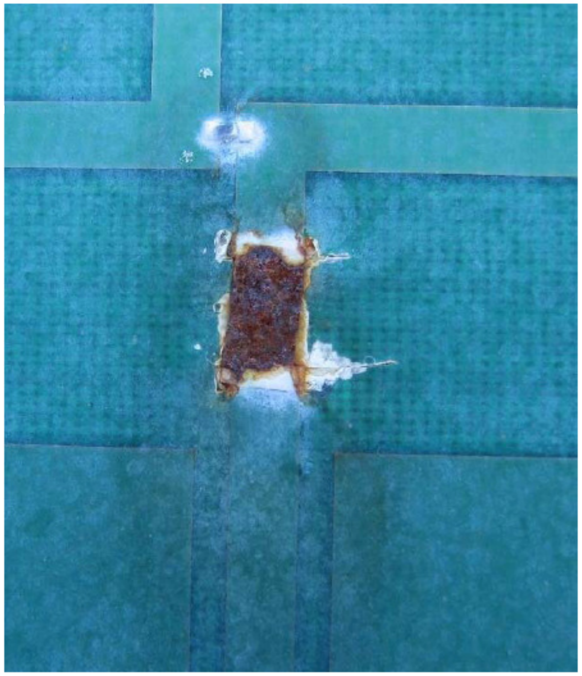


High-speed switching diode

Chemically reactive element

“Good” (uncorroded) element

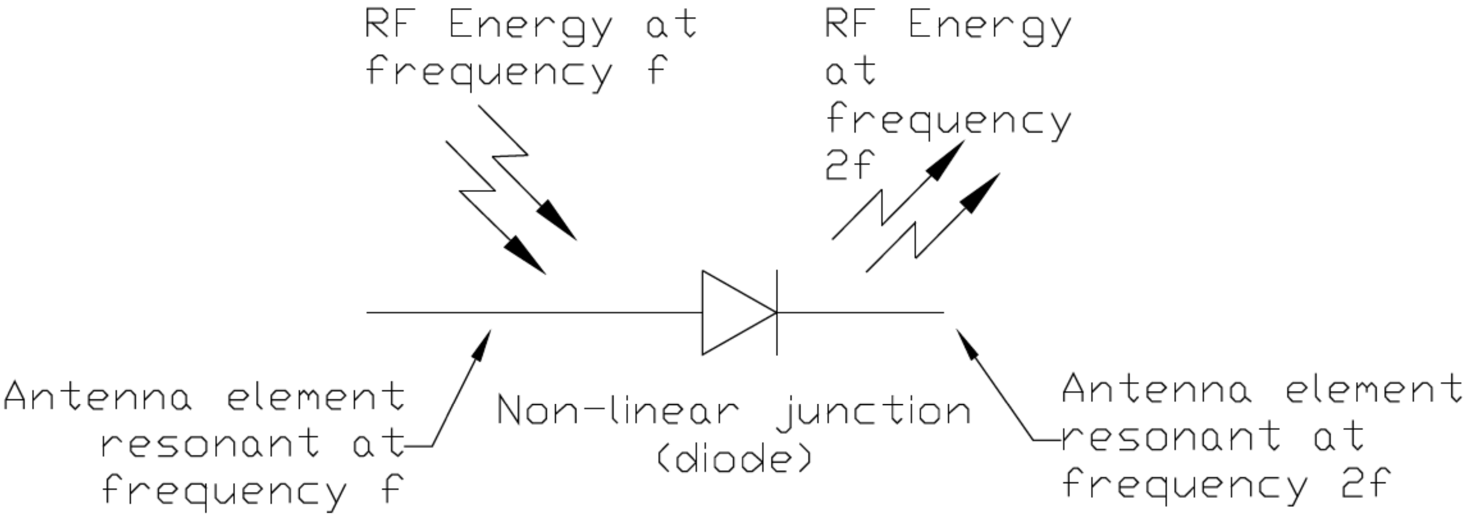
Corroded element: significant decrease in tag return signal strength



“Bad” Corroded element

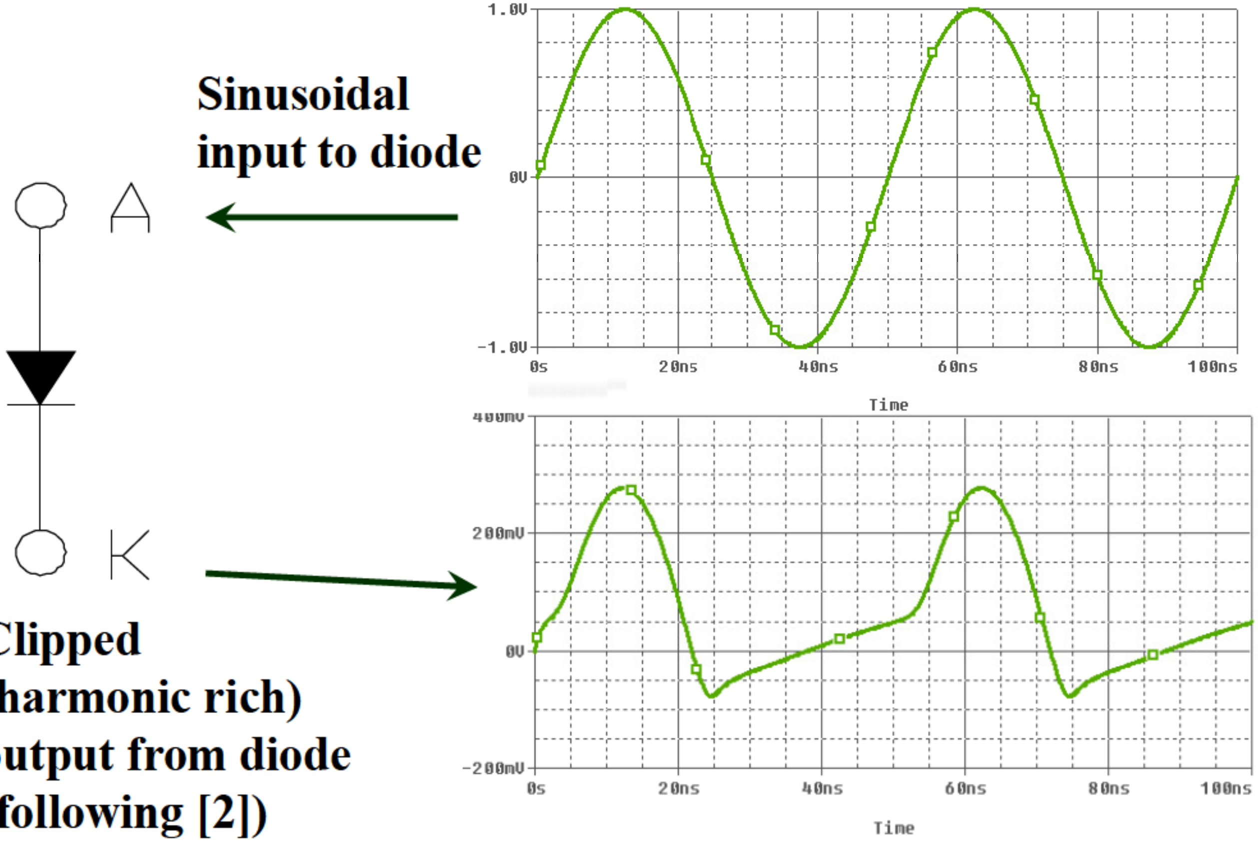
Background

- Harmonic Radar System:
  - Radar receives reflected energy at second harmonic (typically)
  - Allows discrimination between desired targets and highly reflective (e.g. metallic) background objects
  - Antenna "tag" typically uses a high-speed switching diode to generate harmonics from incident radar energy—only the second harmonic is received by the radar



Diode Selection

- The junction potential and zero-bias junction capacitance are two factors of interest for maximizing tag radar response (following [4,5])
- Experimental evidence indicates diode capacitance has a dominant effect on performance with this tag design



Sinusoidal input to diode

Clipped (harmonic rich) output from diode (following [2])

Note: 20MHz, not 917MHz simulation is shown

Diode Selection

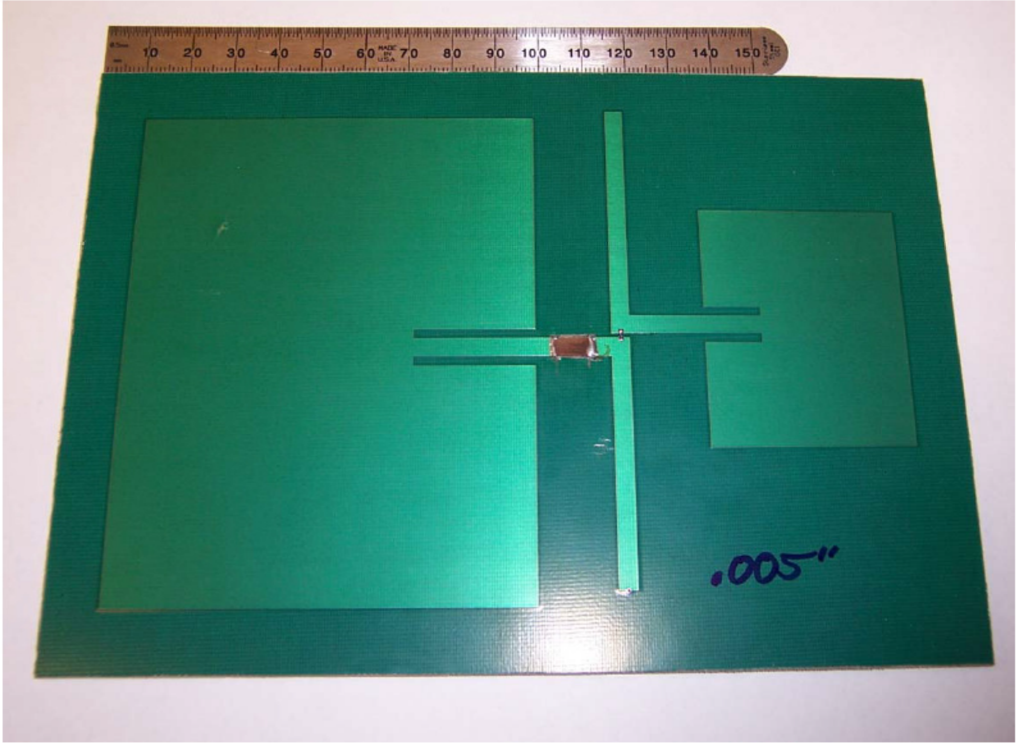
- We decided to pick a few diodes with low zero-bias junction capacitance and low junction potential, to experimentally find which diode/tag combination gave the largest tag return signal strength

- We tried the following low-cost diodes:
    - BAR42FILM
    - BAS19LT1G
    - SS14
    - ES2B
    - DAP202

- Of these diodes, the DAP202 gave the best tag return signal strength with the new tag design. It costs 4.4 cents in quantities of 1000.

First Generation Tag

US Patent # 7,145,453 includes the first generation planar tag. Ultimately, it was determined that the tag cost needed to be reduced to manufacture in large quantities.



- Taconic RF-35 laminate—high cost
- Used two patch antennas—large physical size

Issues:

- **Performance:** 50 ohm traces present high VSWR to diode, increasing loss and reducing range of detectibility
- **Material Cost:** over $7.00 plus need for shorting via
- **Size:** 190x130mm=24700mm^2

Developing a New Tag

Key ideas:

- Use best economical FR-4 laminate
- We felt that the diode interface was a good candidate for improvement
- Simulations predicted the patch edge feedpoint to be ~220 ohms
- But, 220 ohm traces are THIN, DIFFICULT, and EXPENSIVE to make on this laminate

So, use a ¼ wavelength 220:50 ohm back to back with a 50:220 ohm transformer to present a 220 ohm impedance at both ends, through using a ¼ wavelength 105 ohm transformer trace

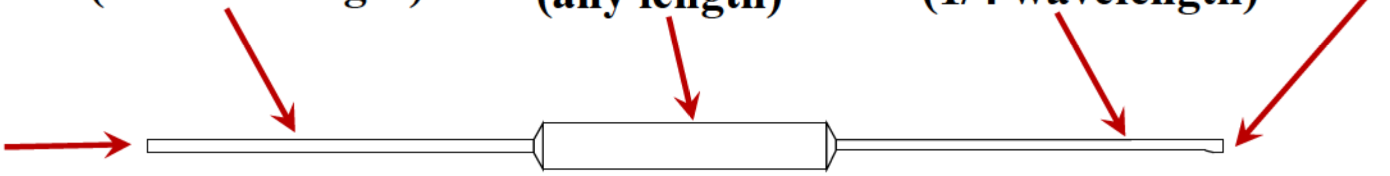
(105 ohm trace is 0.7mm on the new laminate—good)

(220 ohm trace is < 0.1mm on the new laminate—bad)

Following [3,7]:

$$Z_o\Big|_{\frac{l}{\lambda}=1/4} = \sqrt{Z_1 Z_2}$$

and well-known microstrip width formulas (see paper)



105 ohm line (1/4 wavelength)

50 ohm line (any length)

105 ohm line (1/4 wavelength)

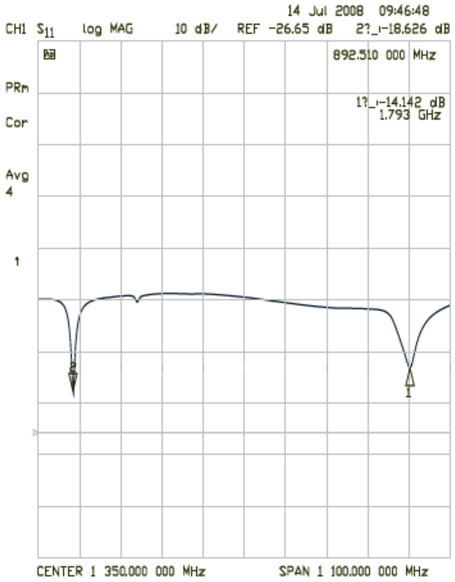
220 ohm feedpoint

220 ohm feedpoint

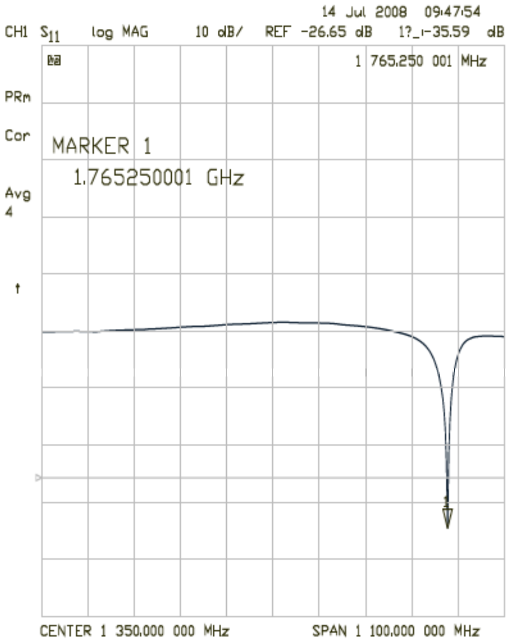
Microstrip impedance transformer (220:50:220 ohms)

Prototype Measurements

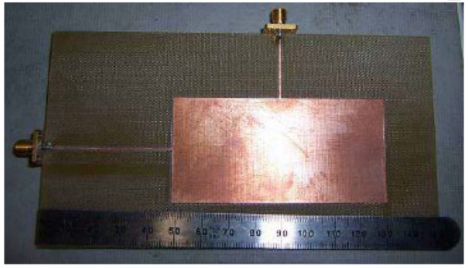
Developed dual-patch prototype, simulated in Sonnet
S11 Measured on HP8510 VNA (unused port was left unterminated)



S11 at input to transformer feeding F1 feedpoint (better than -15dB)



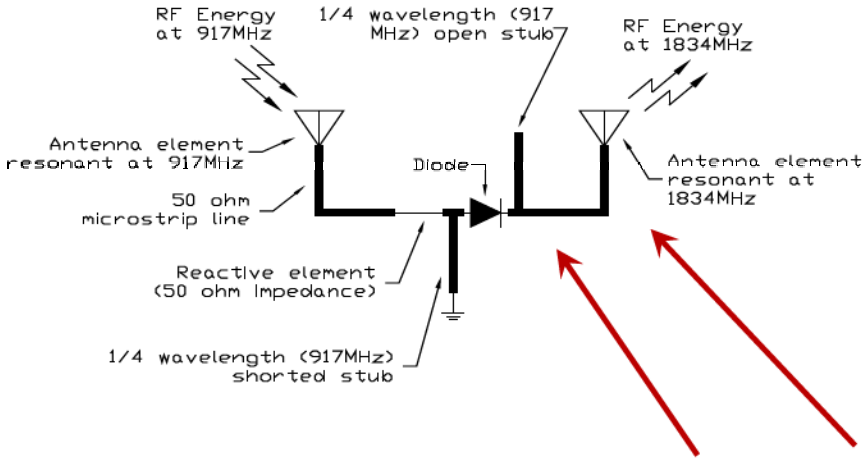
S11 at input to transformer feeding F2 feedpoint (better than -25dB)



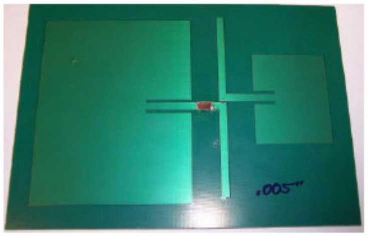
Dual-feed proof of concept prototype

Developing a New Tag

Previous (first generation, patented) tag:

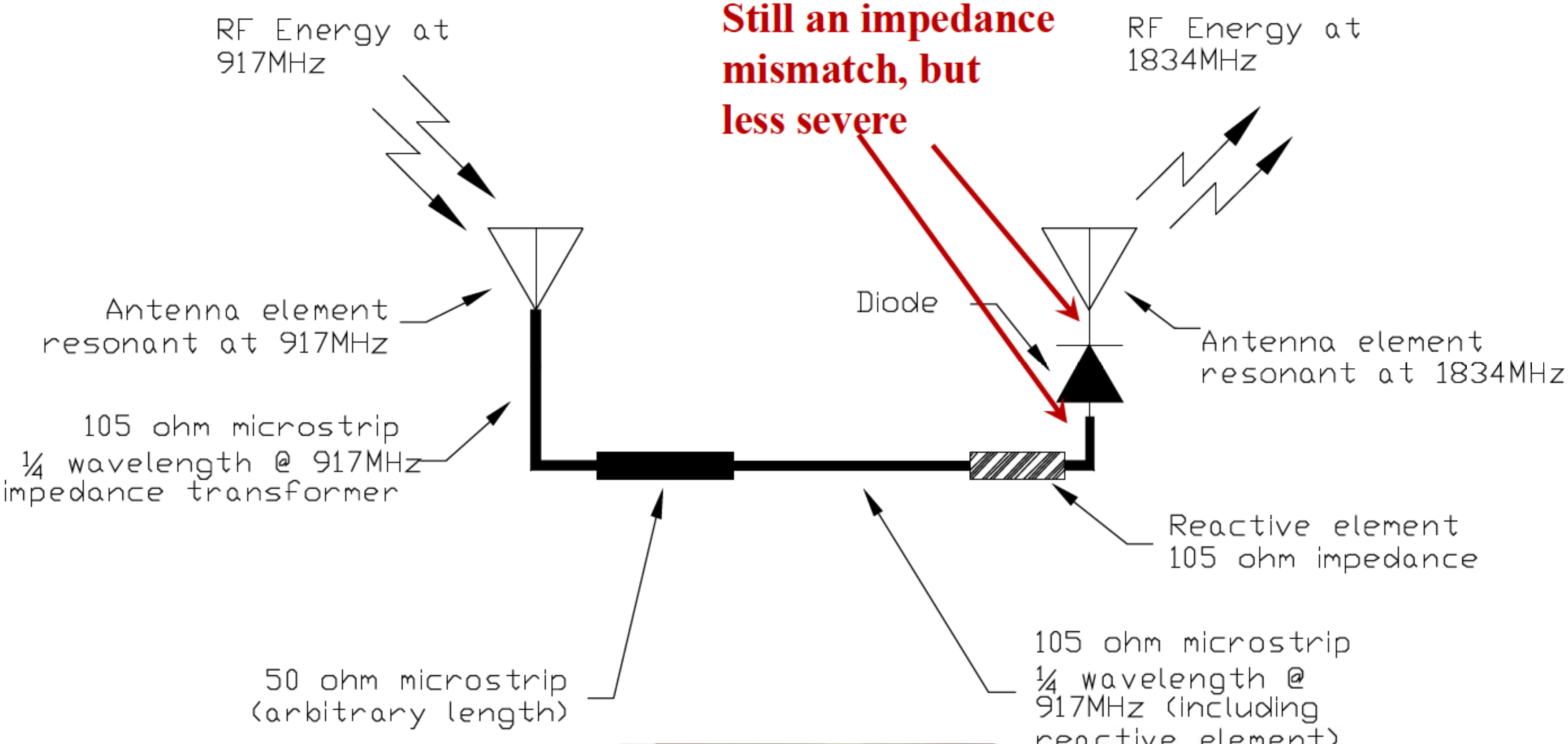


Impedance Mismatch

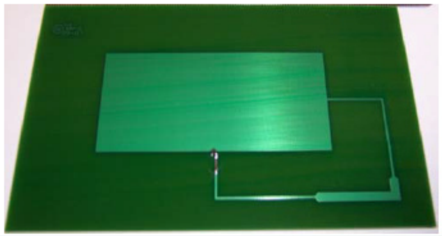


Developing a New Tag

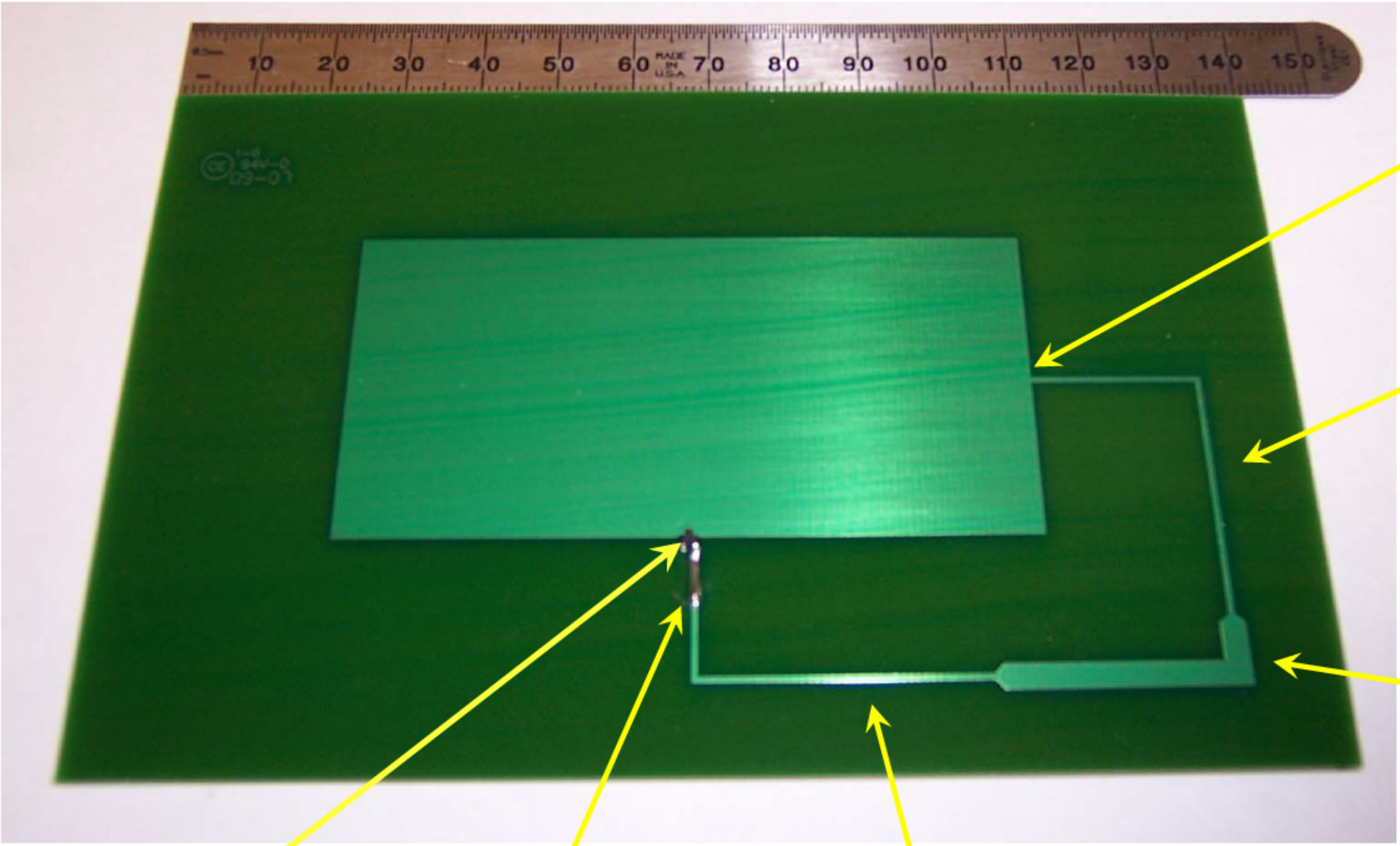
New (second generation) tag, inspired by dual-band patch antenna in [1]:



Still an impedance mismatch, but less severe



Second (New) Generation Tag



917MHz
feedpoint

220:50 ohm
¼ wavelength
Impedance
Transformer

Arbitrary
Length of
50 Ohm line

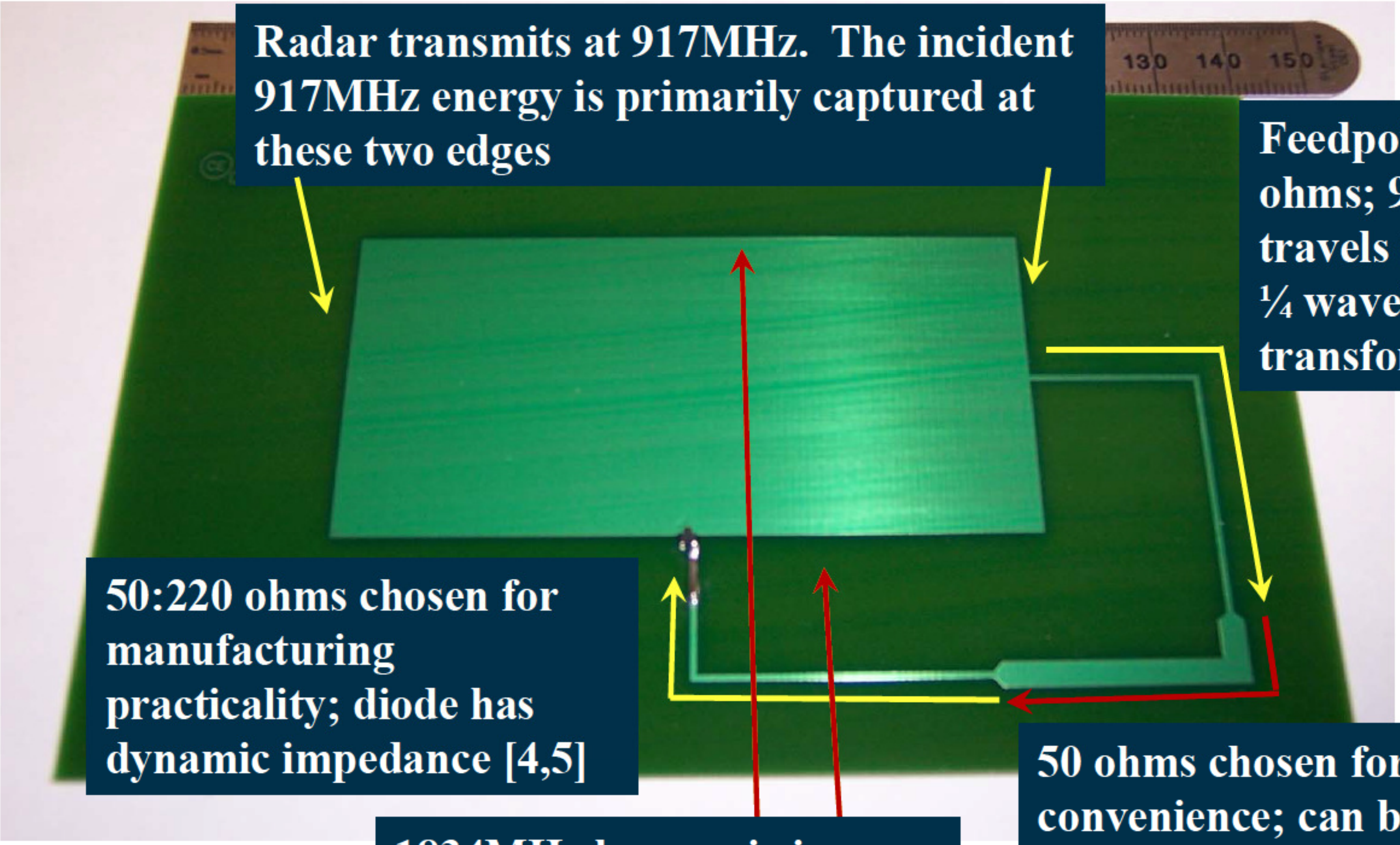
Hi-speed diode
@1834MHz
feedpoint

Reactive
Element

50:220 ohm
¼ wavelength
Impedance
Transformer

Nelco N4000-6
laminate

Second (New) Generation Tag



Radar transmits at 917MHz. The incident 917MHz energy is primarily captured at these two edges

Feedpoint is ~220 ohms; 917MHz travels through ¼ wavelength transformer

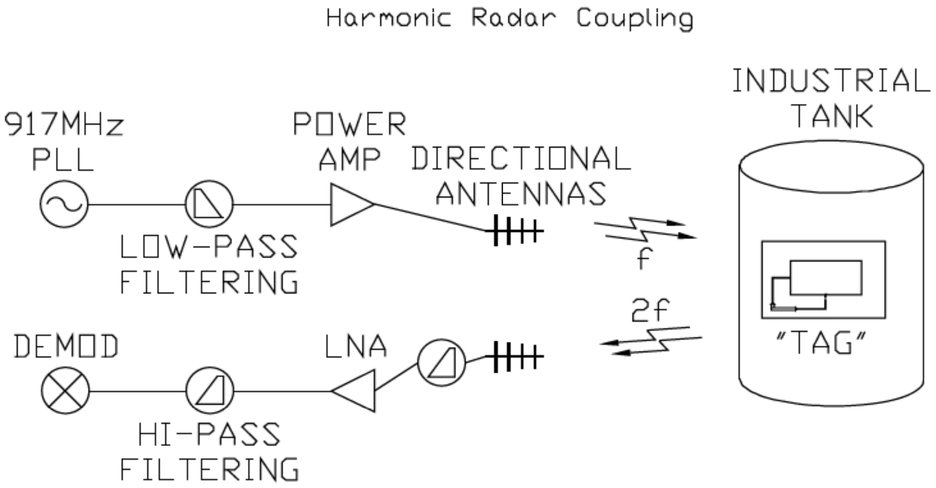
50:220 ohms chosen for manufacturing practicality; diode has dynamic impedance [4,5]

50 ohms chosen for convenience; can be of any length

1834MHz harmonic is primarily radiated at these two edges

Harmonic Radar Hardware

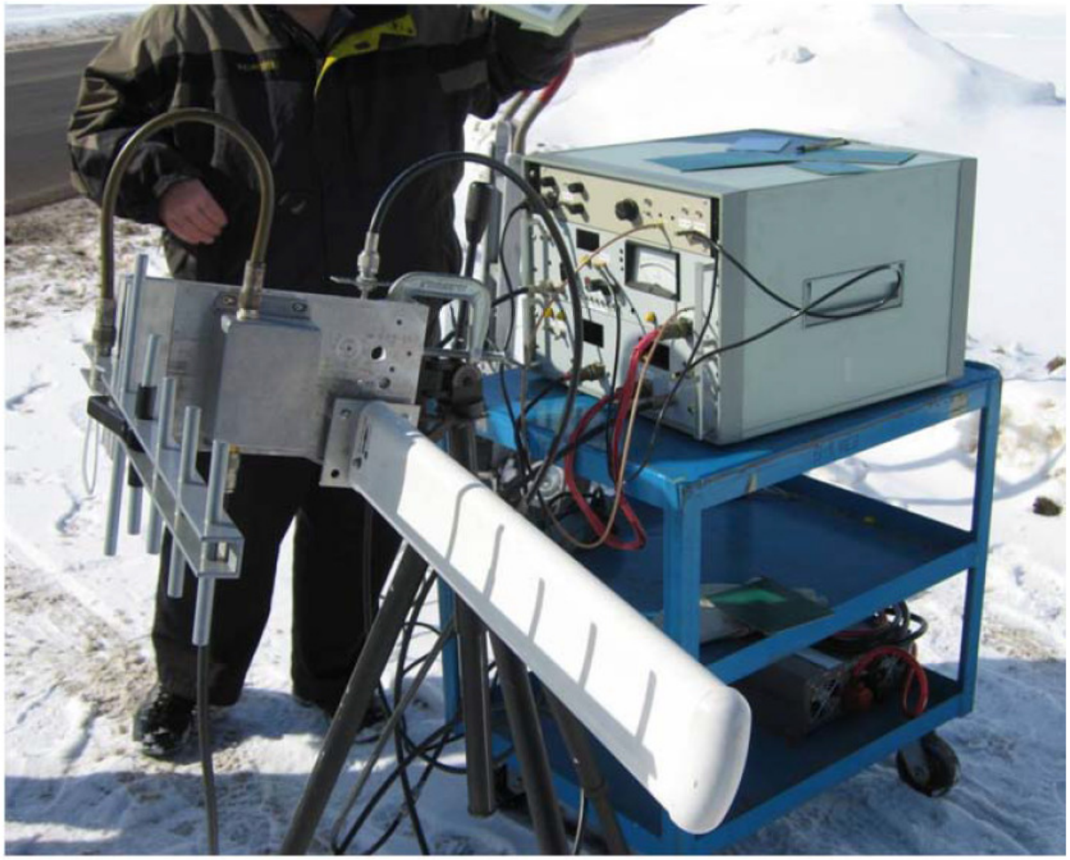
- Current system is CW, transmitting at 917MHz
  - Radar receives at second harmonic—1834MHz
  - Ten filters, superheterodyne receiver
  - TCXO slaved PLLs
  - Demodulator → log amp → front panel meter and BNC jack



Simplified System Block Diagram

Harmonic Radar Hardware

- At present, system runs off of 120VAC (e.g. using 12V car battery with AC inverter)



System in use at Dow Chemical - Midland, MI

Harmonic Radar Performance

- What signal level to expect?

$$\begin{aligned}\text{RX\_signal} &= \text{TX\_power} + \text{TX\_gain} + \text{RX\_gain} \\ &\quad - \text{Outbound\_loss} - \text{Inbound\_loss} - \text{Tag\_loss} - \text{misc\_loss}\end{aligned}$$

$$\text{RX\_signal}\,[\text{dBm}] = 37 + 10 + 15 - 20\log_{10}\frac{4\pi d}{\lambda} - 20\log_{10}\frac{4\pi d}{\lambda} - 30 - 3$$

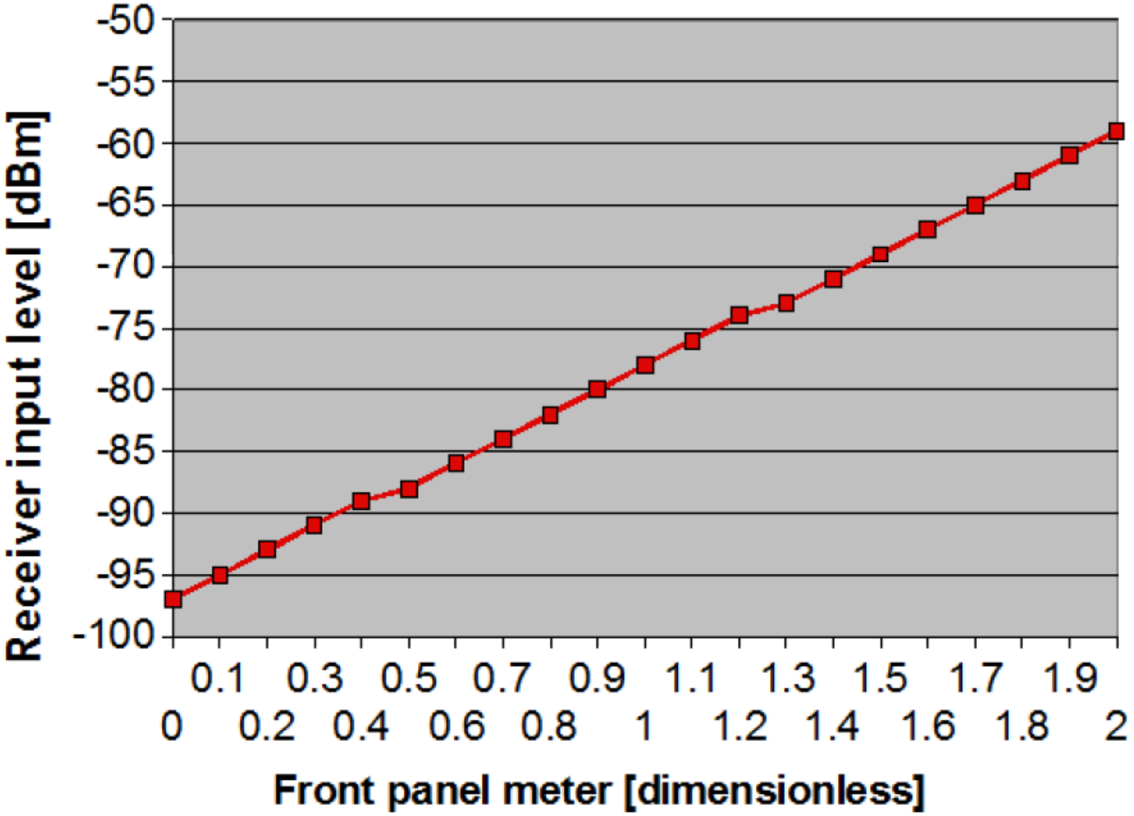
- So, for 5 meters we may expect (following [6]):

$$\begin{aligned}&37 + 10 + 15 - 20\log_{10}\frac{4\pi 5}{.3272} - 20\log_{10}\frac{4\pi 5}{.1636} - 30 - 3 \\ &= -68\text{dBm}\end{aligned}$$

- -68dBm corresponds to an SNR of about 31dB with the present harmonic radar system
- But, diode loss is not fixed due in part to dynamic diode impedance

Harmonic Radar Hardware

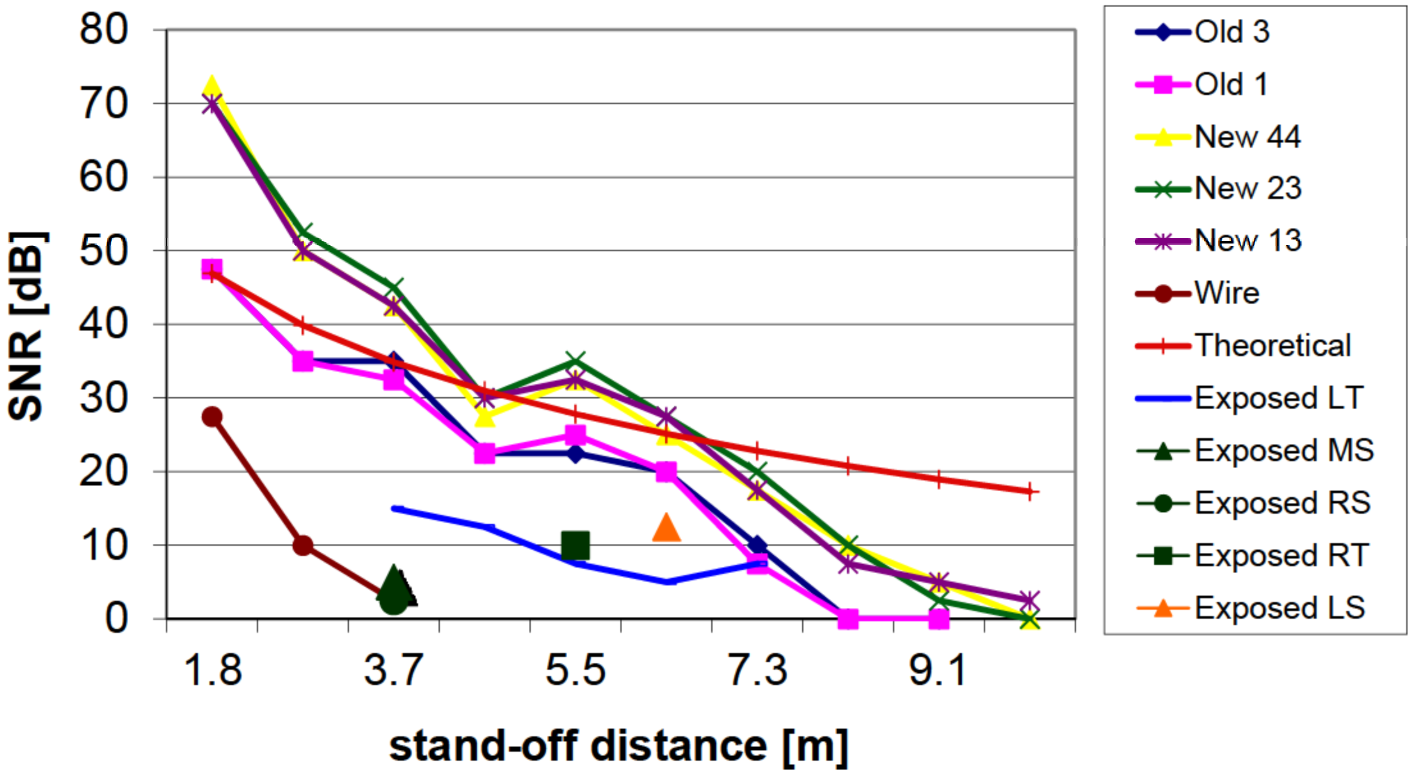
RX noise floor is about -97dBm when TX is on



Tag Performance

- Real-world testing outdoors at MSU and Dow Chemical

Outdoor tag readings



Second (New) Generation Tag

- Goals: **Achieved**
  - Reduce material cost to under $1.00 each (was over $7)
    - **Material cost for new tag is ~$0.85** ✓
  - Reduce size
    - **Surface area is 51% of 1st generation tag** ✓
  - Maintain performance and durability
    - **Detectable at least as far as 1st generation tag** ✓

Future Work

- More detailed characterization of the diode/microstrip interface in order to more fully optimize this interface
- Study effects of corrosion—determine proportionality between corrosion and tag return signal strength

References

[1] R. Bancroft, *Microstrip and Printed Antenna Design*, p. 124-127. Atlanta: Noble Publishing Co., 2004.

[2] S. A. Maas. *The RF and Microwave Circuit Design Cookbook*, p. 138-140. Boston: Artech House, 1998.

[3] K.C. Gupta, R. Garg, I. J. Bahl, *Microstrip Lines and Slotlines*, p. 72,88-94. Boston: Artech House, 1979.

[4] G. Massobrio, P. Antogenetti. *Semiconductor Modeling With Spice*, p. 2-4,8-9,23-28. New York: McGraw-Hill,1993.

[5] D. A. Neasmen. *Semiconductor Physics and Devices*, p. 323-330. Boston: Irwin, 1992.

[6] P. F. Panter. *Communication Systems Design*, p. 101. New York: McGraw-Hill, 1972.

[7] D. M. Pozar. *Microwave Engineering*, p. 15-16, 143-147. New York: John Wiley & Sons, 2005.

[8] S. Ramo, J.R. Whinnery, T.V. Duzer, *Fields and Waves in Communication Electronics*. p. 602-605, 659-661. New York: Wiley, 1994.

[9] Harmonic wireless transponder sensor and method, US patent 7,145,453, Patent and Trademark Office, 2006.