RECENT DEVELOPMENTS IN MINIATURIZED PLANAR HARMONIC RADAR ANTENNAS

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ABSTRACT

Harmonic radar has recently been shown useful for remote state sensing in high clutter environments. This new application of harmonic radar with chemically sensitive "tags" allows long-range state sensing of individual low-cost passive (battery-less) sensors, such as corrosion indicators for industrial storage tanks. The "tag" response is sensed at the second harmonic of the radar transmitter, eliminating clutter from undesired objects. A new miniaturized planar harmonic radar tag design has been developed from a low-cost switching diode and low-cost laminate, without the use of shorting vias. An 85% cost reduction over the previous tag design has been achieved while maintaining similar performance. Data are presented from field testing and the laboratory environment comparing the new tag design to the old tag design as well as a basic wire dipole.

Keywords: CW, Far-Field, Field Strength, Impedance, Planar, Commercial

1. Introduction

Harmonic radar "tags" consist of resonant antenna elements connected to a diode, in series with a chemically reactive element. The non-linear characteristics of the diode cause harmonic energy to be generated [1] from incident radar transmissions on the patch antenna. As the reactive element corrodes due to environmental exposure, the RF path from the diode to the patch antenna increases in impedance, eventually becoming an open circuit. The resultant degradation in radar return indicates that the parameter being sensed (in this case, corrosion) has changed. The presence (or absence) of harmonic energy is detected with a radar receiver designed to receive at the second harmonic frequency. Since the harmonic radar tag will typically have a far greater harmonic return than other non-diodic objects in view of the radar, the clutter from other metallic objects is drastically reduced. Thus, a tag with an element designed to sense the state of an environmental parameter (e.g. temperature, corrosion) can be reliably detected in high clutter environments, such as chemical storage tank facilities. Fig. 1 shows the elementary composition of a harmonic radar tag. While infinitely many harmonics are generated by the diode's clipping action, it is the second harmonic that is of interest for the harmonic radar system, and so the higher order harmonics will be neglected.

The new generation of harmonic radar planar antennas (tags) designed at Michigan State University reduces the physical antenna size by approximately 49% and reduces the materials cost by approximately 85% relative to the previously patented design. The new tag achieves comparable range performance to the previous generation tag. Data are presented in this paper comparing the new design planar tags to wire tags and the previous generation of planar tags.

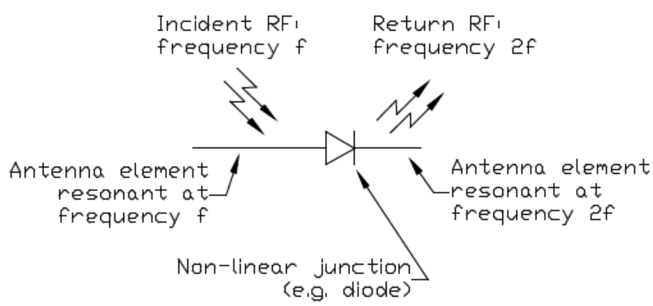

Figure 1 – Elementary Harmonic Radar Tag

2. Motivation

Fig. 2 presents a harmonic radar system application overview diagram. A chemically reactive element with known corrosion parameters is placed on the tag. The tag is affixed beneath the tank insulation. The reactive element is selected to corrode at a known rate relative to the metal chemical tank. The tag thereby comprises an early warning system, giving indication that the tank upon which the tag is mounted has likely corroded to a certain extent. Since periodic tank insulation removal is labor intensive, and may reveal insignificant corrosion, the Dow Chemical Company commissioned the investigation of harmonic radar technology as a lower cost alternative inspection method. The research aim was to develop a lower cost tag with a small chemically reactive element that increases in impedance (eventually becoming an open circuit) as increasing amounts of corrosion occur. This method allows remote sensing of corrosion severity, saving part of the manual inspection labor cost. The ultimate goal was a vehicle transported system, with a driver passing by chemical tanks and an operator pointing the radar antenna at individual tags and recording the results.

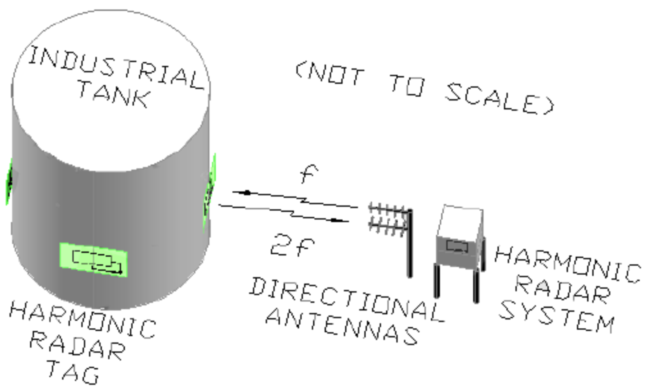

Figure 2 – Overview of Harmonic Radar Application

3. Background

After the first generation of harmonic radar hardware and tags was successfully demonstrated and patented [9], Dow Chemical wished to reduce the tag unit cost. The old tags cost over $7 each in materials, while a unit materials cost of under $1 was desired. It was experimentally known that for the typical RF voltage levels at the tag, the microstrip traces of the patented design did not present a good impedance match for the diode, thereby reducing range. The microstrip had to be manufactured at low cost, precluding the use of very high impedance traces. Following [3], in general, narrower traces yield higher impedance for simple microstrip transmission lines on a given laminate. The research described presently developed a method for presenting higher impedance to the diode with microstrip traces sufficiently wide to be manufactured at low cost.

Fig. 3 shows the patented tags deployed on a chemical tank at Dow Chemical in Midland, MI (in this case, placed for easy visual inspection, not under insulation). The tags have been deployed on this tank since July 2004, and the reactive elements have experienced significant visible corrosion. The reactive elements consist of plain carbon steel. A visual comparison between heavily corroded and negligibly corroded tags is shown in Fig. 4. In Fig. 4, the "Good" tag experimentally exhibits virtually identical radar response to a brand new tag, despite a light brown layer of surface corrosion. The "Bad" tag in Fig. 4 has obvious heavy corrosion. The bad tag was undetectable (below radar noise floor) until the radar antenna was brought to within 3 meters; where the radar response was over 30dB below an uncorroded tag at the same distance. A 30dB tag response difference is likely to be detected by a trained user of the harmonic radar system. Preliminary experimentation with six exposed tags has shown that the exposed tags generally have 6 to 30 or more dB of excess loss relative to a tag without heavy corrosion going across 2m to 10m range. For both the old and new tag design, observed typical signal strengths are generally within 3dB when comparing uncorroded tags (old vs. old or new vs. new).

The basic functionality of a harmonic radar tag arises from the clipping action of a non-linear junction, such as a diode [1]. High-speed switching diodes were likely candidates due in part to their lower zero-bias junction capacitance and lower junction voltage relative to common silicon rectifiers [5]. Experimentation and preliminary simulations indicate that diode harmonic output amplitude is inversely proportional to diode capacitance. Junction voltage differences between samples of various high-speed switching diode models were experimentally found to have noticeably less effect than zero-bias junction capacitance differences on maximum tag detection range. A preliminary simulation of the diode clipping effect at 20MHz is shown in Fig. 5. Higher frequency simulations are in work.

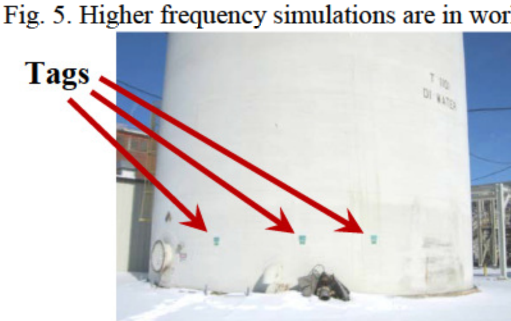

Figure 3 – Tags Deployed on Typical Chemical Tank

It is evident following [8] and NEC2 simulations (omitted here for brevity) that a simple dipole antenna placed from zero wavelengths up to about $1/20^{th}$ wavelength from a large conductive plane will experience significant disruption in feedpoint impedance. The direct placement of wire tags on metal was experimentally found to cause great loss in maximum detectable range. It is thought that the loss in range is due to reduced voltage across the diode [4,5] causing reduced harmonic generation (PSPICE simulation data omitted for brevity). Further, it is known [2] that planar patch antennas with sufficient groundplane are relatively immune to effects from a large conducting surface near the backside of the antenna groundplane. Thus, a planar antenna structure is useful for tags used in chemical tank corrosion detection. Such a tag had been developed and patented, but it was deemed too costly to mass produce at over $7 material cost per tag. Thus, the impetus to develop a new low-cost tag was born.

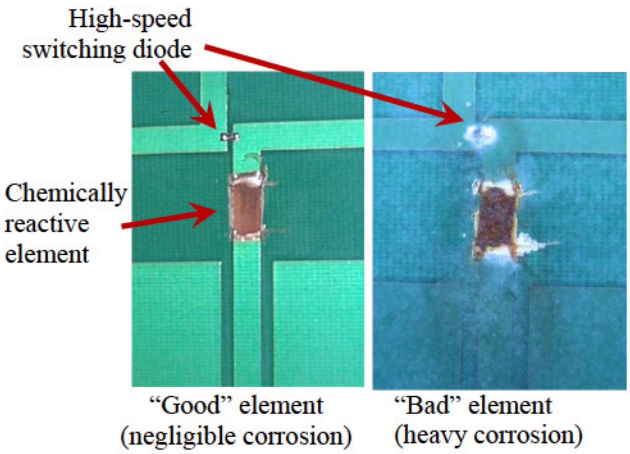

Figure 4 – Photos of "Good" and "Bad" element

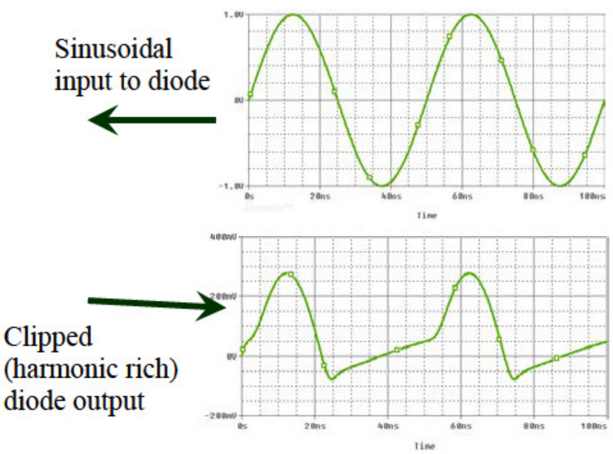

Figure 5 – Simulated 20MHz Diode Generated Harmonics

4. Development of the New Tag

The primary reduction in tag unit materials cost from $7 to less than $1 came from using a lower-cost laminate—ParkElectrochemical Nelco N4000-6. The N4000-6 laminate costs approximately 75% less per unit area than the Taconic Orcer RF-35 used in the patented tag design. Experimentally, improved impedance matching at the diode appears to have offset in part the increased dielectric loss of N4000-6 (specified dissipation factor 0.022) relative to RF-35 (specified dissipation factor 0.0018). Experiments show that the new tag has comparable maximum detection range to the old tag.

Further cost reduction was achieved by going from two discrete patch antenna elements in the old design to one dual-band patch antenna element, as inspired by dual-band patch antenna designs [2]. The tag size was reduced by 49% (to 140x90mm) by using one dual-band patch antenna. The DAP202 high-speed switching diode was chosen for the new tag design. Other diodes tested include: BAR42FILM, BAS19LT1G, SS14, and ES2B. The new tag design construction is shown in Fig. 6, with a schematic diagram shown in Fig. 7.

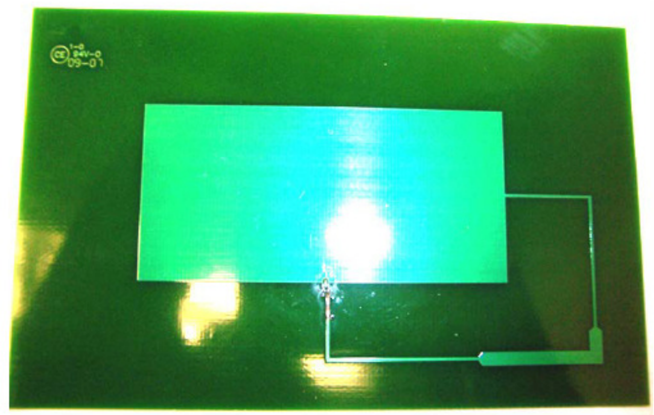

Figure 6 – New Design Harmonic Radar Tag

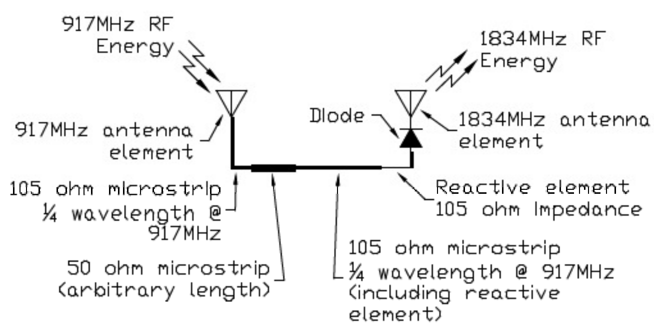

Figure 7 – Schematic Diagram: New Harmonic Radar Tag

We conducted preliminary Sonnet simulations and then fabricated the proof of concept prototype shown in Fig. 8. The S11 was measured at better than -15dB at resonance on the 917MHz port, and S11 better than -25dB at resonance was measured on the 1834MHz port using an HP8510C VNA. S11 measurements are shown in Fig. 9 for the 917MHz port, and Fig. 10 for the 1834MHz port. When measuring prototype S11, the unused port was left unterminated. In actual use on the second generation tag, the 1834MHz feedpoint is connected directly to the diode. The diode and 917MHz feedpoint each connect to the 220:50:220 ohm impedance transformation network. The S11 measurements presented cannot be taken to mean more than that the patch antenna appears to be resonant as fed with the 220:50 ohm transformers. The S11 measurements lent credence to the new tag design idea, and so the full prototype was constructed.

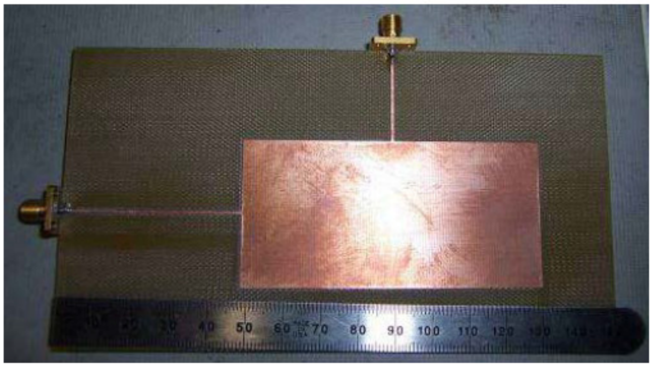

Figure 8 – Proof of Concept Dual-Feed Antenna Patch

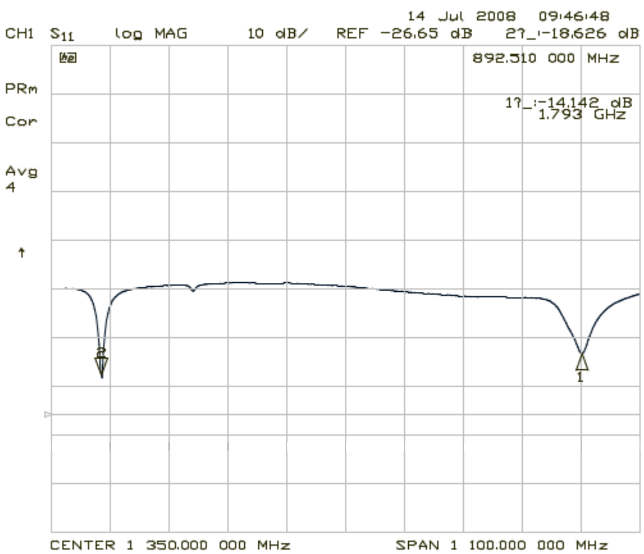

Figure 9 – S11 at 917Mhz Port

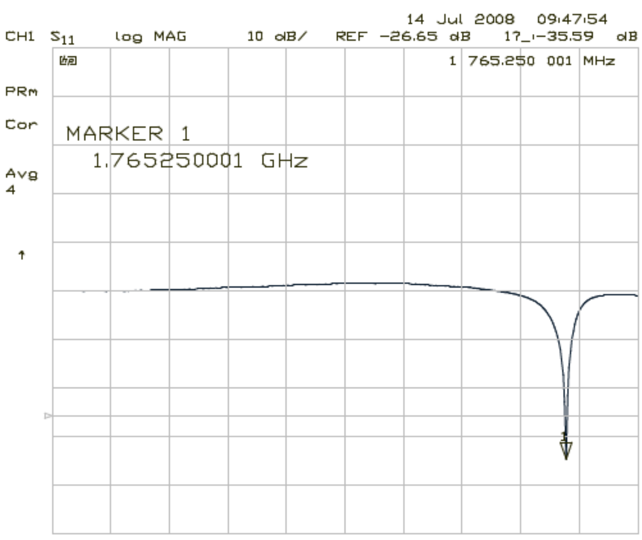

Figure 10 – S11 at 1834MHz Port

The first experimentally complete prototype of the new tag used narrow traces without the impedance transformer network, directly yielding about 220 ohms microstrip impedance. This prototype matched the range performance of first generation tags, however, the 220 ohm traces were too thin (<0.1mm) to manufacture at low cost. A solution for this problem is detailed presently.

An arbitrary lower impedance (50 ohms) was chosen, and ¼ wavelength impedance transformers at 105 ohms were used between 220 and 50 ohm end locations, allowing sufficiently wide (0.7mm) traces to be used with little additional loss and low manufacturing cost. Using the simplified relations for ¼ wavelength transformers: $Z_{TRANS} = \sqrt{Z_0 Z_1}$, and $\lambda = \lambda_0 \frac{1}{\sqrt{\varepsilon_{reff}}}$ [7], we arrive at approximately 105 ohms and 48mm length for the matching section of line. Following [3,7]:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2} \sqrt{1 + 12\frac{h}{W}} + 0.04\left(1 - \frac{W}{h}\right)^2 \right)$$

along with

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{reff}}} \times \left[\ln\left(\frac{8h}{W} + \frac{W}{4h} \right) \right]$$

where:

ε_r is specified relative permittivity of laminate

h is thickness of laminate

W is the width of the microstrip

we find approximately 0.7mm for a 105 ohm trace. A 220 ohm trace is predicted to be less than 0.1mm wide, which is impractical to manufacture at low cost with the desired processes and laminate. Using a similar formula (omitted here for brevity) from [7], we find approximately 3mm for a 50 ohm trace. The trace was optimized through simulations in Sonnet. An overview of the selected transformer design is shown in Fig. 11.

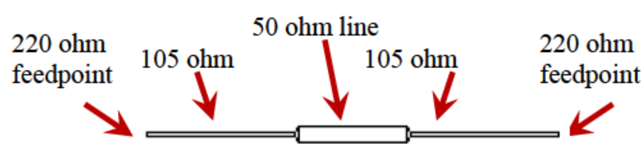

Figure 11 - 220:50:220 Ohm Transformer Strip

The diode impedance varies proportionally with junction voltage [4]; at present it was decided to allow the remaining mismatch to remain since we had achieved the primary design goals. We conducted preliminary Sonnet simulations of the 220:50:220 ohm transformer with similar geometry to Fig. 11, yielding the results in Fig. 12. We note that the S21 indicates low loss for 917MHz (as desired) and good S11 is also observed for 917MHz. High reflection is indicated at 1834MHz by S22, as desired. Note that the

S11/S22 curves and S12/S21 curves overlap each other respectively.

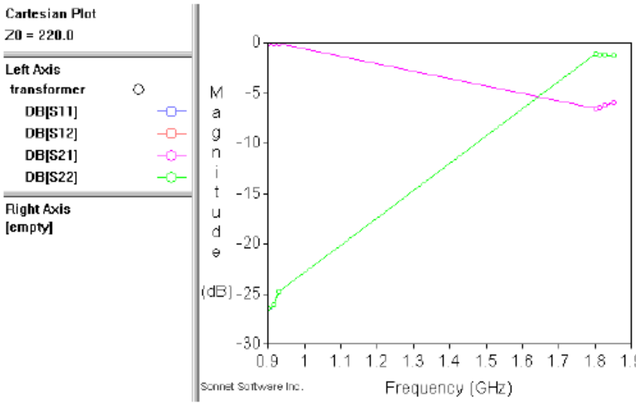

Figure 12 – Sonnet Simulation: 220:50:220 Transformer

5. Harmonic Radar Hardware

The harmonic radar system hardware was developed at Michigan State University. The system is housed in a cabinet approximately 50cm high by 50cm wide by 75cm deep, and is light enough to be carried into a vehicle or wheeled on a cart. The primary system power is 120VAC, and can be powered by a commonly available AC inverter. The overall architecture for the system is depicted in simplified form in Fig. 13.

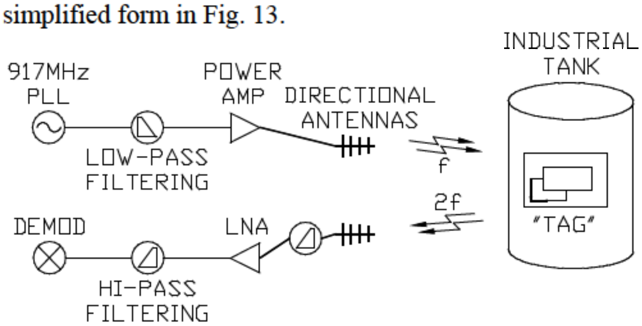

Figure 13 – Simplified Block Diagram

The narrow receiver bandwidth yields sensitivity (with transmitter off) of about –122dBm. The 2.5ppm TCXO feeds the three system PLLs, keeping them on frequency under varying temperatures. The harmonic radar transmitter system incorporates filtering to reduce emissions at 1834MHz. The present harmonic radar system uses CW to detect the tags. The harmonic radar receiver's priorities are filtering out the transmitter fundamental and maintaining good receive sensitivity. The dual-conversion superheterodyne receiver front-end high-pass filtering reduces overloading of the low noise amplifier from the 917MHz transmitter. The final receiver bandwidth is set by a 30kHz crystal filter. We lack space in this paper to further describe the harmonic radar system hardware.

6. Measurements

The new tags have been tested in outdoor and indoor environments. The new tag design performs comparably to the old tag design, where both are uncorroded. A heavily corroded tag experimentally shows at least 30dB less radar return than a non-corroded tag at the same range. Field testing at the Midland, MI Dow Chemical plant verified the stability of the harmonic radar system under adverse conditions. Fig. 14 shows the system in actual winter use at Dow Chemical in Midland, MI.

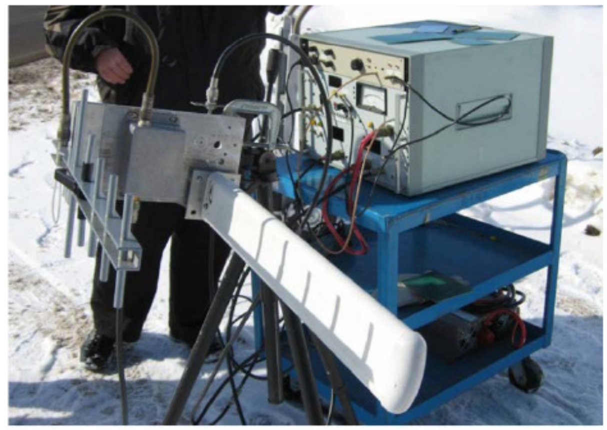

Figure 14 – Harmonic Radar System: Outdoor Winter Use

A graph of tag signal strength observed during outdoor testing at MSU and Dow Chemical is given in Fig. 15. We observed that one tag of the six exposed first generation tags was not detectable at 6 meters stand-off distance due to corrosion, but with the radar was brought to within 3 meters of the tag, it could be detected. After four years, six exposed first generation tags generally had significantly lower return signal strength than an uncorroded tag across the 2m to 10m range. These results suggest that tag return signal strength is inversely proportional to corrosion—it apparently does not take a completely open reactive element to detect that corrosion status has changed. The new tags have not yet been placed on tanks at Dow Chemical. Considering the change in physical size (narrower) and operating impedance (higher) of the new reactive elements on the new tags, it is not obvious if the new tags will exhibit decreased radar response sooner or later than the old tag design for a given environment.

To determine the expected return signal strength at the radar receiver, as a first order approximation we may consider Friis' free-space loss equation [6]: $loss[dB] = 20\log_{10}\frac{4\pi d}{\lambda}$ along with other system losses.

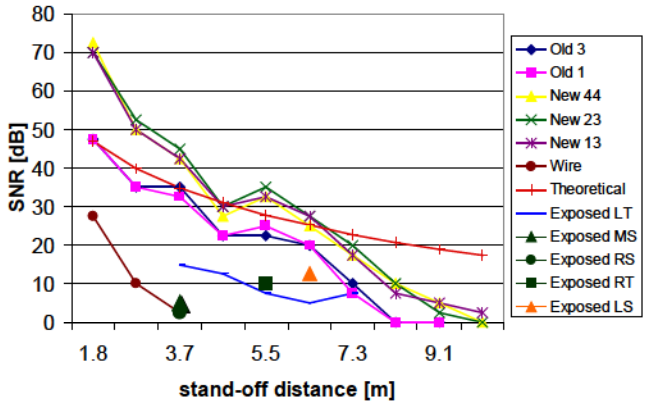

Figure 15 – Outdoor Harmonic Radar Tag Data

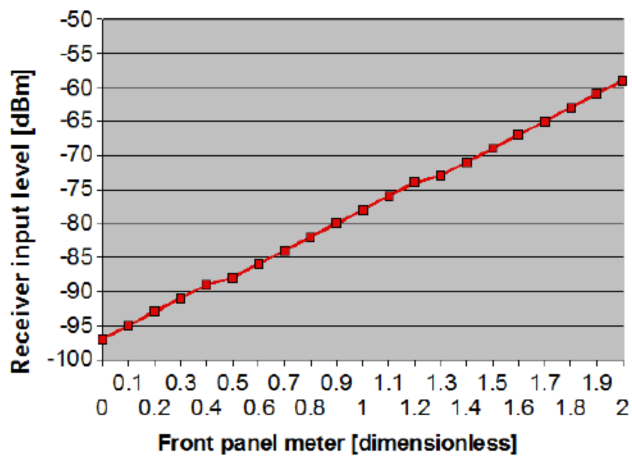

Figure 16 – Analog Front Panel Meter Reading vs. 1834MHz Receiver RF Input Level

The overall system gains and losses are thus considered:

$$RX\_signal = TX\_power + TX\_gain + RX\_gain - Outbound\_loss - Inbound\_loss - Tag\_loss - misc\_loss$$

For the present harmonic radar system and tag, we find:

$$37 + 10 + 15 - 20\log_{10}\frac{4\pi 5}{.3272} - 20\log_{10}\frac{4\pi 5}{.1636} - 30 - 3$$

$$= -68\text{dBm at 5m range}$$

-68dBm corresponds to an SNR of about 31dB with the present harmonic radar system, which is a strong signal.

Experimental evidence and preliminary simulations show about 30dB of overall tag loss at 5 meter range. However, since in general diode impedance is dependant on applied voltage [4], we expect the tag loss to be proportional to range. Effort is underway to gain more detailed insight into tag operation through more detailed simulation and experiments. Further work is also needed on characterizing tag response to varying amounts of corrosion. Preliminary simulations indicate a 500μm reactive element gap yields about 30dB of additional tag loss.

The receiver noise floor is -122dBm when the transmitter is off, but becomes -97dBm when the transmitter is on. The change in sensitivity is due to second harmonic coupling from the 917MHz transmit chain to the 1834MHz receiver front end. We have applied ten filters throughout the harmonic radar system to avoid receiver overload and transmitter harmonic coupling. If the radar sensitivity could be improved, the range of detectability of tags would likely be increased. The relation between the front panel analog meter reading and the applied 1834MHz RF level to the receiver front end is shown in Fig. 16.

7. Conclusion

The new harmonic radar tag developed at Michigan State University has been successful in each design goal:

- antenna size reduction of about 50% (actual 49%)
- material cost reduction of 85% (less than $1 cost)
- manufacturing cost reduction (no shorting vias)
- similar range performance to first generation tags

The new harmonic radar system architecture was shown to be stable at below freezing temperatures and with the vibration and shock typically experienced outdoors. The sub-one dollar per tag cost goal set by the Dow Chemical Company has been successfully achieved and demonstrated under real-world conditions by the Michigan State University researchers.

8. References

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