CAAP Quarterly Report

Date of Report: *January 10, 2018*

Contract Number: *DTPH5614HCAP04*

Prepared for: *Arthur Buff, Project Manager, PHMSA/DOT*

Project Title: *Embedded Passive RF Tags towards Intrinsically Locatable Buried Plastic Material*

Prepared by: *Deepak Kumar, Saikat Mondal, Dr. Yiming Deng, Dr. Dan Connors and Dr. Prem Chahal*

Contact Information: *Dr. Yiming Deng (MSU) and Dr. Prem Chahal (MSU)*

For quarterly period ending: *January 10, 2018*

Business and Activity Section

(a) Generated Commitments

Project abstract: Accurate and reliable locating, identifying and characterizing the buried plastic pipes from the ground surface in reducing the likelihood of hit them is critical and imperative to reduce the pipeline incidents. In this collaborative research, a new harmonic radar (frequency doubling) mechanism for smart RF tags design that can detect plastic pipes deeply buried in various soils conditions will be investigated, achieved through efficient tags and highly sensitive readers design, and coupled with intelligent signal processing. The proposed low-cost, small thin-film form passive RF tags can directly be embedded in plastic pipes. It will be able to withstand high temperature processing of plastics and stress involved with horizontal tunneling/drilling of buried pipes. The embedded RF tags have the capability to not only precisely locate the buried plastic pipes, but also have integrated sensing functionality, which can measure the strain-stress changes in the plastic materials. Finally, the vast amount of acquired sensing data from individual tags will be integrated to the advanced signal processing for better data categorization and mining. An innovative prognostics framework for better asset life-cycle management will be developed.

A complete solution is needed that helps in identifying individual buried pipes, their precise location, determining their integrity and sensing for leaks. Buried pipes are expected to have a lifetime of greater than 30 years that are designed to carry a range of liquid and gaseous materials. Among the many pipe technologies, demand for plastic pipes is growing largely because of their low-cost and potential for long life time. Any tags or sensors that are incorporated within these pipes should be able to withstand harsh conditions with a lifetime meeting or exceeding that of the pipes, and should be battery free (passive tag). Furthermore, the overall system should be compact, low-cost, and easy to operate. With advanced techniques to bury the pipes using tunneling approaches it is necessary that tags withstand the associated stress and handling during construction work. Typically, the pipes are buried 3 feet or deeper in the ground and thus the reader should be able to interrogate the tags at these and at higher depths (greater than 5ft is desired).

As summarized in Introduction section, significant advances have been made in the area of electronic tagging of buried objects. However, most of these tags are an afterthought as they are not integral part of the infrastructure. These tags are typically large and are buried along with the objects. This is simple if open trenching is carried out. However, for plastic pipes that are buried using tunneling this approach will not suffice without making the tags an integral part of the plastic pipe. Furthermore, no RF tags are commercially available that will allow in sensing of the environment and the integrity of the buried object during its life time. Smart RF tag designs are necessary as power harvesting and storage techniques will also have limited life time as the rechargeable batteries (or capacitors) and the associated circuit (e.g., piezo power harvester) will have a limited lifetime. Meanwhile, no advanced data processing algorithms are available for optimally manage and use the vast amount of information embedded into the received RF signals from the proposed new tags. Under this three-year project, the specific technical objectives/goals of the proposed research are:

1) Design and development of new passive harmonic radar based smart RF tags with long range detection guided by industry partners;
2) Design robust and miniature tags such that they can directly be embedded in plastic pipes during manufacturing;
3) Investigate on-tag strain-stress sensing capabilities and efficient data transmission;
4) Investigate new massive RFID data mining, processing and classification algorithms with experimental testing;
5) Develop a Bayesian Learning based pipeline hazardous prognostics methodology using discrete sensing data;
6) Intrinsically locatable pipe materials demonstration and field testing using representative pipe specimens with GPGPU acceleration.

Another equally important objective of this proposed research is to engage MS and PhD students who may later seek careers in this field by exposing them to subject matter common to pipeline safety challenges. Since the project being kicked off, three PhD students from both universities and several MS students have been recruited and trained through this CAAP program and apply their engineering disciplines to pipeline safety and integrity research. The PIs think the educational component is a very important part of the CAAP project and will integrate with research activities with various educational activities to prepare the next generation engineers for gas and pipeline industry. The educational and research impacts sponsored by CAAP has been recognized within the university (see *support letter 3 from Associate Vice Chancellor of university*) and nationally (Two current CAAP-funded students at CU haven been recognized at ASNT annual research symposiums in 2014 and 2015). Specific educational objectives and goals are:

1) Guide and train graduate students at University of Colorado-Denver and Michigan State University for the pipe integrity assessment and risk mitigation;
2) Integrate with existing mechanisms for undergraduate research at University of Colorado-Denver and Michigan State University for early exposure of pipe industry research to potential engineers;
3) Improve the current curriculum teaching at University of Colorado-Denver (ELEC5644 Nondestructive Evaluation and ELEC3817 Engineering Probability and Statistics) and Michigan State University (ECE802-1 Microwave and Millimeter Wave Circuits and ECE802-2 Electronic Systems Packaging) using the achievement from the proposed research;
4) Invite pipe industry expert (see support letters later in this proposal) to deliver seminar/workshops to undergraduate/graduate students about the challenges and opportunities in gas and pipeline industry;
5) Encourage the involved students to apply internships at DOT and industry to gain practical experiences for the potential technology transfer of the developed methodologies.

The above-mentioned goals and objectives of the proposed Competitive Academic Agreement Program (CAAP) project will be well addressed and supported by the proposed research tasks. Development, demonstrations and potential standardization to ensure the integrity of pipeline facilities will be carried out with the collaborative effort among different universities and our industry partners.

The quality of the research results will be overseen by the PIs and program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and presented papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and attending university-wide research symposium and workshop, e.g. RaCAS at CU-Denver. The proposed research involves pipeline industry to validate and demonstrate scientific results and quantify engineering principles by working closely with industry partners. They will also collaborate with the CAAP team on this research which may include but is not limited to information exchange, mutual meetings, providing CU and MSU with appropriate technical support for the target application.

(b) Status Update of Past Quarter Activities

Task 1 – On-tag Sensing and Signal Processing

A: Stress Sensor

Capacitive based pressure sensors are commonly used in detecting pressure or stress, which directly correlates the any changes in stress. This has been used as the basis of the research and a RF platform is designed to communicate with sensor passively. Another problem of sensor placement inside the pipeline is addressed in this work, which is eliminated by sensing the circumferential stress while installing the sensor on top of the pipe.

A capacitive sensor is designed for fixed installation onto the pipeline in a specific orientation with one fixed electrode shown in Fig.1 (cross-sectional view). At a high operating pressure, the pipelines expand normally outwards due to the axial and circumferential stress. The attached parallel plate capacitor can sense the expansion of the pipe as the separation between the electrodes changes with the pressure.

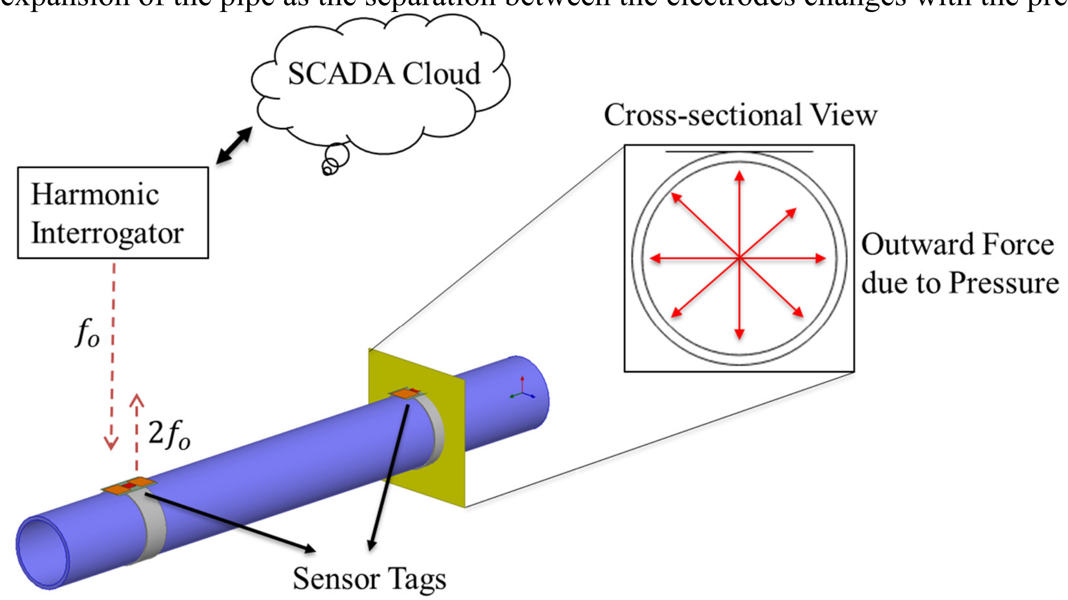


Fig. 1 RF Tag integration on pipeline with cross-sectional view

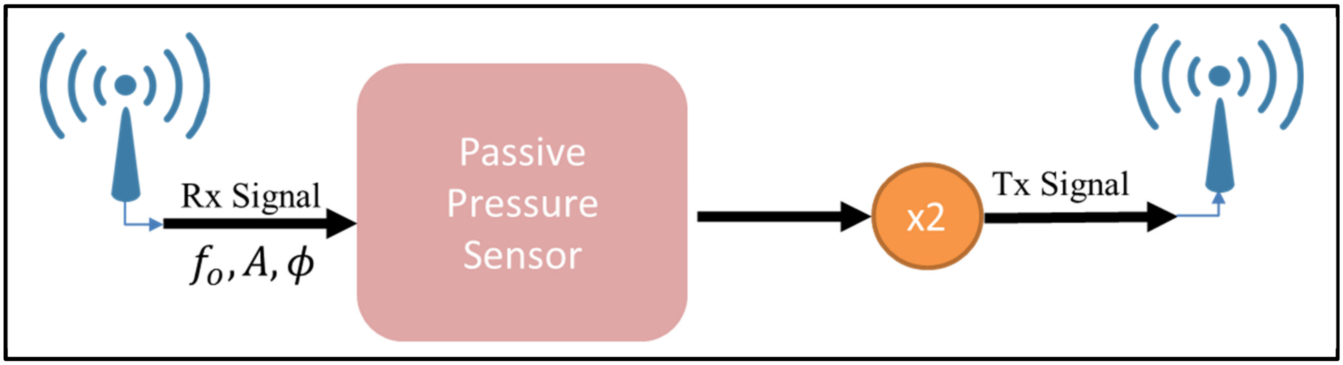
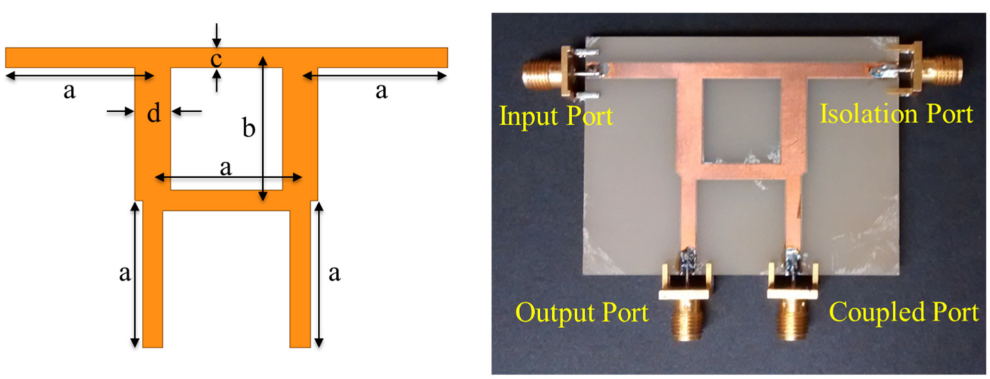


Fig.2 Schematic of integrated pressure sensor with RF Tag

The separation between capacitive plates is inversely proportional to the capacitance. The expansion of the pipeline highly depends over the material type and its expansion ratio. Two separate materials may deform differently at the same operating pressures. The resulting change in capacitance cannot be generalized with absolute stress; rather it gives the relative stress readings.

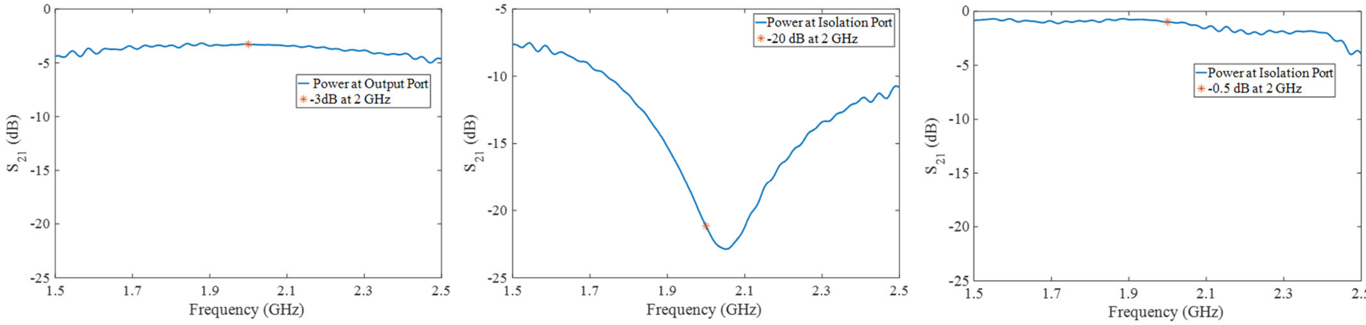
The passive wireless sensing can be achieved by transforming the capacitance into phase information using a hybrid coupler. The analog phase modulation over the carrier frequency can transmit the pressure information passively. The carrier frequency is generated by the interrogator and get to the hybrid coupler via receiving antenna connected with the sensor tag. The capacitive sensing element is connected to the output and coupled ports of the coupler. This would lead to sending all the input power to the isolation port due the total reflection of power at the two other ports because of the presence of only the purely reactive elements. The reactive elements or the capacitor affect the phase of the signal going out from the isolation port, which can be considered as the analog phase modulated signal. The output modulated signal is forwarded to the harmonic doubler for transmitting the pressure information back at twice the fundamental or carrier frequency. This technique of harmonic communication would eliminate the single frequency cluttering and increase the signal to noise ratio at the receiver.

A simple 90 degree phase shifting hybrid coupler is designed using ADS (Advanced Design System) for transforming the small change in capacitance into phase difference. The designed coupler is fabricated on a FR-4 board with 1.52 mm thickness.



Parameter	a	b	c	d
Dimensions (mm)	20.5	19.9	2.86	4.92

(a) Design and fabricated hybrid coupler



a b c

(b) Frequency response of hybrid coupler

Fig.3 Designed hybrid coupler and its response measured using VNA

The coupler is designed for operating at 2GHz fundamental frequency with -3dB coupling factor. Fig.3b-a&b confirms the design configuration with -3dB output power, -20dB isolation at 0 dB input reference and all other ports matched to 50 ohm loads. Fig.3b-c shows that all the power goes out from the isolation port if power-coupling ports are left open. The -0.5dB power decay is due to lossy conductor and dielectric.

A four port hybrid coupler is simulated in ADS for operating at a frequency of 2GHz. The output and the coupled ports are connected to the capacitor and the response is measured at the isolated port. The capacitor connected to the coupler is varied from 0.7pF to 1.3pF.

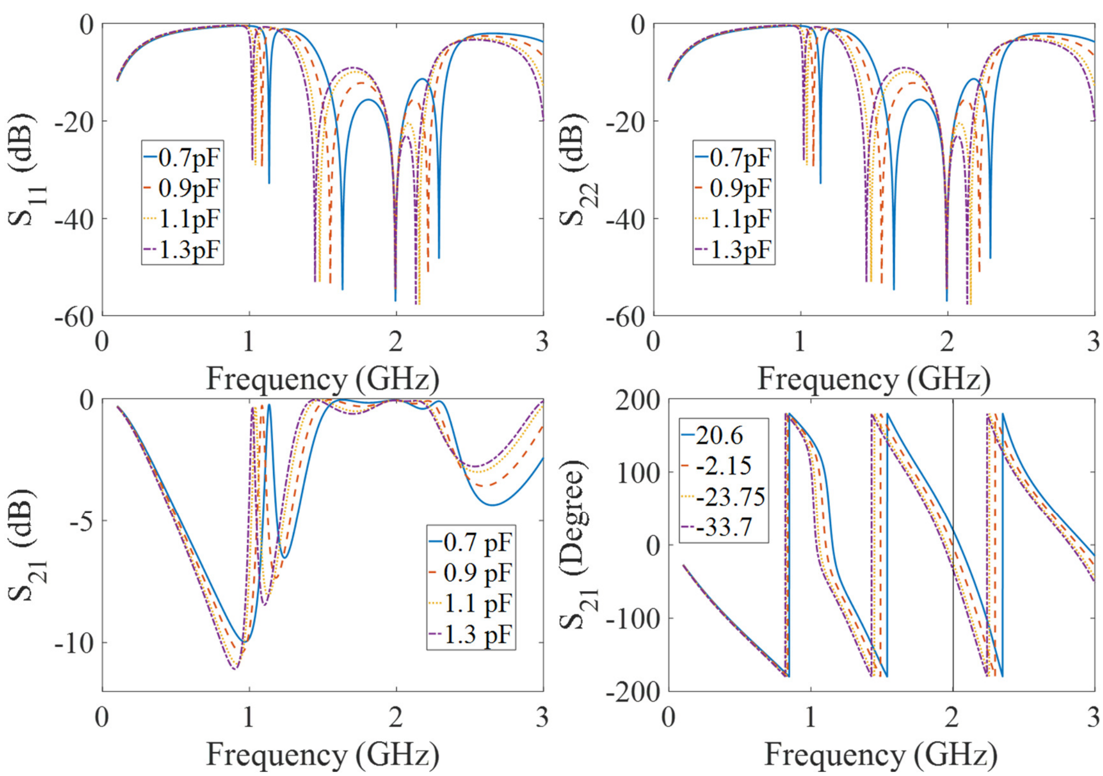
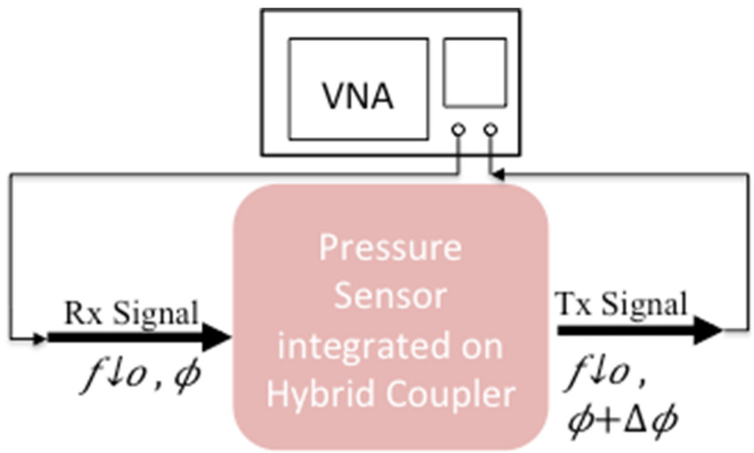
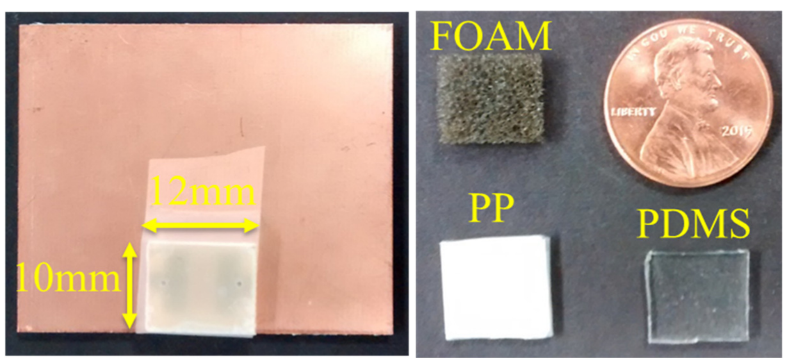


Fig.4 ADS simulation of capacitive based phase shifter

According to the simulation no changes are observed in power going into either of the ports (S11 and S22) or coming out of the ports (S21 or S12). The reflection coefficient at port 1 and 2 is observed to be very low and stay at resonance with changing capacitance. The transmission coefficient (S21= S12 due to reciprocity) observed to be high, which represents no or very minimal losses. The phase of S21 or transmitted signal has been changed at resonance. The phase is observed to be decreasing with the increase in capacitance. A small change in capacitance of 0.6 pF has led to the change of -55 degree in phase. The simulated results are shown in Fig.4.



(a)



(b)

Fig.5 Schematic of single frequency operated pressure sensor and different substrates used in capacitor

The capacitive sensing element is mounted onto the two ports of the hybrid coupler. The two remaining input and output ports are connected to VNA for verifying the phase response. The change in phase of the S21 (Transmission coefficient) is acquired. All three sensors are tested with the schematic shown in Fig.5a. The reflection coefficients of both ports are measured to be below -15dB over the complete range of pressure loadings. The phase of the transmission coefficient is acquired and shown in Fig.6, where (a) shows the relative phase change with each substrate while applying direct pressure on the sensor. The phase of the output signal decreases with the increase in capacitance as observed in the simulation. Different type of substrate dictates the rate of decrease in phase. The PDMS, PP and foam give a phase shift of -4.63, -2.23 and -27.72 degrees with the same amount of pressure respectively. Fig.6 (b), (c) and (d) shows the same phase shift but as a function of change in separation or displacement.

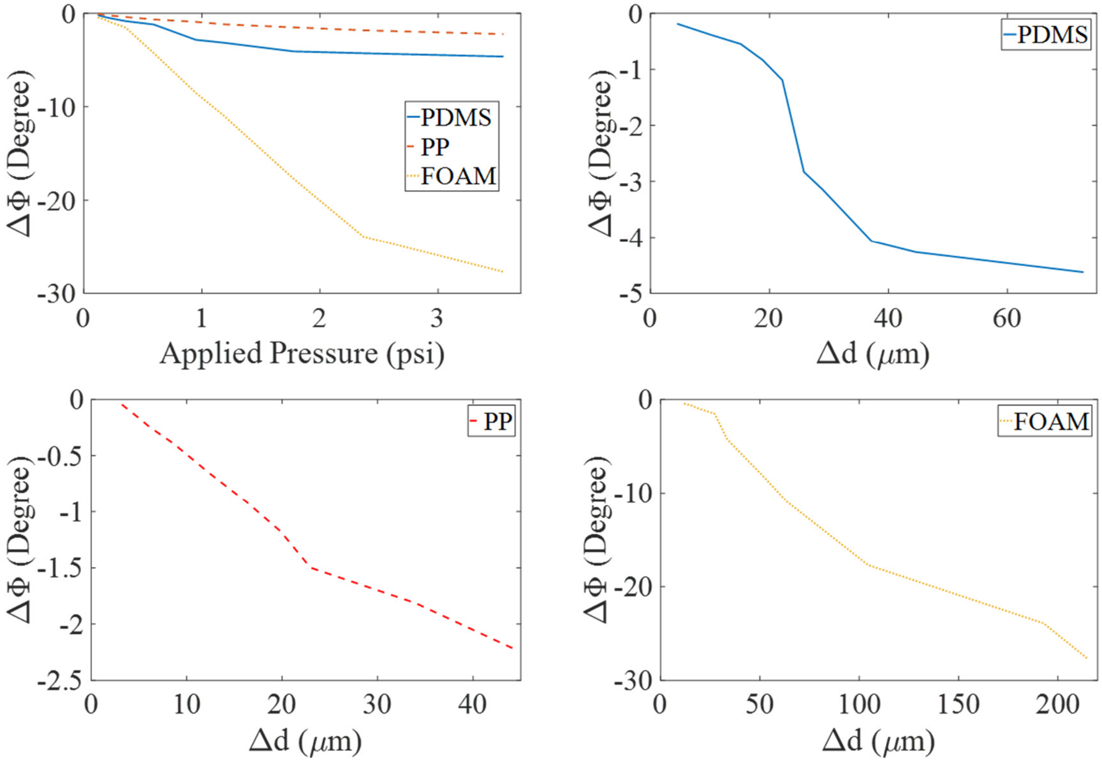


Fig. 6 Change in phase vs capacitor plate displacement due to applied stress

<u>Task 2 – Design and development of passive harmonic radar based smart RF tags</u>

A: Wide band antennas

Soil analysis was performed in earlier quarterly report to show soil dielectric property varies with different frequency and moisture content. When the antenna is buried underground, the surrounding soil medium changes the resonance frequency and impedance of the antenna. Hence, a narrow-band frequency antenna would not be appropriate for underground communication. A wide-band antenna was designed for two aspects 1) Multi-frequency phase estimation and 2) Proper functioning due to resonance frequency shift.

Two wide-band antennas for 430 MHz band and 860 MHz band were designed.

<u>860 MHz</u>

An 860 MHz bow-tie antenna was designed for wide band application. The schematic of the antenna is provided in Fig. 7.

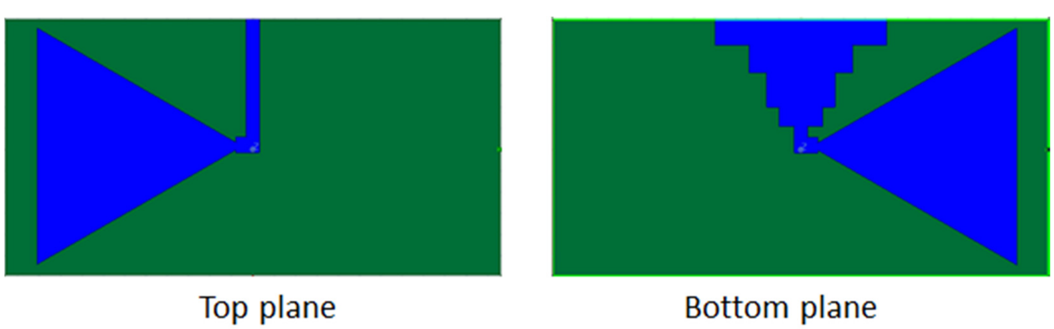


Fig. 7 Bow-tie antenna of 1) Top plane and 2) Bottom plane (Board size 60cm*116cm).

The antenna was fabricated on top of a Roger's 4350 board with thickness of 1.52 mm. The reflection coefficient of the antenna was measured in a VNA and the result is shown in Fig. 8.

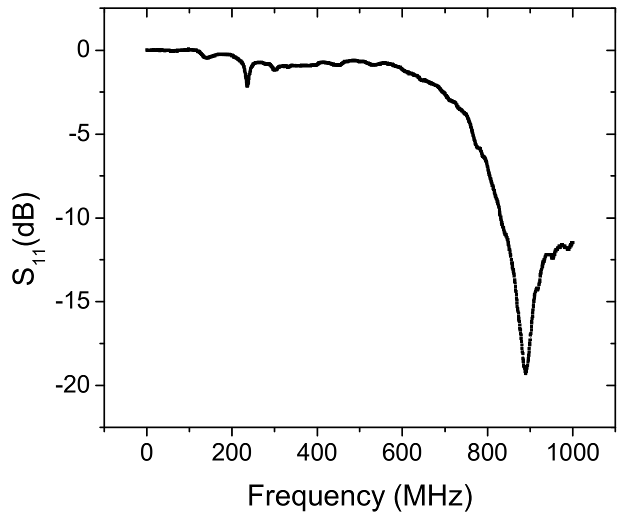


Fig. 8 Measured reflection co-efficient of the 860 MHz antenna (BW of 200 MHz).

430 MHz

Similarly for low frequency, a meandered bow-tie antenna was designed as shown in Fig. 9. The antenna size increases for low frequency operation. Meandered antennas are popular for their compact size. However, the bandwidth decreases due to meandering. The reflection co-efficient is plotted in Fig. 10 for the frequency band.

Fig. 9 Meandered bow-tie antenna of 1) Top plane and 2) Bottom plane (Board size 60cm*162cm).

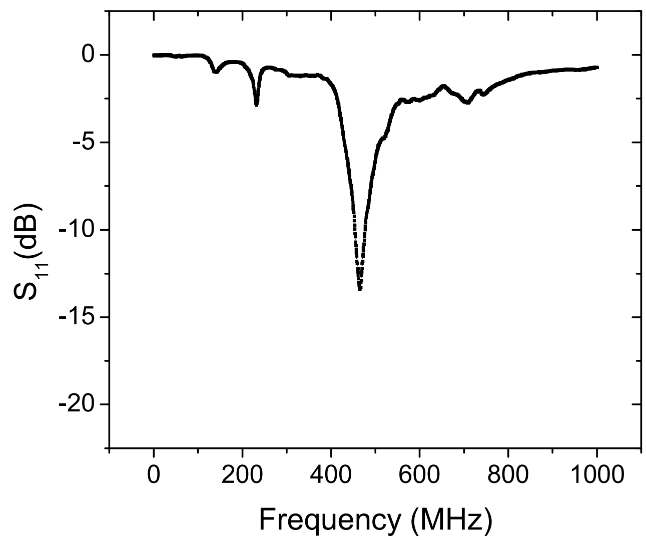


Fig. 10 Measured reflection co-efficient of the 430 MHz antenna (BW of 25 MHz)

B: Improved Read Range

The performance of the antenna changes with change in surrounding medium. The permittivity of the soil varies around 4 depending on the property and condition of soil (from very dry soil to saturated wet clay soil). The loss tangent of the soil also increases with increase in moisture content. The effect of soil on the antenna properties is simulated based on the data reported in quarterly report 7. The dataset is provided in Table 1.

Table 1. Dielectric properties of soil

ε_r' (Dry)	ε_r'' (Dry)	ε_r' (2.3% moisture)	ε_r'' (2.3% moisture)	ε_r' (4.6% moisture)	ε_r'' (4.6% moisture)	ε_r' (6.9% moisture)	ε_r'' (6.9% moisture)
2.9625	0.12325	3.195	0.2305	3.4975	0.297	3.985	0.40975

The reflection co-efficient and the input impedance of the wide-band antenna were simulated for different permittivity of the soil as shown in Table 1. As expected, the resonance frequency decreased with higher moisture content in soil. Simultaneously, the quality factor of the antenna response reduced with increased loss tangent.

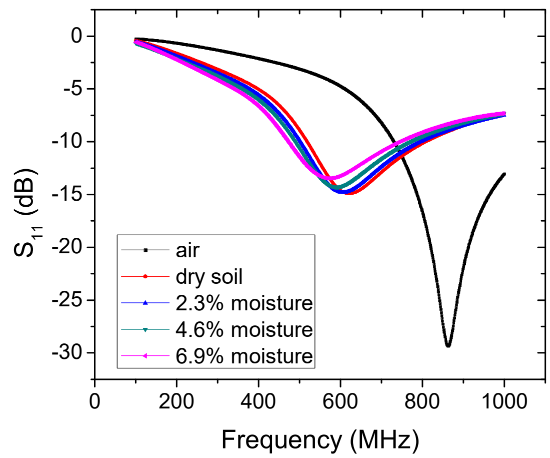


Fig. 11 Reflection coefficient change in air and soil with different moisture contents.

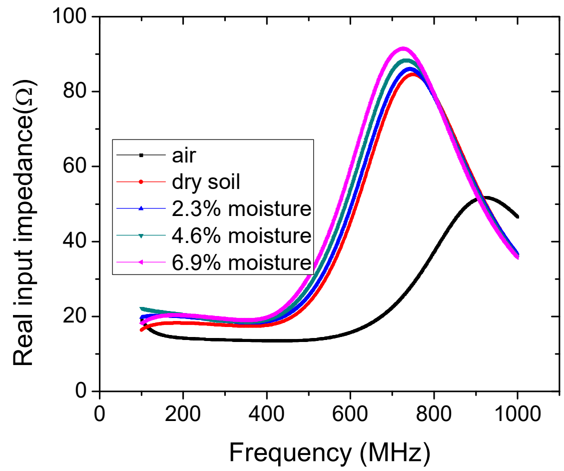


Fig. 12 Real input impedance change in air and soil with different moisture contents.

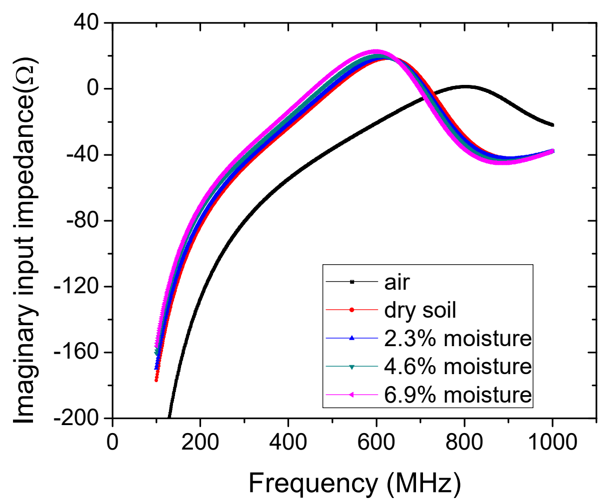


Fig. 13 Imaginary input impedance change in air and soil with different moisture contents.

(c) Planned Activities for the Next Quarters

Besides the planned activities mentioned in section (b), here is the future work for the next quarter:

ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- Antenna integration with sensing platform
- Multiple Tag Detection and Data Processing
- Numerical model of data analysis

NEW PASSIVE RFID TAG DESIGN:

- Develop the wide-band antenna operable in different soil condition
- Testing of the designed antenna under soil
- Develop the phase estimation technique using the wide-band antennas