CAAP Quarterly Report

Date of Report: *April 10, 2017*

Contract Number: *DTPH5614HCAP04*

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

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

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For quarterly period ending: *April 10, 2017*

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

<u>Task 1 – On-tag Sensing and Signal Processing</u>

A: Stress Sensor

Feroelectret Nano-Generator (FENG) is a flexible thin film nano-generator base on polypropylene ferroelectret with harvest mechanical energy. FENG's are flexible and highly efficient that shows portability and promise applicability to any surface. The deposited silver on both sides polypropylene thin film acts as electrodes and the film induce charge of opposite polarity in each electrode.

By applying mechanical stress, the internal voids change their thickness and resulting change in dipole moment drives the electrons from –ve electrode to +ve electrode. As shown in Fig.1 the continuous pressing and releasing generates potential change across two electrodes.

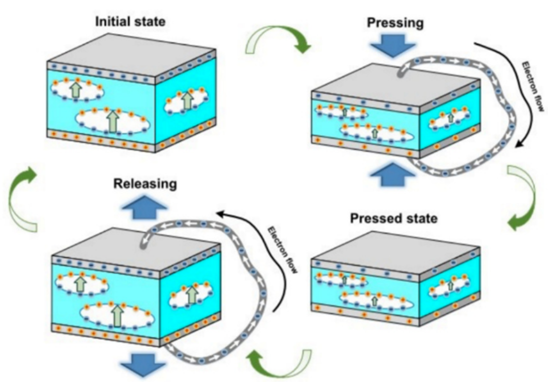

Fig.1 Working principle of FENG

The developed polypropylene thin film sandwiched between two silver electrodes shown in Fig.2 (a) and a protective layer is built over it shown in Fig. 2 (b).

Underground pipes are always under continuous stress and even if there is any change in stress that can rupture the pipe is develop with time. So the change in stress is very slow and FENG couldn't be used as generator over pipe. But the external constant stress changes some properties of polypropylene thin film. The changes are in internal void size that are responsible for the impedance of the device.

FENG has a high internal impedance, as it generates very high voltage peaks with low current value.

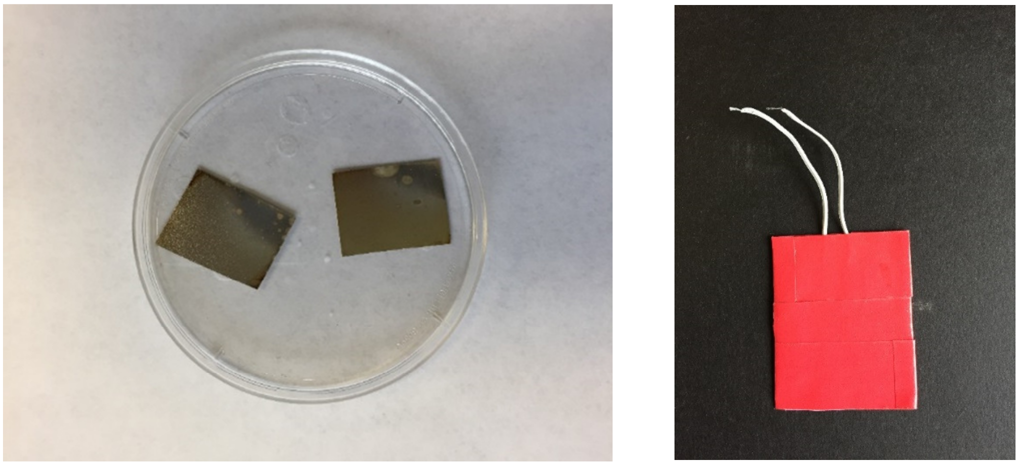

Fig.2 (a) Develeoped FENG in lab environment (b) FENG with a protective layer

The changes in internal impedance of FENG have been observed with external stress. Stress has been applied using a stepper motor shown in Fig.3. The changes in before and after applied stress are recorded shown in Fig.4.

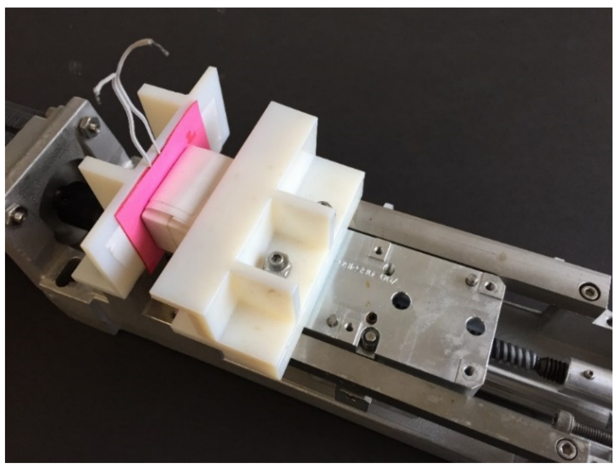

Fig.3 Applied Stress using Stepper motor

Different frequency range shows different impedance measure. The measured response from 20-30 MHz shows consistency over many trials as well as similarity between different sensors. The more impedance has been noticed with the operation at lower frequency.

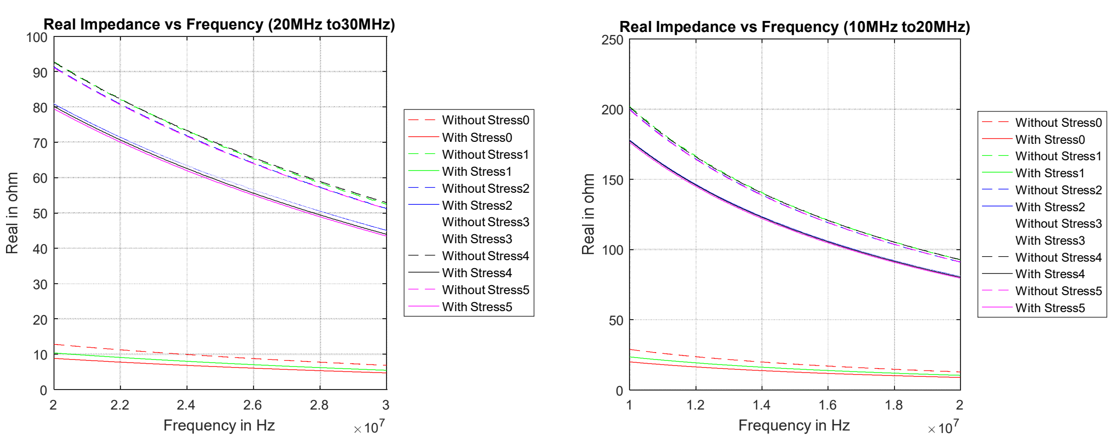

Fig.4 Impedance change with applied stress

The impedance changes with stress, a quantitative response is shown in Fig.5. The linear increment in stress has corresponding decrement in impedance. The stress and impedance relation has been followed at both lower and higher frequency ranges.

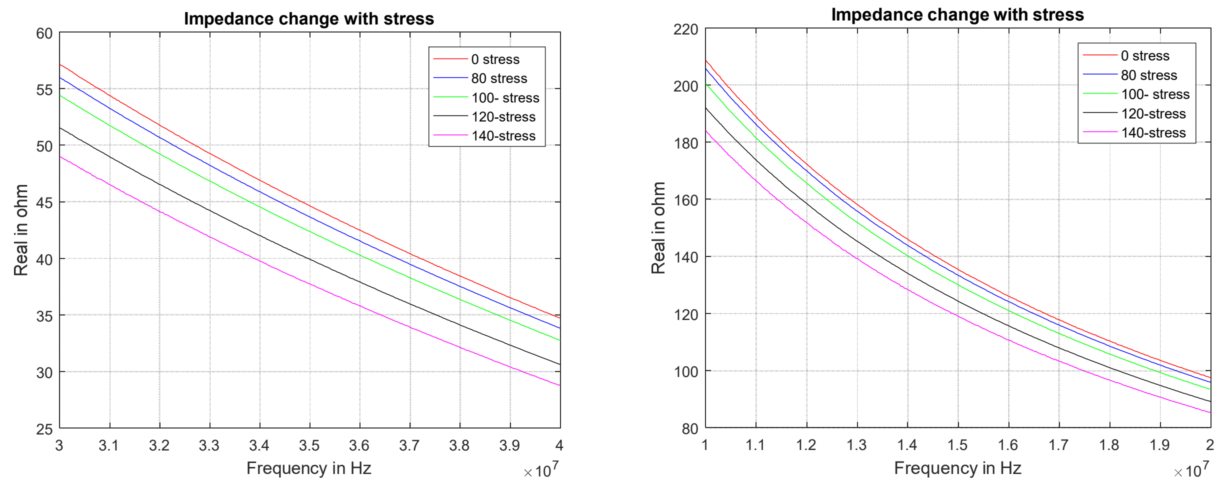

Fig.5 Impedance decreases with increse in stress

The units of above shown stress is a single step of stepper motor. The additional stress from 80 units to 100 units makes a little change in impedance at higher frequency. But for the same stress change at lower frequencies shows larger change in impedance, shown in Fig.6 and Table.1.

The current target is to increase the operation frequency to 500 MHz by keeping the stress resolution as the sensor shows at lower frequency. It would be easier to power the stress sensor using antenna's operational frequency and eliminates the requirement of additional RF source.

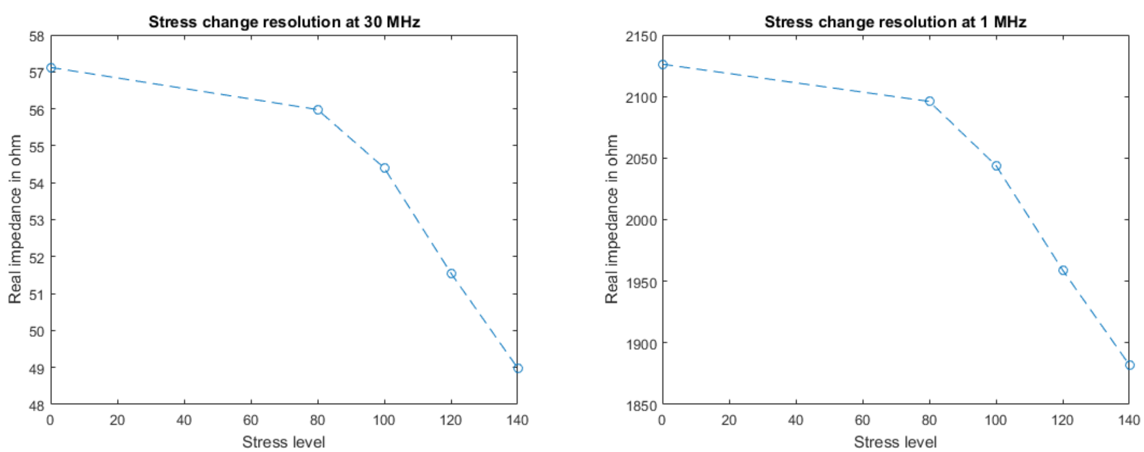

Fig.6 Resolution increases with operation at lower frequencies

	80 to 100	100 to 120	120 to 140
@ 30 MHz	1.58	2.85	2.57
@ 1 MHz	46	85	77

Table.1 Resolution comparison at lower and higher frequency

B: Depth Estimation

The concept of depth estimation have been demonstrated in last quarter report. The experimental setup for capturing phase information has been changed to get better accuracy. According to the last report, we could estimate the separation between source and target with an error of 27% in a meter. The 27% error margin in a meter is not so good for practical use. So the new idea is built upon previous method to estimate the depth or separation more accurately.

For a specific separation (*r*), signal at multiple frequencies needs to be transmitted and received. The received signals have a different corresponding phase. The separation can be defined as follows using the signal parameters.

$$r = n_i\lambda_i + \phi_i^\lambda + \delta_i^\lambda$$

Where,
r , is the depth needs to be estimated
$n_i\lambda_i$, is the number of wavelengths for i^{th} corresponding frequency
ϕ_i^λ , is measured phase in unit of wavelength
δ_i^λ, noise in system

The above equation would be true for all frequencies. In the above equation wavelength (λ_i), measured phase (ϕ_i^λ) are known, number of wavelength (n_i) can have a bound according to the largest distance needs to be measured and noise (δ_i^λ) also has a bound of $\pm$ 15°. The only unknown parameter is separation (*r*) can be found by solving the following minimization problem for n_i and δ_i^λ.

$$\underset{n}{\arg\min} \sum_{i=1}^{m-1} \left| \left(n_m\lambda_m + \phi_m^\lambda + \delta_m^\lambda\right) - \left(n_i\lambda_i + \phi_i^\lambda + \delta_i^\lambda\right) \right|$$

The above equation finds a combination of *n*'s for with all the constraints over n_i and δ_i^λ are satisfied. An ideal situation with no noise has been generated to test the developed algorithm. The phase of the received signal is shown in Fig.7 after multiple distances.

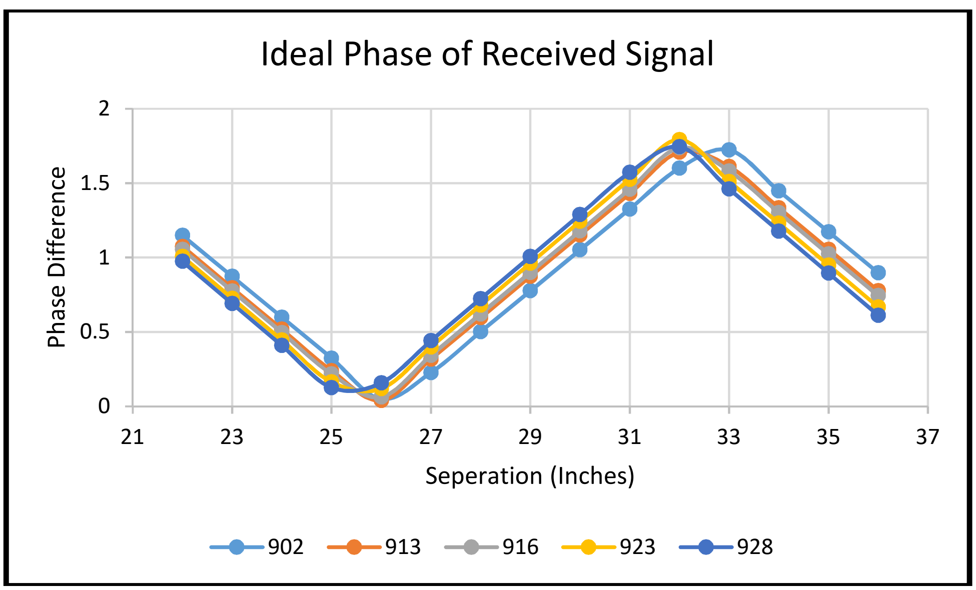

Fig.7 Ideal Data

According to above mentioned ideal data, the estimated distance was a perfect match. For all shown distances with a separation of an inch are estimated correctly. It proves that the developed algorithm is working correctly. Now it's time to test the new method over real measured data. Fig.8, shows the measured phase at the corresponding distance. The phases are shifted by the RF devices like directional coupler, transmitting antenna, receiving antenna and transmission lines.

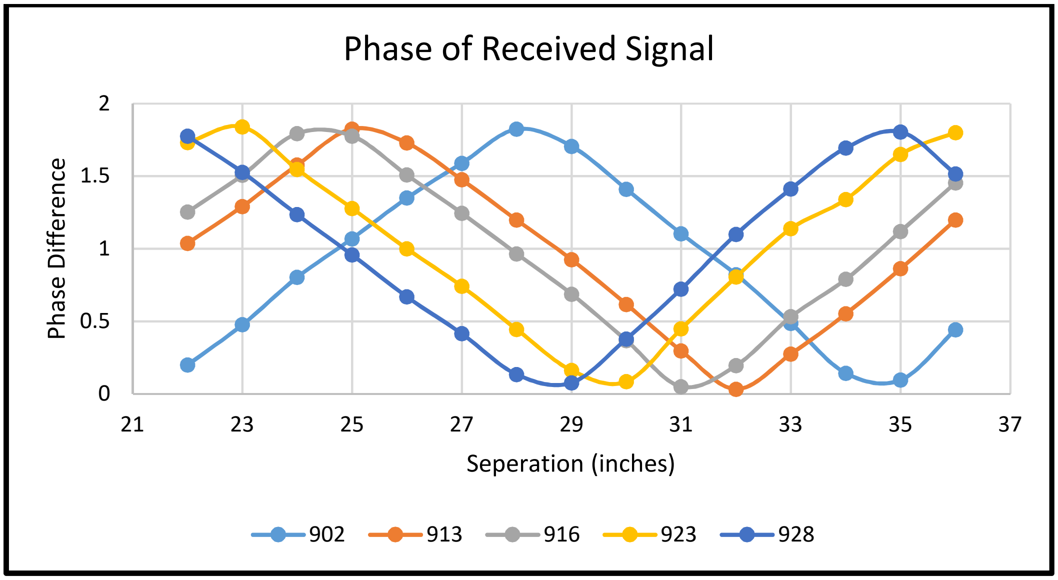

Fig. 8 Measured Data

For each frequency there is a respective phase shift, which needs to be referenced out before estimating the distance. The phase can be referenced out by comparing the readings in ideal situation and measured phase. After correcting the phase shift in data, the received phase signal is shown in Fig.9.

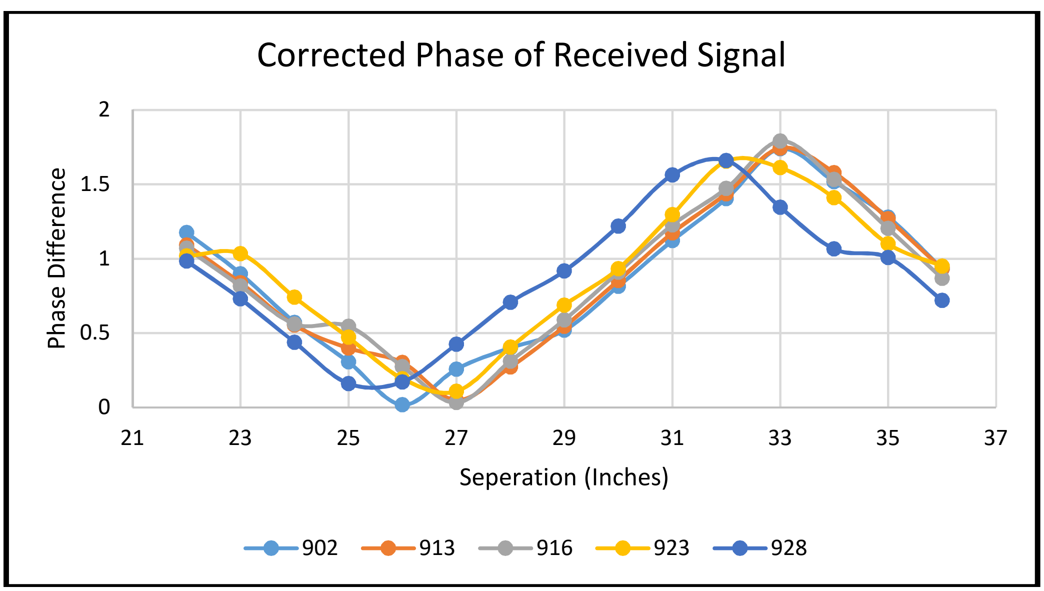

Fig. 9 Corrected phase from reference

Feeding the above phase information into depth estimating algorithm give the results shown in Table.2.

Actual	Estimated	Error
Inches	Inches	(%)
24.0	24.4	1.7
26.0	26.88	3.4
30.0	29.07	3.1
34.0	33.49	1.5
36.0	36.68	1.9

Table.2 Estimated Distance with error margin

It can be seen in above table that the error margin of 27% ha come down to $\pm$ 3%. The method can locate the target within few inches.

The next step towards depth estimation is to make the system wireless. A block diagram is presented in Fig.10 to estimate the separation between RFID transponder and tag. An additional phase shifter is needed to eliminate the phase anomaly out of mixer. A frequency doubler is required to match the reflected frequency for phase measurement.

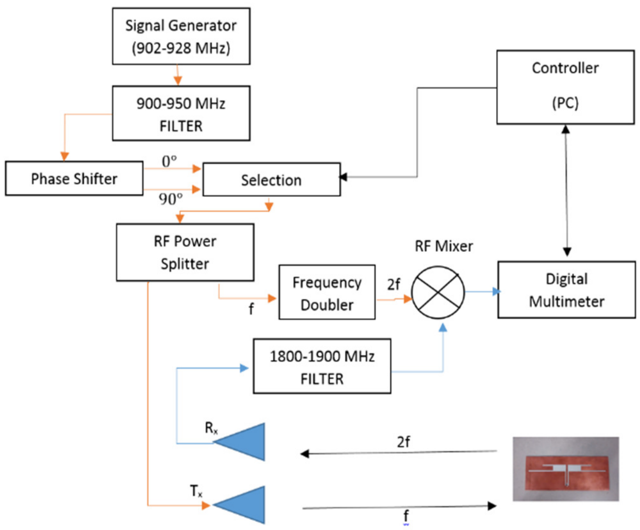

Fig. 10 Improved experimental setup for wireless communication

Task 2 – Design and development of passive harmonic radar based smart RF tags

A: Development of Non-linear Transmission Line (NLTL) based tag

As the path loss in soil is high, a high efficiency harmonic tag capable of operating at low input power is desired for underground pipe sensing. In our last quarterly report, we found that the varactor diode based harmonic tags perform efficiently at low input power compared to schottky diode based tags. During this reporting period, we examined the following issues 1) Improve the efficiency of the existing tag, 2) Power harvest to bias the tag, 3) Design and integrate antennas for the receiving and transmitting signals at the tag.

To improve the efficiency even better, we have developed a Non-linear Transmission Line (NLTL) based tag, which is nothing but multiple varactor diodes connected with inductors along a chain as shown in Fig. 11. It was found that the harmonic power increases with more number of NLTL stages. More importantly, the NLTL based tag provides a good impedance match at low frequency operation. Low frequency (<500 MHz) operation is desired because the signal experiences relatively small attenuation in soil compared to high frequency signal. However, the dc biasing is one drawback of the

NLTL. This problem was solved by implementing an energy harvesting unit along with the tag. A two stage Dickson charge pump circuit is implemented to convert the RF interrogation power into DC biasing. It can be verified from Fig. 13 that the charge pump circuit can work at very low input power (<-20 dBm).

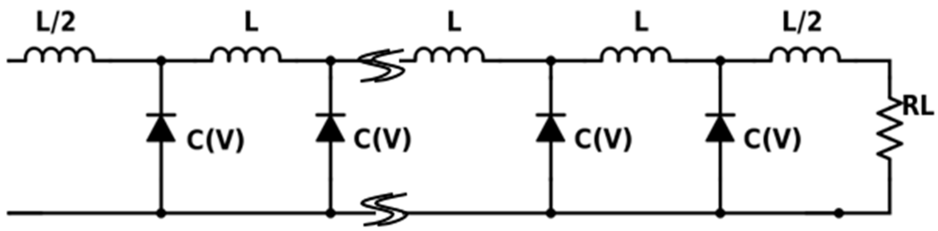

Fig.11 Nonlinear transmission line (NLTL) realization with discrete components and load termination.

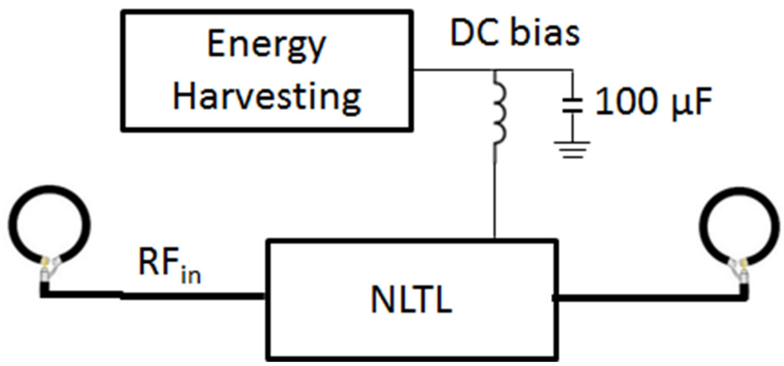

Fig. 12 Complete tag circuit with integrated antenna.

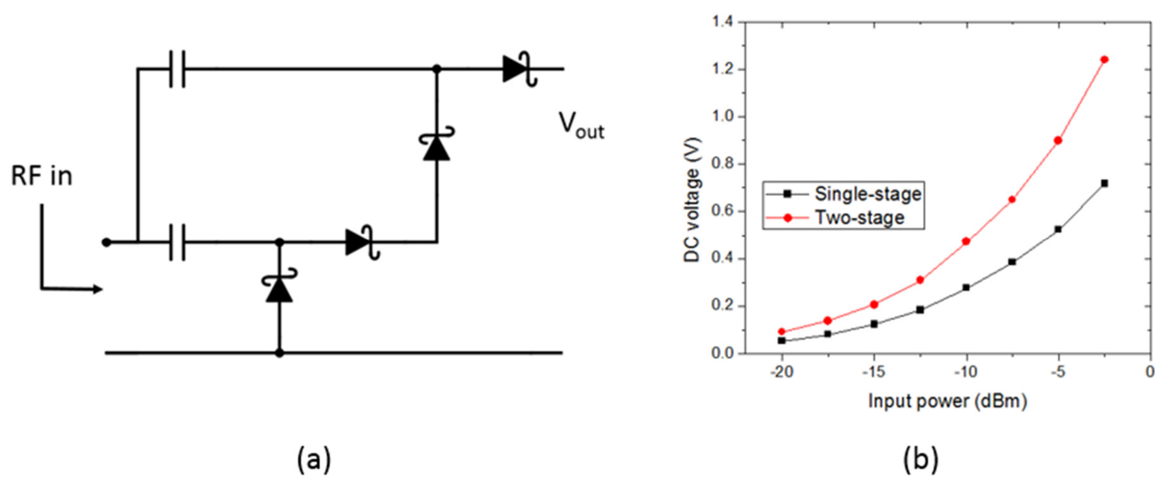

Fig.13 (a) A two stage Dickson charge pump circuit and (d) Converted DC voltage for different number of stages.

The number of varactor diodes in the NLTL are important because the efficiency is a strong function of the number of stages being used. NLTL tags were made with different number of varactor diodes and the harmonic contents were observed. Three different NLTL circuits were excited at 100 MHz and -10 dBm input signal. After measurement, the 2nd harmonic power for the six stage NLTL was found better by around 10 dB compared to single stage NLTL as shown in Fig. 14.

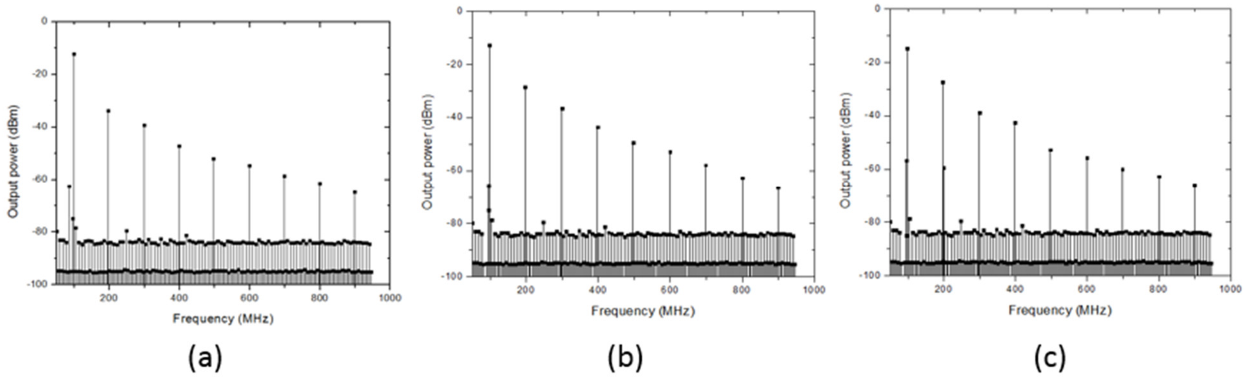

Fig.14 Harmonic power contents for different number of stages (a) Single, (b) Three and (c) Six of varactor diodes at input signal of 100 MHz of power -10 dBm.

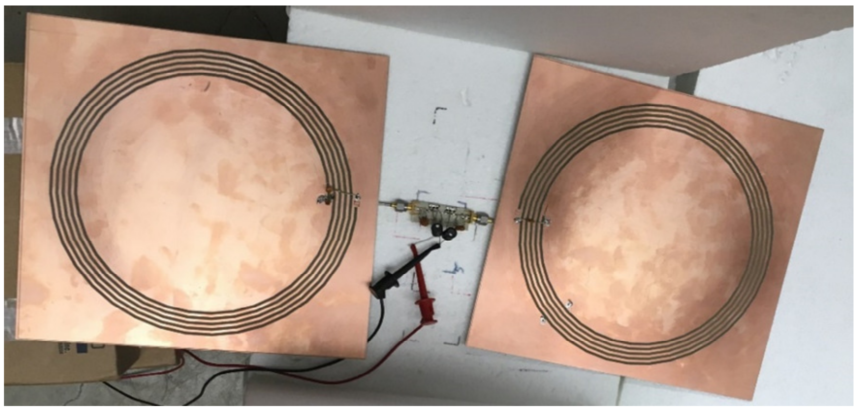

Fig.15 The fabricated NLTL tag with planar loop antennas

The tag was tested at input operating frequency of 450-500 MHz and it was capable of transmitting power back at 900-1000 MHz. The transmitted power was kept at 15 dBm and the received power was -65 dBm at air distance of 45 inches.

Fig.16 The measurement setup of the NLTL based tag.

(c) Planned Activities for the Next Quarters

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

<u>CU: ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:</u>

- Integration of stress sensor with harmonic RFID tag
- Operate the stress sensor at higher frequencies
- Depth estimation of a an harmonic tag
- Detection of multiple tags

<u>MSU: NEW PASSIVE RFID TAG DESIGN:</u>

- Miniaturize the antenna size for the desired frequencies
- Develop the harmonic reader for the underground pipe depth sensing
- Power budget analysis in soil medium for different moisture content and operating frequencies