CAAP Quarterly Report

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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, 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

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

A: Wireless Stress Sensor

An interrogator is designed by applying some changes in wired harmonic phase measurement system shown in previous quarter to wirelessly transmit the power or signal to the remote sensor tag, which consist of two transmitting and receiving antennas. VNA is used as the power source and the phase detector as in previous setup. The output of the splitter (+7dBm) is connected to a Vivaldi antenna with linear vertical polarization for transmitting at 2 GHz. The sensor tag is placed 12 inches (1-ft) away from the interrogator and receives -10dBm input power. The received signal is forwarded to the coupler for phase change and the harmonic doubler. The harmonic doubler gives an output of -38dBm at 4 GHz with -10dBm as input at 2 GHz. The phase shifted, frequency doubled signal is transmitted back to interrogator using designed planar antenna with linear horizontal polarization. The received signal at the interrogator has a very low power strength (-60dBm), which is amplified to -18dBm using low noise amplifiers. The amplified signal (4 GHz) is mixed with the reference signal (2 GHz) and the phase change in output signal is acquired. The schematic of interrogator is shown in Fig. 1 with image of the wireless phase measurement setup.

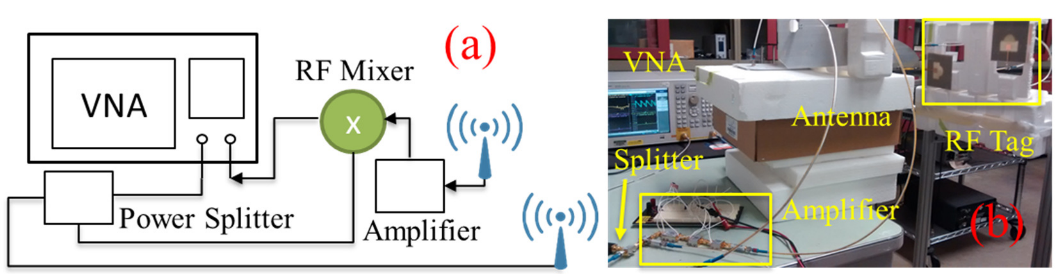

Fig.1 (a) Schematic and image of the Wireless phase interrogator and (b) Wireless Setup

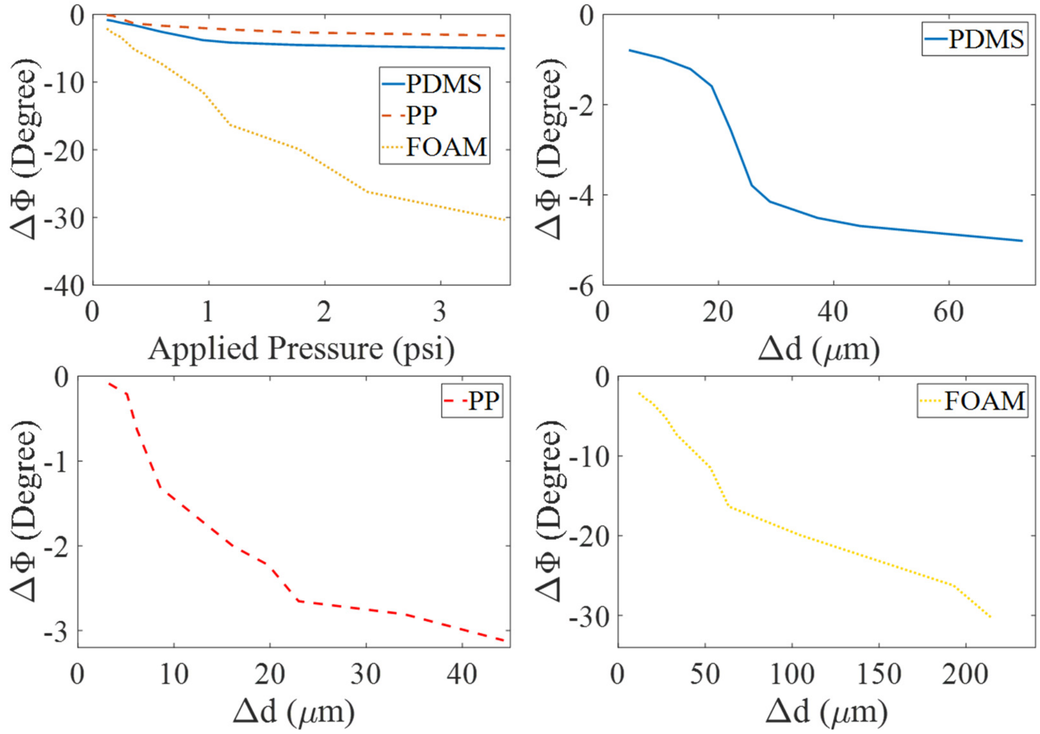

Fig.2 Measured change in phase due to separation (a) sensor with PDMS substrate, (b) sensor with PP substrate, (c) sensor with foam substrate

The acquired phase of the wirelessly received signal is shown in Fig. 2, where (a) represents a relative relation in behavior of different substrate materials at same amount of applied pressure. Fig 2 (b), (c) and (d) represents the phase change in PDMS, PP and foam w.r.t. change in separation of the electrodes. The wireless phase measurements are in complete agreement with the wired dataset, which shows the potential and novelty of the work. The phase changes in wired harmonic setup were comparatively larger than the wirelessly acquired data that may be due to the smaller power level of the harmonic signal going into RF mixer. Another stage of amplification of the received signal is required for larger changes in phase and operating the RF mixer in efficient region.

B: Pipeline Prognostics

Pipelines are the primary means of transportation for natural oil and gas. The widespread industrial applications and common households need of these natural resources leads to a huge pipeline infrastructure. The buried and surface pipelines (gathering, transmission, and distribution) are primarily made from steel, polymers and composites. Each material has its own advantages like high strength, light weight, corrosion resistance, etc. Despite all these advantages, there are several issues that get associated during the manufacturing, installation and operation, hence it requires a routine maintenance and replacement for avoiding any failure or complete shutdown. The minor manufacturing defects are inevitable and may evolve during operation and grows rapidly due to cyclic pressurization.

Fig.3 shows the health degradation of a pipeline over time. The current health can be quantitatively measured using the distributed sensor network or structural health monitoring techniques installed over the pipeline infrastructure. The proper maintenance according to the sensor data can extend the usable life or the number of operation cycles.

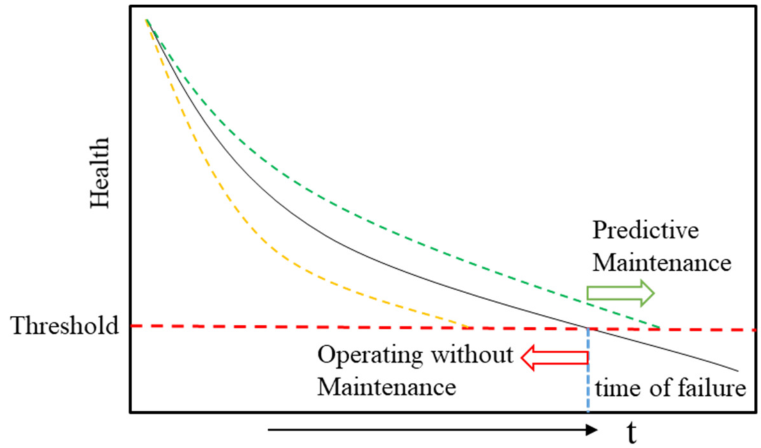

Fig.3 Health degradation of a pipeline with time and effects of maintenance

Predictive maintenance can be a tool for efficiently managing and mitigating the potential risks of failures. But predicting a failure is still a challenging task due to involved uncertainties in the system. For example, the environmental conditions, heat cycles, variable pressure range, data inaccuracy, device error, etc. are critical parameters for prognostics methods.
The goal of damage prognosis is to construct the damage growth curve or estimate function f which maps health index (y) computed from NDE measurements for every time instants (or loading cycle) x at which NDE is performed.

$$\boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x}(\mathbf{1}:\boldsymbol{k}); \boldsymbol{\theta}) \quad \textbf{(1)}$$

f is a generalized damage growth model described by parameters θ. Using estimated values of θ, future health indices $\hat{y}$ are predicted upto time X_{th} when the system reaches its failure threshold Y_{th} or when the system is expected to fail. This information is generally obtained from domain experts.

$$\hat{\boldsymbol{y}} = \boldsymbol{f}(\boldsymbol{x}(\boldsymbol{k}+\mathbf{1}:\boldsymbol{X}_{\boldsymbol{th}}); \hat{\boldsymbol{\theta}}) \quad \textbf{(2)}$$

For pipeline inspection, information from sensor data measuring the pressure can be used to predict change in general health of the structure which may include both crack initiation and crack propagation in the pipeline geometry. Accurate prediction can be achieved by implementing Bayes inference on measurements data acquired at periodic intervals of time using appropriate damage growth models which may be obtained through numerical modeling of cracks in pipeline geometry or through experimental failure testing of the structures.

Theory of Bayes Inference

Bayes inference [1] is widely used for estimation of damage-growth function parameters $\hat{\theta}$ which derives the posterior distribution by updating an initial prior estimate combined with information obtained from new measurements, according to equations (3) - (7).

$$\boldsymbol{f}_{Y,\Theta}(\boldsymbol{y}, \boldsymbol{\theta}) = \boldsymbol{f}_{Y|\Theta}(\boldsymbol{y}|\boldsymbol{\theta})\boldsymbol{f}_{\Theta}(\boldsymbol{\theta}) \quad \textbf{(3)}$$

$$\boldsymbol{f}_{Y}(\boldsymbol{y}) = \int_{\Omega} \boldsymbol{f}_{Y,\Theta}(\boldsymbol{y}, \boldsymbol{\theta})\boldsymbol{d\theta} = \int_{\Omega} \boldsymbol{f}_{Y|\Theta}(\boldsymbol{y}|\boldsymbol{\theta})\boldsymbol{f}_{\Theta}(\boldsymbol{\theta})\boldsymbol{d\theta} \quad \textbf{(4)}$$

$$\boldsymbol{f}_{Y|\Theta}(\boldsymbol{y}|\boldsymbol{\theta}) = \frac{\boldsymbol{f}_{Y,\Theta}(\boldsymbol{y}, \boldsymbol{\theta})}{\boldsymbol{f}_{Y}(\boldsymbol{y})} = \frac{\boldsymbol{f}_{Y|\Theta}(\boldsymbol{y}|\boldsymbol{\theta})\boldsymbol{f}_{\Theta}(\boldsymbol{\theta})}{\boldsymbol{f}_{Y}(\boldsymbol{y})} \quad \textbf{(5)}$$

$$E\left[\left(\hat{\theta}(y)-\theta\right)^2\right] = \int_{-\infty}^{\infty}\int_{\Omega}\left(\hat{\theta}(y)-\theta\right)^2 f_{Y,\Theta}(y,\theta)\,dy\,d\theta \tag{6}$$

$$E\left[\left(\hat{\theta}(y)-\theta\right)^2\right] = \int_{-\infty}^{\infty} f_Y(y)\left[\int_{\Omega}\left(\hat{\theta}(y)-\theta\right)^2 f_{\Theta|Y}(\theta|y)\,d\theta\right]dy \tag{7}$$

For complex damage growth functions, it is non-trivial to solve equation (7) analytically. Approximate solution of Bayes inference or $E(\theta|Y)$can be achieved by Kalman filtering [2] for linear systems with Gaussian noise. However for non-linear systems, particle filtering [3] is a more suitable approach. Apart from computational ease, particle filtering approach can be implemented in systems with non-Gaussian noise as well [4].

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

After investigating with existing and new architectures of harmonic tag design over the last quarters, the key factors of the harmonic tag design are identified as:

1) The tag should be very efficient in producing harmonics at low input power.
2) The antenna should be wide band to operate effectively under different soil condition.
3) The tag should be compatible with the manufacturing process of the pipe.

Different type of harmonic generators such as 1) Schottky diode based harmonic generator and 2) Non-linear Transmission Line (NLTL) based harmonic generator were investigated. It was found and reported earlier that the Schottky diode based harmonic generator works better at comparatively high input power (> -5 dBm). For underground application, the received input power would be very low (< -10 dBm). Hence, Schottky diode based harmonic generators are not a good choice for underground application. A discrete component NLTL based harmonic generator was proposed earlier for the underground application. However, the NLTL needs a DC bias for effective harmonic generation. Hence, the harmonic generator requires an energy harvesting circuit, which can provide bias to the NLTL. Until last report no energy harvesting scheme was shown. A complete design of energy harvester and NLTL is proposed and shown for the final tag circuit design.

Proposed Tag Circuit

The NLTL based harmonic generator circuit is presented as explained before. The harmonic generator consists of 1) A NLTL and 2) An energy harvesting Circuit. The design and performance of the NLTL was shown in previous report. The energy harvester performance would be demonstrated in detail here. The integrated performance of the Energy harvester along with the NLTL would be demonstrated finally. The energy is harvested by converting a part of RF input signal into DC power. Commonly rectifier circuits are used for the RF to DC conversion. However, the harvested voltage by a single diode is not enough to drive the DC circuit. Hence, multiple diodes were used in a Dickson charge pump configuration to drive the whole circuit. A 1.8 V DC voltage regulator was used to maintain the voltage at a fixed reference. The DC bias was used to create a 0.6 V reference suitable for driving the NLTL circuit. The schematic design of the circuit is shown in Fig.4 below.

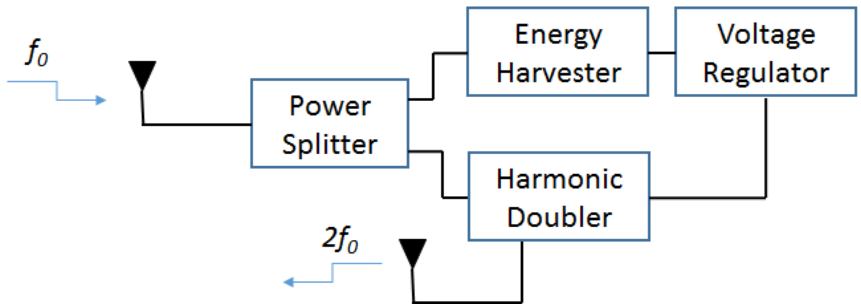

Fig.4 Schematic of the harmonic doubler

Once the circuit is designed, it is integrated on top of PCB. The photograph of different fabricated components is shown in Fig. 5. The power splitter divides the incoming signal into two different parts: 1) The first part is harvested in the Energy Harvester and DC bias is produced, 2) The second part is used in the harmonic generator to produce the second harmonic signal. After different components of the tag circuit were designed, the complete tag performance was measured. Fundamental input signal was fed into the tag and the output harmonic power was measured.

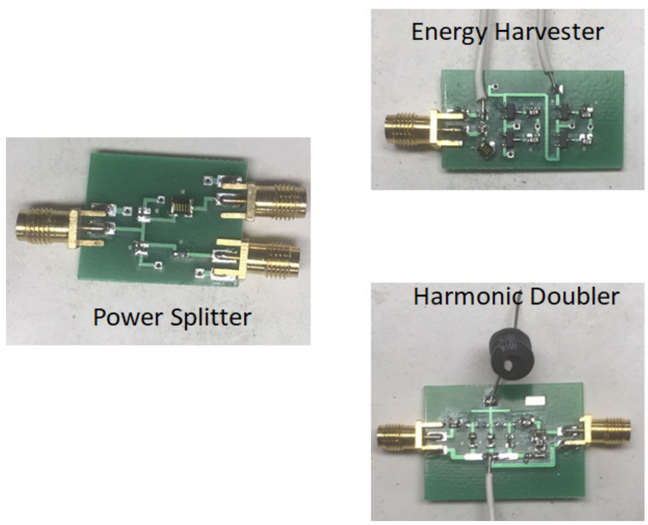

Fig.5 Integration of different components of complete tag design

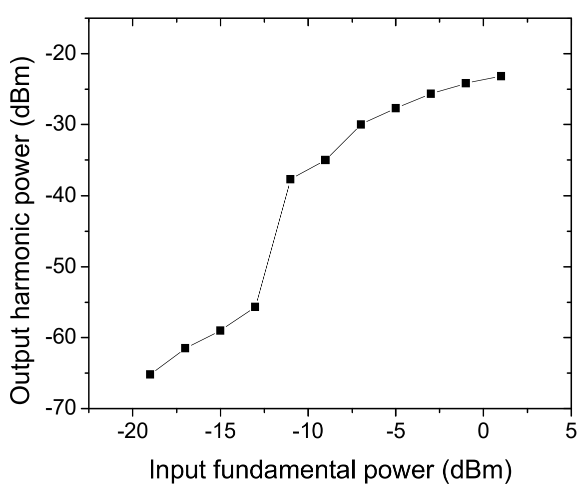

Fig.6 Measured results of harmonic power for different input power at 440 MHz

The measurement result is presented in Fig.6 for the complete tag circuit. The tag circuit performances well until the input power is -11 dBm without any external DC bias under direct probing. The efficiency falls below this input power primarily falls because the voltage regulator cannot regulate the required DC voltage level. An alternate energy source can be integrated with the design for better performance even at low input power of -20 dbm. The tag circuit is developed separate from the antenna, so that the antenna can be post integrated depending on applications with the pipe using a long range additive manufacturing process.

Proposed Antenna

The antenna has to be wide band in nature to operate efficiently underground. The free space antenna design won't work underground because the ground material would load the antenna and change its properties. Hence, a wideband antenna was required working at different soil permittivity from 4.4 to 20. The proposed harmonic antenna is shown in Fig.7 with its reflection co-efficient in the soil medium for a 100 Ω load impedance.

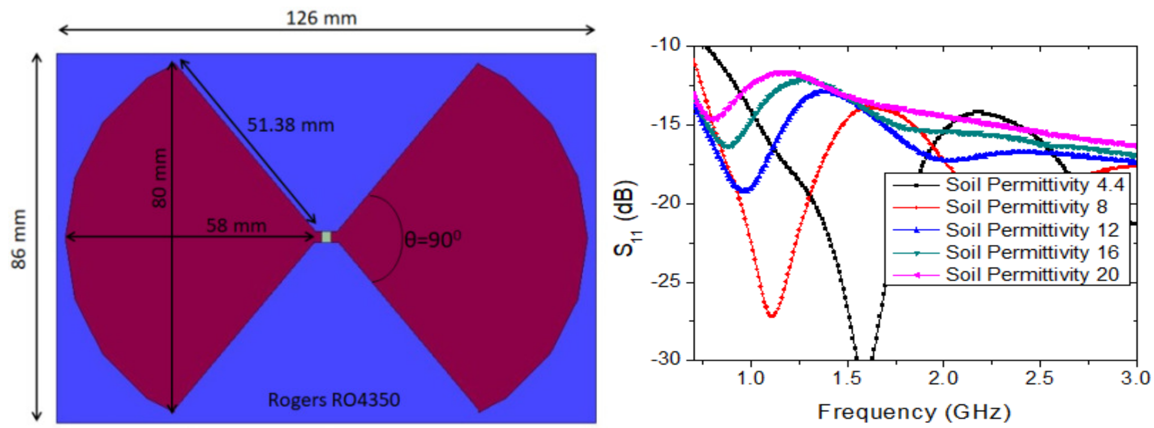

Fig.7 The wideband bow-tie antenna with its simulated reflection co-efficient

Proposed Reader Architecture

The reader would contain a Spectrum Analyzer for the power measurement. Additionally, it would require a filter, transmitting and receiving antennas, a power amplifier and LNAs. The complete schematic is shown in Fig.8.

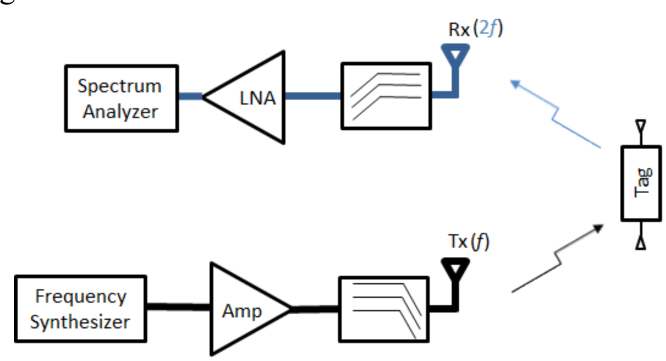

Fig.8 The design of the reader circuit at the left half

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

- Investigate the data mining algorithms for RF sensing data
- Sensing from RF tag buried in soil

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

- Design the low frequency soil compatible wideband antenna
- Show high temperature integration capability of the tag during pipe manufacturing
- Provide the final report of the project

References:

[1] C. N. Morris, Parametric empirical bayes inference: theory and applications, Journal of the American Statistical Association 78 (381) (1983) 47-55.

[2] R. E. Kalman, et al., A new approach to linear filtering and prediction problems, Journal of basic Engineering 82 (1) (1960) 35-45.

[3] P. Del Moral, Non-linear filtering: interacting particle resolution, Markov processes and related fields 2 (4) (1996) 555-581.

[4] M. S. Arulampalam, S. Maskell, N. Gordon, T. Clapp, A tutorial on particle filters for online nonlinear/non-gaussian bayesian tracking, IEEE Transactions on signal processing 50 (2) (2002) 174-188.