Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

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Project Overview

Objectives

Study material development, sensor design, multivariant analysis, and wireless interrogation of flexible antenna sensor arrays to realize distributed condition monitoring of coal fired boilers at a low cost. The research focuses are: a) monitoring temperature and strain distribution of steam pipes; b) detecting soot accumulation on steam pipes.

Technical Challenges:

- Wireless interrogation without electronics
- Simultaneous measurement of strain, temperature, & soot
- Dielectric property control of high temperature materials

Potential Benefits:

- Distributed wireless sensing at a low cost
- Novel material development for high temperature harsh environment
- In-situ process and structural health monitoring
- Improved understanding of combustion and heat exchange processes of boilers.

Project Duration: Jan. 1st, 2015 – Dec. 31st, 2017

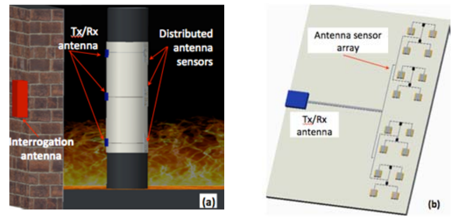

Figure 1. System overview: (a) wireless interrogation; (b) distributed antenna sensor array on flexible substrate.

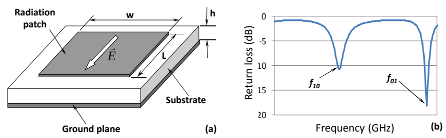

Figure 2. Microstrip patch antenna sensor; (a) configuration and (b) radiation characteristics. The two resonant frequencies are sensitive to strain, temperature, soot and can be wirelessly measured.

Research Approaches

- Conduct fundamental and applied research on materials development and fabrication techniques that facilitate convenient and low-cost production of flexible dielectric substrates;
- Perform comprehensive parametric studies to understand the effect of design parameters on the sensor performances;
- Develop a multi-variant parameter identification algorithm to facilitate extracting multiple measurands from one single antenna measurement;
- Characterize wireless interrogation and sensing capability of the antenna sensor array up to 1000 °C.

Expected Outcomes

- Low-cost antenna sensor array that can sustain high temperature and is conformal to pipe surface;
- Distributed wireless sensors capable of measuring multiple parameters at multiple locations;
- Long distance and dynamic wireless interrogation
- Material recipes/fabrication techniques for producing flexible dielectric substrates with controlled dielectric properties.

Research Activities and Progresses

Accomplishments

- Hired and trained graduate students;
- Purchased and tested capital equipment (Automatic Film Applicator-III , MTI Corporation) for sensor fabrication;
- Developed and validated efficient antenna simulation model;
- Validated wireless interrogation scheme by simulation;
- Initiated work on using ring resonator for dielectric property measurement of substrate material.

Antenna Sensor Design

Alumina wafers were selected as the substrate and Platinum was selected as the conductive material. The simulation model of the antenna sensor, built using a commercial electromagnetic simulation tool Sonnet, is shown in Figure 3(a). The designed dielectric constant of the substrate is 9.9 and the thickness is 0.254 mm. The electrode material has a conductivity of 9.5×10^6 S/m. The antenna sensor was designed to resonate at 2.4 GHz, resulting in a radiation patch of 26.75 mm by 19.85 mm. The antenna sensor has a 155 mm long transmission line to increase the delay time of the antenna backscattering. The simulated S11 curve and E-field propagation pattern of the antenna sensor are shown in Figure 3(b) and 3(c). The maximum interrogation gain of the designed antenna is simulated to be -7.55 dBi.

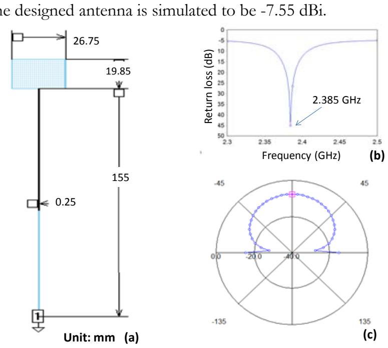

Figure 3: Antenna sensor design; (a) simulation model; (b) simulated S11 curve; (c) simulated E-field propagation pattern.

Acknowledgements

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Antenna Sensor Fabrication

The antenna pattern was fabricated from platinum paste using a tape casting technique. Tape casting is a well-established technique used for fabricating layered structures. An Automatic Film Applicator-III (MTI Corporation) was purchased with the support of this project. A picture of the tape casting machine is shown in Figure 4(a). By adjusting the speed and height of casting blade, we managed to fabricate a transmission line as narrow as 0.8 mm on a substrate, which proved the usability of tape casting technique for the sensor fabrication. A picture of the fabricated antenna pattern is shown in Figure 4(b) and 4(c).

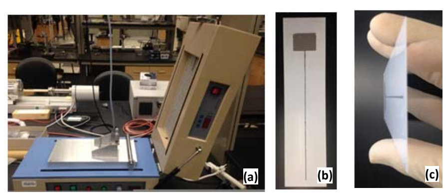

Figure 4: Sensor fabrication; (a) tape casting machine; (b) antenna pattern made from platinum paste; (c) side view of thin alumina substrate.

Efficient Antenna Simulation Model

An efficient S_{11} simulation model for a rectangular microstrip patch antenna (RMPA) was developed based on the cavity model, which has been extensively described in [1]-[3]. A RMPA with a Rogers RO3006 substrate [4] operating at 5 and 6 GHz was simulated. The RMPA dimensions were 9.8 mm in width and 11.8 mm in length. For validation, the simulated S11 parameter was compared with results obtained using a commercial electromagnetic simulation tool, Sonnet. As shown in Figure 5, the simulated results are in very good agreements with a difference of less than 0.3% at the resonant peaks, which confirms the accuracy of the cavity model.

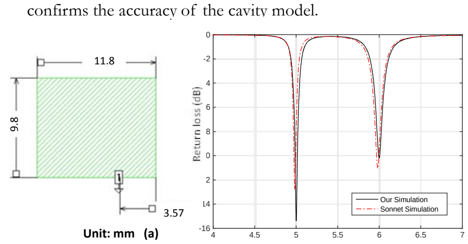

Figure 5. (a) Sonnet model; (b) comparison of S11 parameters simulated using cavity model and commercial simulation tool.

Simulation of Wireless Interrogation Scheme

In order to interrogate the antenna sensor wirelessly based on its resonant delay, RF simulations were carried out using ADS. As shown in Figure 6(a), the resonant response of the antenna sensor is represented with an inductor-capacitor (LC) resonator circuit having a quality factor of 150. The FMCW interrogation signal was generated by a VCO that is controlled by a sawtooth wave generator, which produces an interrogation frequency sweeping from 1.9 GHz to 2.9 GHz with a sweeping frequency of 1 MHz. The signal reflected by the LC resonator is processed by a homodyne receiver. Filtering the receiver output using a band pass filter is equivalent to time-gate the resonator signal with a given time window. Figure 6(b) shows the simulated output of the filter. The amplitude of the filter output is directly proportional to the return loss of the resonator. Based on Figure 6(b), we determined that the resonator has a resonant frequency of 2.4 GHz. Thus, the concept of the wireless transmission system is validated.

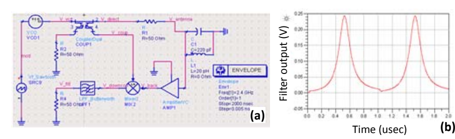

Figure 6: Simulation of wireless interrogation scheme; (a) circuit model; (b) simulated output.

Future Work

- Investigate conductive ceramics as electrode material
- Tailor dielectric properties of substrate materials
- Develop multivariant regression algorithm to inversely extract the measurands
- Demonstrate wireless interrogation of antenna sensor

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