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A Capacitively-Loaded MEMS Slot Element for Wireless Temperature Sensing of up to 300°C

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***Abstract* — In this paper we present a new slot antenna with an embedded temperature sensor for remote sensing in harsh environment applications. When the antenna is illuminated with a plane wave it returns a signal. The returned signal's frequency is modulated by the loaded capacitance formed by an array of MEMS bimorph (metal-dielectric) cantilevers. The MEMS cantilevers deflect downwards when the temperature is changed from 20°C to 300°C. As a result, the resonant frequency of the slot is linearly tuned from 19.45 to 19.30 GHz. The design yields a totally passive and integrated antenna/sensor. The MEMS fabrication is inherently robust, does not suffer from the creep or fatigue problems of traditional bimorph temperature sensors, and has a very high manufacturing yield, even in an academic clean room environment.**

***Index Terms* — Capacitance, Microelectromechanical Devices, Harsh Environment, RFID Sensing, Sensors, Wireless**

I. INTRODUCTION

The telemeter technology has already penetrated a very wide variety of markets, and is now facing the next frontier of integrating RFID devices with sensing technologies. A typical RFID sensor system includes a) a transceiver, b) a battery or battery-equivalent energy providing unit, c) a sensing element, d) a sensor interface circuit for transforming the sensor data to electronic signals and e) an antenna. In high-temperature applications where conventional low-cost CMOS technologies cannot be employed, it is very desirable to eliminate all active elements and opt for a totally passive sensor. This typically results in simple, reliable, and low-cost solutions [1], [2]. An attractive way to accomplish this is to eliminate the sensor interface and directly integrate the sensor on the antenna.

In this paper we accomplish this by symmetrically loading a slot antenna with harsh-environment MEMS temperature sensors. We present the design, fabrication technology, and characterization of this wireless sensor. In this configuration (Fig. 1), an incident wave hits the surface, and the reflected wave is shifted in frequency according to the capacitive loading on the slot.

II. DESIGN

The two main building blocks of this sensor are a) a slot antenna and b) a MEMS temperature-sensitive capacitor. The slot antenna resonates when the length of the slot is equal to one half of the wavelength. The MEMS cantilever beams are placed at the two ends of the slot as shown in Figs. 2 and 3. These are bimorph (metal-dielectric) beams which deflect downwards if the temperature is changed. The top 0.5-μm thick layer of the beam is metallic (gold), while the bottom 0.5-μm layer is thermally-grown SiO_2. One set of the beams is anchored on the left side of the slot, while the second one is anchored on its right side. The beams form a comb whose coupling capacitance depends on the relative orientation of the beams. At room temperature, the cantilever beams are bent upwards by approximately 200 μm and the coupling capacitance is very low. Thus they do not interfere significantly with the slot, and its resonant frequency is nearly identical to that of the unloaded slot.

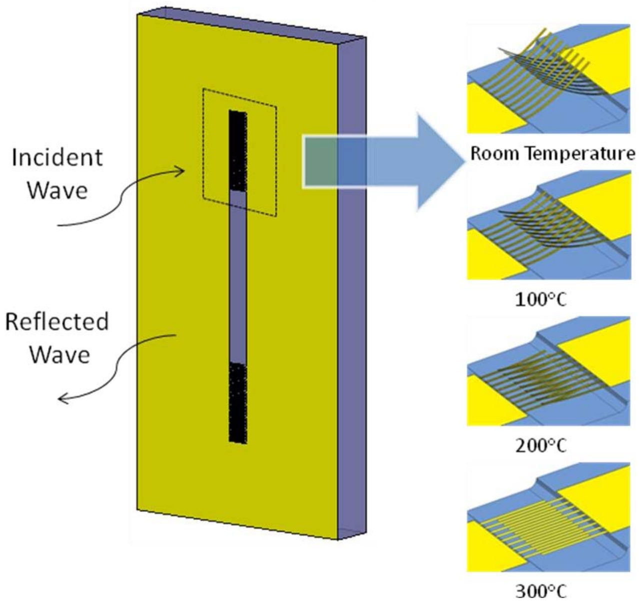

Fig. 1. Concept image – A plane wave incident on the surface is reflected, and the resonant frequency is shifted according to the capacitive loading on the slot.

As the temperature is increased, the beams bend downward and therefore the loading capacitance is increased. This results in a lower resonant frequency for the slot. This trend is monotonic until the beams become parallel to the plane of the slot. Any further increase in temperature will result in a reduced capacitance and increased frequency. Consequently, the beams need to be designed so they become parallel at the maximum desired temperature.

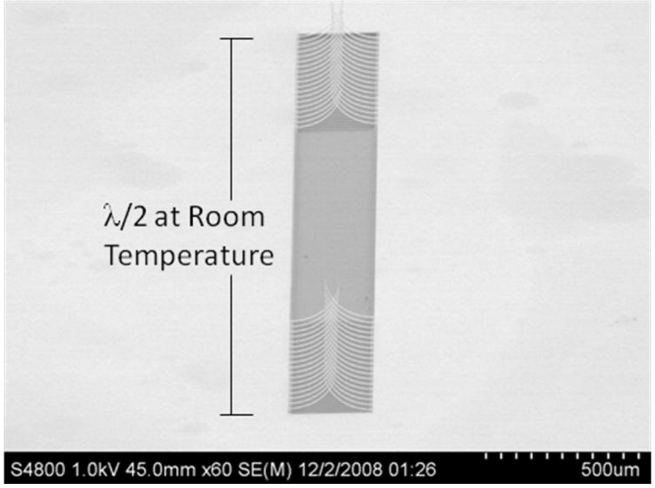

Fig. 2. SEM Image of slot with released MEMS cantilevers. The unloaded slot resonates when its length is one half of a wavelength.

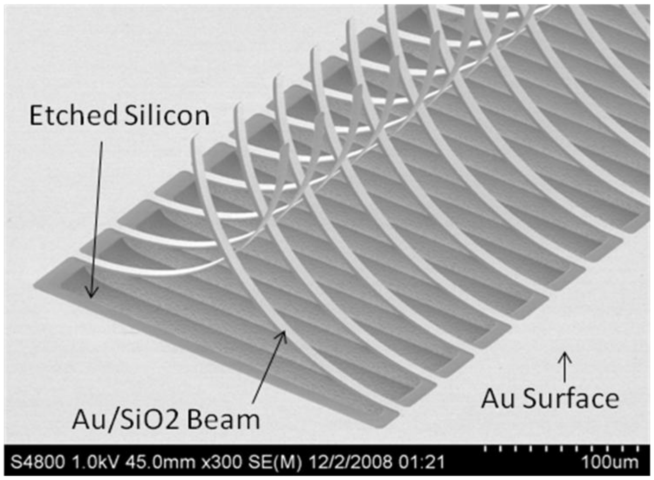

Fig. 3. Closer SEM of MEMS cantilevers. Because of the thermal mismatch of materials, the cantilevers are naturally curved upward at room temperature. Increasing temperature to 300°C restores them to their flat, pre-release state. This is when capacitance between the fingers is the highest.

This design has three main advantages:

- The capacitance is based solely on fringing fields. Parallel plate fields can generally create a larger capacitance, but nearly all of it is generated when the tip is close to fully-deflected. Using fringing fields, the capacitance sensitivity is much more constant over the temperature range.
- As part of the fabrication process, the substrate beneath the cantilevers is etched. Because nothing is directly beneath the released cantilevers, stiction is virtually impossible in normal operation.
- The oxide used is thermally grown. This is much higher quality than the typically-used PECVD and sputtered films, which suffer from mechanical problems at high temperatures. These problems usually result in hysteretic behavior of the sensor.

The capacitance is viewed as an increase in the length of the slot, as in [3], causing the slot to resonate at a lower frequency than it normally would unloaded. The cantilevers are bimorph beams (metal on top of a dielectric). The thermal expansion of the metal layer far exceeds that of the dielectric, so as the temperature increases, the beams deflect downward. Because the fringing fields are stronger when the beams are closer to being parallel, the capacitance of the structure increases, causing the resonant frequency to shift further down, until the beams are flat and they obtain the maximum capacitance. To determine what these capacitance values would be, computer simulations were performed. Displacement of the beam tip was observed at each recorded temperature, and from this, the beam geometries were drawn in Ansoft's Maxwell 3D. An electrostatic simulation was then completed for the beam geometries at each temperature, and Fig. 4 was obtained. The capacitance at each temperature is then placed into an equivalent circuit model in Agilent ADS to extract the expected resonant frequency versus temperature data.

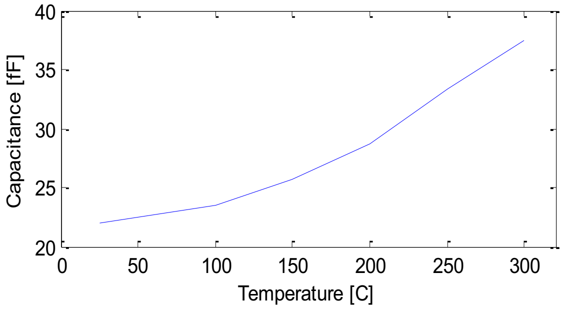

Fig. 4. Simulated capacitance vs. temperature for an array of MEMS cantilevers.

The cantilevers are made of 0.5-µm thick gold, and 0.5-µm thick silicon dioxide. The ratio of these thicknesses, as well as their respective coefficients of thermal expansion are what determines what temperature they will lay flat at, and in this case, it is at about 300°C. As previously mentioned, low temperature PECVD or sputtered dielectric films are typically used in bimorph beams [4], [5]. Because these films are deposited at lower temperatures, they cannot withstand high temperatures. Also, there are many pinholes in the film, which reduces the mechanical quality needed for long-term reliability. In our case, the dielectric layer is grown thermally at 1100°C. This is the highest quality oxide on silicon, and even 400°C is well within its range of operation. Testing also shows no noticeable hysteresis, making the structure ideal for harsh and frequently-changing conditions.

III. FABRICATION

The antennas were fabricated in the cleanroom in Birck Nanotechnology Center at Purdue University. Fig. 5 outlines the employed fabrication process. The details and advantages of this fabrication process are elaborated on in detail in [6], so here we just review the main steps. First, starting with a high-resistivity silicon wafer, an oxide is thermally grown. The thickness of this oxide is around 0.5 µm. This oxide is then patterned using an image reversal with traditional lithography. This reveals the bare silicon wafer in the areas between the beams, and in the slot in the center. Then, a thin layer (~50nm) of titanium is deposited with about 0.5 µm of gold on top. The titanium layer is used only for adhesion between the gold and oxide layers. Because of the thermal-mismatch of the gold and oxide layers, residual stresses exist, and the beams are naturally curved up at room temperature (Fig. 3). The fabrication process is extremely high yield, exceeding 99.9%, even in an academic cleanroom.

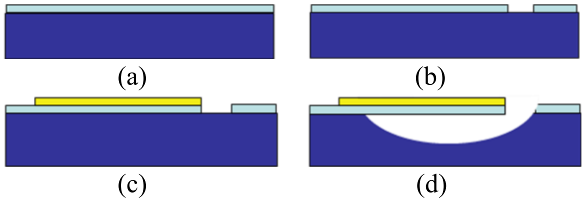

Fig. 5. Fabrication procedure - a) 0.5 µm thermal oxide grown b) oxide patterned using lithography and BOE etch c) 50nm Ti (for adhesion) and 0.5µm Au deposited and patterned and d) XeF_2 dry-etch of silicon to release cantilevers.

IV. MEASURED RESULTS

Measurement of the device was accomplished by placing a standard gain horn antenna in front of the surface, and measuring the reflected power with a GPIB connection to an Agilent 8722 vector network analyzer. A one-port calibration was done using short, open and load standards. This calibrated out resonances from the cable. The horn was then attached to this cable. Isolation and reflection measurements were taken on the horn antenna to verify proper calibration. The horn antenna was attached to a custom-made fixture to direct it at the antenna. Wafer pieces were used which were much smaller than beam width of the antenna, so to keep the area under test within the beam of the antenna, the pieces were mounted to a PCB with a slot milled in the center for the wafer piece to sit. A high-temperature silver paste adhesive was used to electrically connect the surfaces, with a thermocouple wire embedded in the paste. A hot air gun was used to heat the wafer piece, while the thermocouple reader indicated the temperature and the VNA recorded the data. The resonant frequency which was observed is shown in Fig. 7 for several different temperatures, and the subsequent resonant frequency versus temperature of the slot is recorded in Fig. 8.

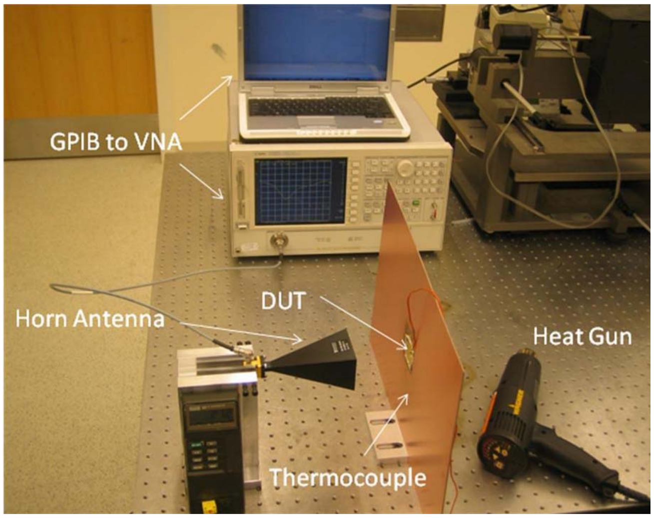

Fig. 6. Measurement Setup – Heat is applied to back side of the wafer piece and thermocouple is read to determine the current temperature seen by the MEMS. The reflected wave is read by a GPIB connection to the VNA.

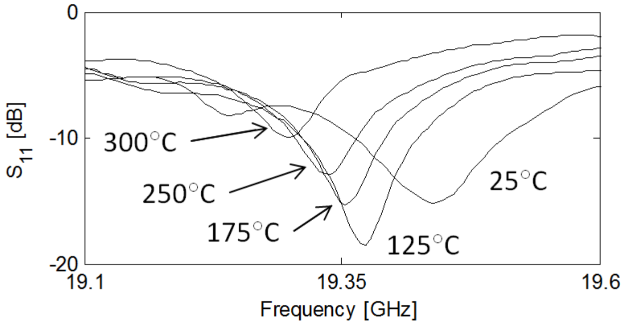

Fig. 7. Measured S_{11} for selected frequencies (right to left): 25°C, 125°C, 175°C, 250°C, and 300°C.

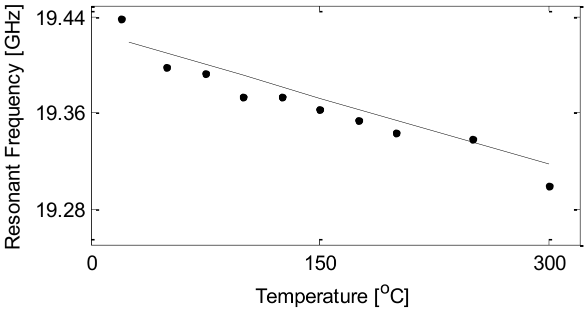

Fig. 8. Measured resonant frequency vs. temperature

V. CONCLUSIONS

A new slot antenna with an embedded temperature sensor has been presented for remote sensing in harsh environments. When a plane wave is incident on the surface, the reflected wave has a resonance which is modulated by the capacitive loading on the slot. The sensor has a linear frequency response, changing from 19.45GHz to 19.30GHz when the temperature changes from 20°C to 300°C. The MEMS bimorph cantilevers used to load the slot are designed in a manner which is extremely robust, doesn't suffer from creep or fatigue, and also has a very high fabrication yield. This passive architecture is optimal for conditions in which a harsh environment's temperature needs to be monitored, but a wired connection is not possible.

ACKNOWLEDGEMENT

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