A Novel Ultrasensitive Millimeter-Wave Pressure Transducer utilizing a Si membrane and a stacked-patch configuration

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Introduction

Pressure transducers refer to devices that can transform the pressure change in the monitored environment into a change in the electrical signal. Common pressure transducer classes include resistive, piezoresistive, and capacitive based sensors, while others are based on inductive-capacitive circuits whose detection relies on resonant frequency shifts. Pressure sensors are essential for controlling and monitoring great number of everyday applications ranging from physiological monitoring in medical technology, automotive control with measurements on fluid flow, acceleration, and displacement in industrial uses, and various military applications, as well monitoring structural integrity in critical infrastructure components, such as levees, water dams and aircraft wings. Pressure transducers usually employ a diaphragm that deflects in response to pressure change. Most transducers require physical wires to connect to an electronic device (to record and process information) and an antenna (in wireless applications to transmit or receive data). However, due to high demand on portability and power consumption, remote sensing and power saving devices are more strongly desired.

In this paper, a highly sensitive and compact radio frequency (RF) transducer is presented that can address portability, conformality, ruggedness and stringent power requirements as discussed earlier. The RF transducer utilizes a stacked-patch resonator that has dual resonances operating in the millimeter-wave frequency range. This device is the first of its kind to be reported, since it can function as both a pressure sensing agent based on frequency shift in the range of 47-55 GHz, and a wireless communicating front-end that operates at 32 GHz. Therefore, it eliminates not only the use of a signal processing circuit, but also the need for an antenna as the front-end component along with any matching circuit. As a result, the power consumption can be reduced by an order of magnitude while easy integration and miniaturization are achieved.

Design of the Radio Frequency Transducer

The sensor structure consists of two metal patches that are stacked above a ground plane that form a stacked patch resonator. The top view and side view of the resonator are shown in Fig. 1 indicating a square patch positioned right above another square patch, both of which are centered on top of the grounded cavity. The upper patch is attached to the bottom of the Si membrane that seals over an

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air cavity. The cavity is surrounded by metalized walls that are grounded. The lower patch is placed on top of the first LTCC substrate using GL550 ($_r$ = 5.6) by Kyocera Corp. The second substrate, identical to the first one, is placed underneath the ground plane to support a microstrip line (50Ω) that feeds the lower patch through a signal via that passes through a hole with size 'g' in the ground (Fig. 1b). The metalized walls can be realized in fabrication by using vias, and the Si membrane may be supported by additional LTCC layers as a frame for the air cavity. The major parameters for the RF transducer designed for 30-55 GHz range are follows: Lt = 3340 um (total length of the square ground), Lp = Wp = 1800 um (length and width of the upper patch, respectively), L = W = 1670 um (length and width of the lower patch, respectively), h1 (thickness of LTCC substrate) = 82 um, and h2 (air gap) = 40 – 100 um.

Principles of Operation

The RF pressure transducer operation is based on frequency shifts in order to indicate the change in pressure of the sensor surrounding environment. As the pressure changes, the Si membrane deflects from its equilibrium position, thus changes the height h2 (Fig. 1b). As a result, the higher resonant frequency of the dual-band stacked-patch resonator is shifted. The dual-band performance of the stacked-patch resonator is due to the presence of the two close resonant frequencies introduced by the two patches. The upper patch's resonance is controlled through the coupling between the upper and lower patches through the air gap h2, which can be modeled by the equivalent circuit shown in Fig. 2 [3], in which the two patches are modeled as two parallel resonant circuits with R_1, R_2 representing the radiation resistances for each patch, L_1, L_2 and C_1, C_2 representing the equivalent inductances and capacitances, respectively, for each patch, and M and C corresponding to the coupling inductance and capacitance, respectively. (Subscript 1 and 2 refer to the lower and upper patch, respectively.) The two resonant frequencies depend on L_1C_1 and L_2C_2, while the coupling effectiveness is due to the coupling capacitance C and mutual inductance M [3].

From the surface current analysis (shown in Fig. 3 and simulated using the time domain simulator, Microstripes by CST), it is observed that the fundamental mode surface current, dominant at 32 GHz, is produced in the upper patch; meanwhile, the fundamental mode surface current dominant at 48 GHz is produced in the lower patch. This indicates that the lower frequency is mainly generated by resonance of the upper patch, while the higher frequency is mainly generated by resonance of the lower patch. In terms of the equivalent circuit (Fig. 2), as h2 varies, C1 parameter is directly affected, which consequently shifts the higher resonant frequency while the change in C only alters the coupling effect leaving C2 almost the same, thus resulting in a change in the return loss of the lower frequency but not a frequency shift. Since the upper patch is attached to the Si diaphragm, the deflection of the diaphragm due to pressure changes directly corresponds to changes in h2, which is responsible for the frequency shift. Therefore, the stacked-patch resonator functions as a transducer that transforms the difference in pressure between the air cavity and that of the surrounding environment into a shift of resonant frequency for detection.

Simulation Results of the RF pressure transducer

For simplicity and without loss of generality, the deflection of the Si membrane due to differential pressure is approximated with uniform displacements. That is, the flat surface of the upper patch together with the Si membrane is displaced uniformly by different heights corresponding to different pressure in practice. The return loss of the stacked-patch resonator is shown in Fig. 4 presenting a dual-band frequency response: the first one is at 32 GHz for communication, and the second one is centered at 50 GHz. The resonant frequency in the higher band is shifted from 47.6 to 54.6 GHz as the gap h2 between two patches decreases from 100 to 40 um. The lower resonant frequency remains almost constant during this range of displacement because, as discussed above, it is mainly due to the current on the upper patch, which is relatively unaffected by the height h2 in this small range of variation. Therefore, a reliable wireless communications link can be established at the lower band. On average the RF transducer design shows a very high sensitivity of 116 MHz /um which is Measurement results verifying a very good agreement with simulations will be presented at the conference.

Conclusions

A new highly sensitive radio frequency pressure transducer has been designed to operate in the millimeter wave frequency range that can be seamlessly integrated with other RF circuits in the LTCC multilayer packaging technology. The resonator consists of a stacked-patch based on LTCC multilayer packaging technology, having an air cavity embedded by a silicon (Si) diaphragm that deflects due to pressure change. Furthermore, the RF transducer presented here, operating in two frequency bands between 30-55 GHz, serves as both a wireless communications link and a remote sensing differential pressure indicator. This device can simultaneously simplify the design process, reduce the device's size, and reduce power consumption of the sensor at device level, providing a sensitivity of 116 MHz/um with respect to the diaphragm deflection due to pressure change. The pressure inside the air cavity can be calibrated to detect differential pressure anywhere from zero to several bars. The transducer can be directly employed in a typical remote sensing / radar system without the need for additional circuits such transceivers required in traditional wired transducers. Thus, it significantly reduces the power consumption and greatly minimize the sensor. Due to its high sensitivity and portability, in future work the RF transducer design will be modified to use multilayer organics, such as LCP so that it may be utilized as wireless implantable sensors for biomedical applications and conformal structural health monitoring devices. A prototype of the RF transducer will also be presented to demonstrate the operation of the device.

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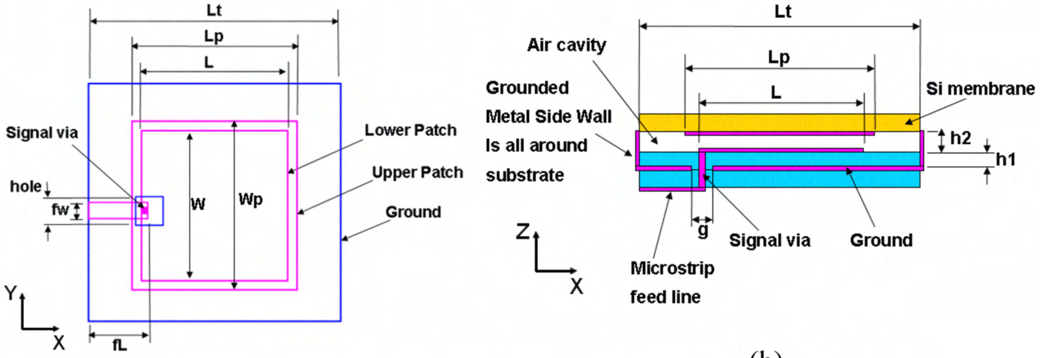

(a) (b)

Fig. 1. a) Top view and b) Side view of the RF pressure transducer.

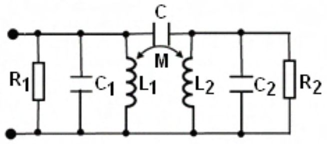

Fig. 2. Equivalent circuit.

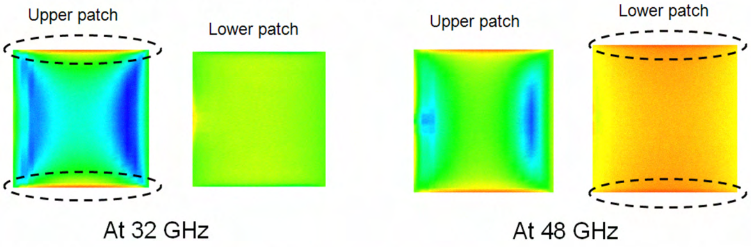

Fig. 3. Surface currents (RMS values) of the patches at 32 GHz and 48 GHz with dominant current is circled.

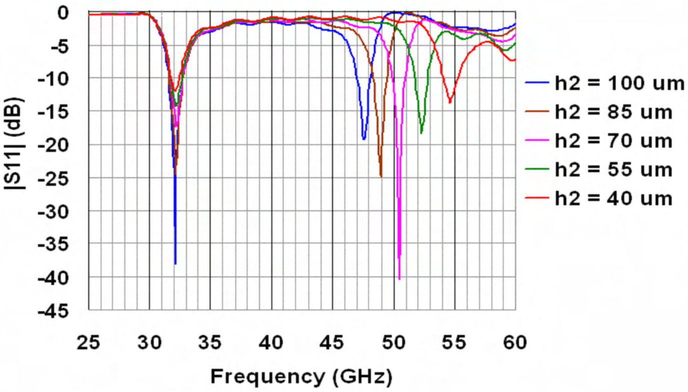

Fig. 4. Return loss of LTCC based RF pressure transducer with a) h2 = 100 um (blue line), b) h2 = 85 um (brown line), c) h2 = 70 um (pink line), d) h2 = 55 um (green line), and e) h2 = 40 um (red line).