

Wide pressure range operation of air-coupled CMUTs

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Abstract— We present measurement results of capacitive micromachined ultrasonic transducers (CMUTs) in permanent contact mode over a wide pressure range (1 – 8 atm). The CMUT plates are in contact with the bottom of the cavities due to atmospheric pressure, even without any dc bias voltage. The electrical input impedance at various dc bias voltages are measured at elevated pressure to characterize individual devices. The open and short circuit resonant frequencies are extracted from the impedance data, and the acoustic performance of pairs of devices is evaluated by performing pitch-catch measurements. A frequency matching method is proposed and used to determine the optimal dc bias voltages for the transmitting and receiving CMUTs individually.

Our electrical impedance results show good agreement with the finite element model results (modal and harmonic analysis performed with ANSYS) over the entire pressure range. Moreover, the pitch-catch measurement results validate the proposed frequency matching method for an optimal biasing scheme, and a received signal with good signal-to-noise ratio of 45 dB was observed at a pressure of 7 atm. In conclusion, the behavior of CMUTs in permanent contact mode can be predicted well with our FEA, and they are indeed a promising solution in providing ultrasonic transducers that can operate over a wide pressure range.

Index Terms—CMUT, permanent contact mode, wide pressure range, FEA, electrical impedance, pitch-catch.

I. INTRODUCTION

Many applications of gas-coupled ultrasonic devices involve extreme ambient conditions, such as chemical sensing in process industry, range finding in harsh environment, and ultrasonic flow metering. The wide and varying pressure in these environments imposes a challenge on ultrasonic transducers. The main goal of this research is to provide transducers that can efficiently receive and transmit ultrasound over a wide range of pressure.

Based on finite element analysis (FEA) results, we previously proposed a new CMUT operational mode [1], in which the CMUT plate is in permanent contact with the bottom of the cavity, even at only 1-atm pressure and zero dc bias voltage [Fig. 1(a)]. This structure features larger electric field in the gap, and thus better coupling efficiency. Further, it provides a more stable static operational point over a wider pressure range compared to conventional CMUT devices. We further proposed a cell structure in which only a portion of the bottom electrode is connected to the hot electrode to reduce parasitic capacitance and the likelihood of electrical breakdown through the contact area [Figs. 1(b) and (c)].

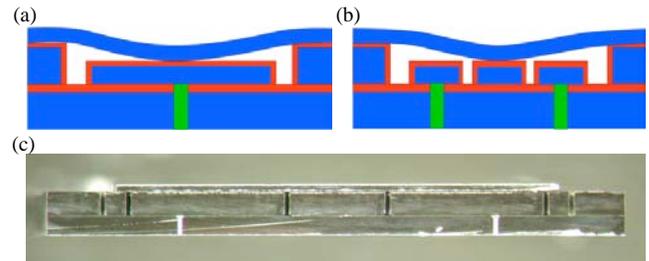


Fig. 1 shows the schematic cross-sectional view and the optical picture of a single CMUT cell as proposed in [1], where (a) is a cell in the permanent contact mode, i.e. with the plate in contact with the bottom of the cavity at 1 atm and zero dc bias; (b) and (c) show a cell in the same operational mode, but with a donut-shape, partially connected backside electrode. The central island in the bottom electrode is floating.

The proposed CMUTs were successfully fabricated [2] based on the process with a thick-buried-box-layer introduced in [3]. Also reported were the plate profile, electrical impedance, and ac displacement characterization results under a pressure of 1 atm, which validated the FEA models for both static and dynamic device behavior at 1 atm.

In this paper we present further measurements at elevated pressure, which includes electrical input impedance and acoustic pitch-catch measurements in a pressurized chamber of up to 8 atm. These results confirm that our FEA models well predict the behavior of permanent-contact CMUTs not only at 1 atm, but also at elevated pressure.

II. MEASUREMENTS AT ELEVATED PRESSURE

A pressurized chamber [Fig. 2(c)] and fixtures for the devices [Fig. 2(a)] were built to perform measurements at elevated pressure. Each fixture contains a printed circuit board (PCB) with the required circuitry (*e.g.* pre-amplifier for the receiving device) and also allows for a small tilt and translation adjustments so that we can align the devices during pitch-catch measurements [configuration shown in Fig. 2(b)]. The fixtures are inserted into the pressure chamber, each through a NPT (National Pipe Thread) plug with some polytetrafluoroethylene-based sealing paste applied to prevent air leakage. Through the NPT plugs, the electrical connections to the outside are established, so that bias-T's located in the two aluminum boxes [Fig. 2(c)] and cables can be connected. An air compressor pumps air into the chamber and supplies the required pressure.

At each pressure, the electrical impedances for both devices in the chamber are measured at various dc bias voltages. Open and short circuit resonances are then extracted from the

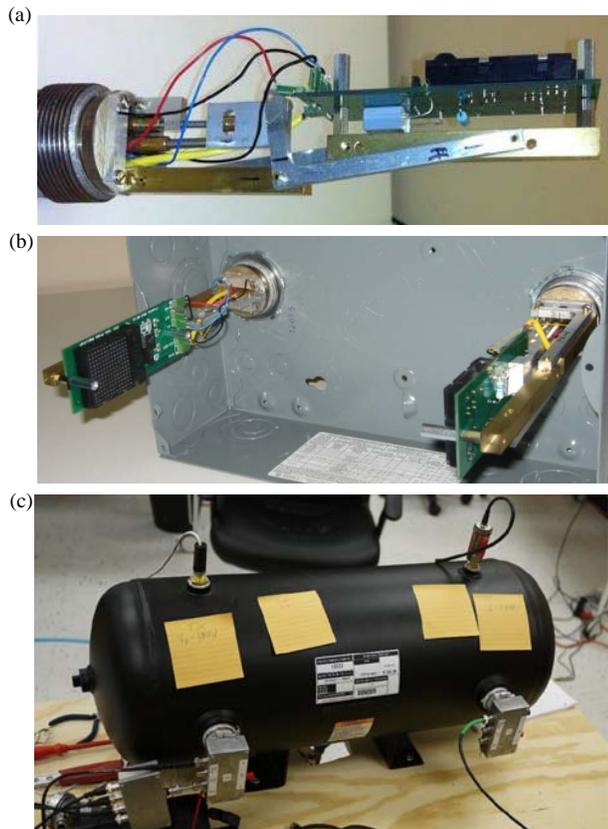


Fig. 2 The setup we use to do electrical impedance and pitch-catch measurements at elevated pressure: (a) shows the fixture to mount the device, which contains a PCB for the required circuitry and allows for some tilt and translation adjustment for pitch-catch alignment; (b) shows the pitch catch configuration for the fixtures; (c) shows the pressurized chamber; two fixtures were inserted into the chamber thru two NPT plugs, and the bias-T circuits are located in the aluminum boxes connected to the NPT plugs.

impedance data as a function of the dc bias. This information is used to determine the optimal dc bias combination for the two CMUTs and the frequency for the excitation signal (sinusoidal burst) for pitch-catch measurements.

i. ELECTRICAL IMPEDANCE MEASUREMENTS

The electrical impedance is measured by an impedance analyzer HP 4192A (now Agilent Technologies Inc., Palo Alto, CA, USA). The raw impedance data is adjusted by the measured data of the standard calibration kit (open & short loads). As an example, the input impedance of a CMUT operated at a dc bias voltage of 250 V at various pressures ranging from 1 to 8 atm is presented in Fig. 3(a). The single-cell CMUT has a cell radius of 2100 μm , a 75% electrode ($e75$, the definition was described in [2]), a 60- μm thick single crystal silicon plate, and an 8- μm gap height.

An FEA was performed for this CMUT design [Fig. 3(b)]. The simulation uses the linear harmonic analysis in ANSYS with medium loading on top of a single CMUT cell. The medium properties, such as air density, as a function of pressure, are included in the model accordingly.

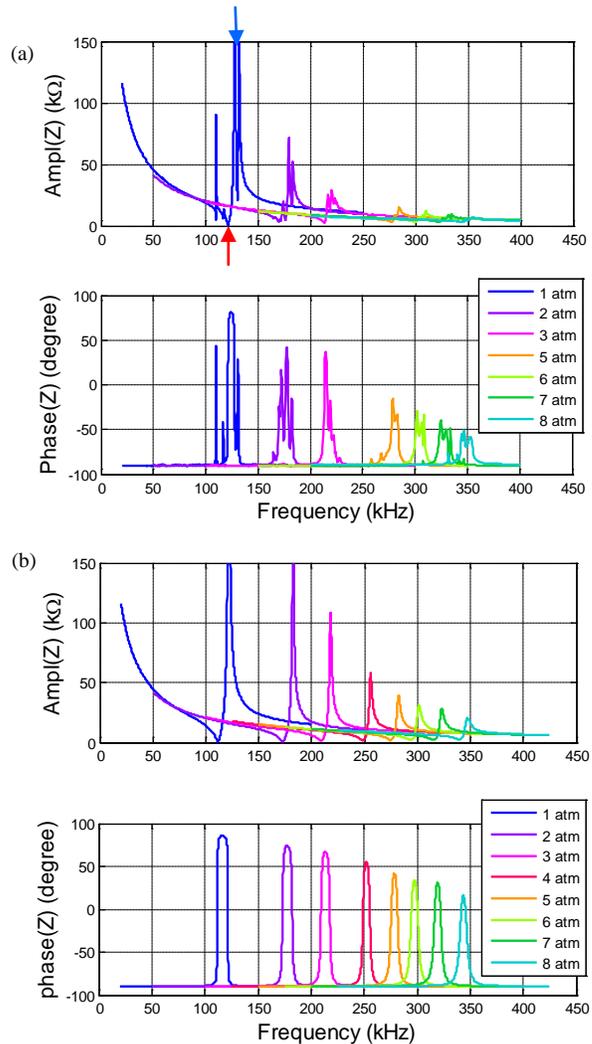


Fig. 3: Direct comparison of electrical impedance between measurements and FEA harmonic analysis. This CMUT cell has 2100 μm radius, a 8 μm gap, a 60- μm -thick plate, and a 75% partial electrode. (a) summarizes the measurement results at 250 V dc bias, while (b) shows the linear harmonic analysis result with the air loading at 250 V dc and with an added parallel parasitic capacitance of 29 pF.

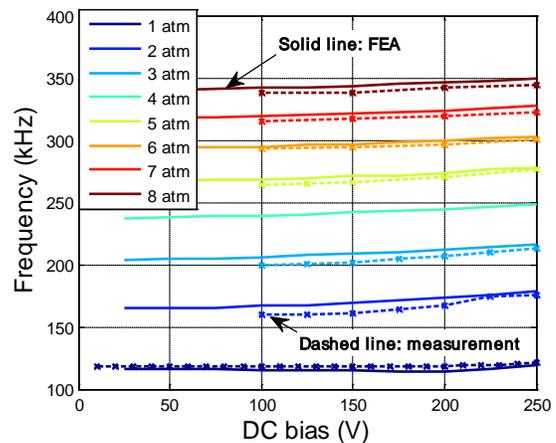


Fig. 4: Direct comparison of short circuit resonances between measurements and FEA nonlinear modal analysis at various dc bias voltages. This CMUT cell has 2100 μm radius, an 8 μm gap, a 60- μm -thick plate, and a 75% partial electrode.

The direct comparison reveals a good agreement between our measurements and FEA results. In both cases, when the pressure increases, the resonant frequencies increase, and the magnitude of the impedance decreases (Fig. 3). This is because the plate is pushed more against the bottom of the cavity at higher pressures, and thus the actual vibrating portion of the plate decreases. The FEA overestimates the magnitude of the electrical impedance because it does not contain all loss mechanisms [4] that are present in the CMUT device.

The open-circuit (blue arrow) and short-circuit (red arrow) resonances can be extracted from the impedance data as indicated in Fig. 3(a). The short-circuit resonances extracted from measurements are compared to the nonlinear modal analysis results from ANSYS in Fig. 4, and again the simulation agrees with the measurement. Furthermore, the frequencies obtained from the nonlinear modal analysis agrees with those from the linear harmonic results, which implies that for our devices in the permanent contact mode, the model does not demonstrate obvious stress stiffening effects [5] and thus the linear harmonic analysis is valid.

ii. PITCH-CATCH MEASUREMENTS

In the pitch-catch measurement setup, the transmitting device is driven by a function generator (HP33120A, now Agilent Technologies Inc., Palo Alto, CA, USA) which has a low output impedance of 50Ω , and the receiving device is connected to a pre-amplifier which has high input impedance in the $M\Omega$ range. Since matching the impedance will give maximum power transmission, the transmitting CMUT will perform the best at the short-circuit resonance where the device impedance is at a minimum, and the receiving CMUT will perform the best at the open-circuit resonance where the device impedance is at a maximum. Hence, the implication is that, even for two identical CMUTs, simply applying identical value for the dc bias voltage on the two devices will not make them to transmit and receive at the same frequency efficiently. Note that the underlying assumption is that the bandwidth of the CMUT is narrow enough, which is the case for our single cell devices used for this work. For optimum pitch-catch performance, we purposely tune the dc bias voltages applied to the transmitting and receiving CMUTs separately, and thus, the operating frequencies are matched during the pitch-catch measurements for maximum response.

The pitch-catch measurement results at 3 atm and 7 atm are given in Fig. 5 and Fig. 6, respectively. Device B is the same CMUT that has been presented in the previous section for electrical impedance measurements, while Device A has a radius of $2000\ \mu\text{m}$, a 50% electrode ($e50$, the definition was described in [2]), a $60\text{-}\mu\text{m}$ thick plate, and an $8\text{-}\mu\text{m}$ gap height.

Fig. 5(a) shows the short circuit resonance for the transmitting Device A and the open circuit resonance for the receiving Device B at 3 atm, which are extracted from the electrical impedance measurement, as a function of dc bias voltages. If it is required to operate both devices at the same dc

bias, $\sim 208\ \text{V}$ will match the frequency for this pair of CMUTs. However, if we can tune the dc bias for the two devices individually, operating the transmitting device (TX) at $250\ \text{V}$ (V_{TX}) and the receiving device (RX) at $225\ \text{V}$ (V_{RX}) will also give a matched frequency of $214\ \text{kHz}$, and in this case the higher biasing voltages will also improve the device efficiency.

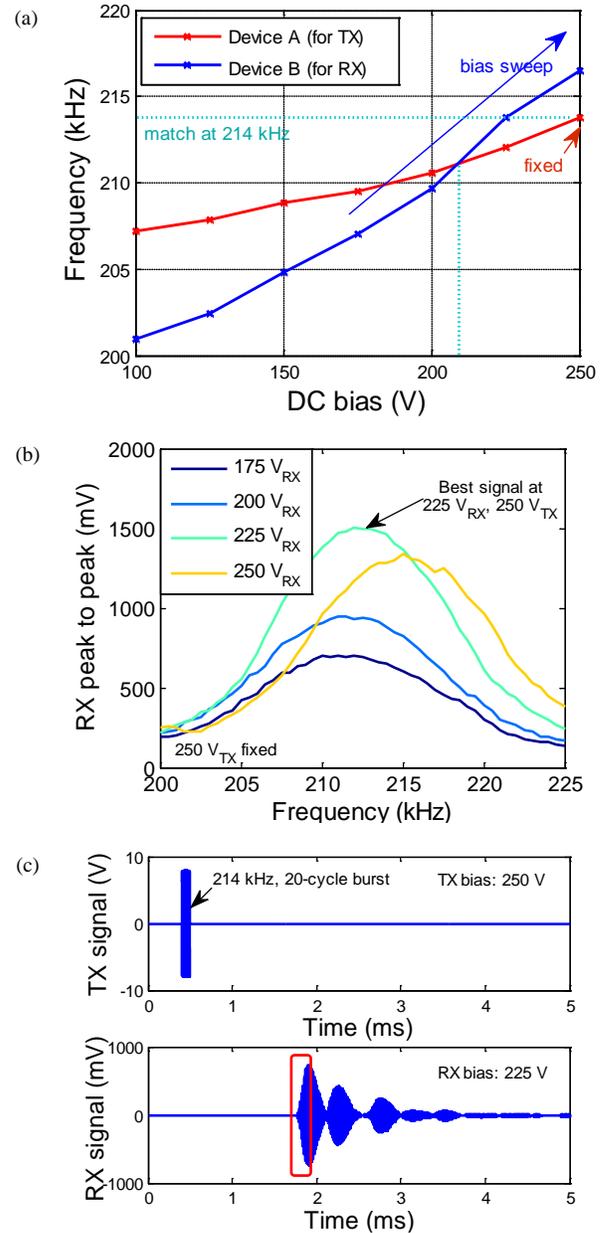


Fig. 5: Pitch-catch measurement result for a pair of devices at 3 atm: (a) shows the short circuit resonance for the transmitting Device A and the open circuit resonance for the receiving Device B; (b) shows the frequency response of the peak-to-peak voltage for the received signal with the dc biasing scheme indicated in (a); (c) shows the time domain transmitting and received signals at the point of best signal as indicated in (b). Due to the interference from the chamber side wall reflections, only the first 0.24 ms of the received signal (in the red box) is considered in extracting the RX peak-to-peak value in (b).

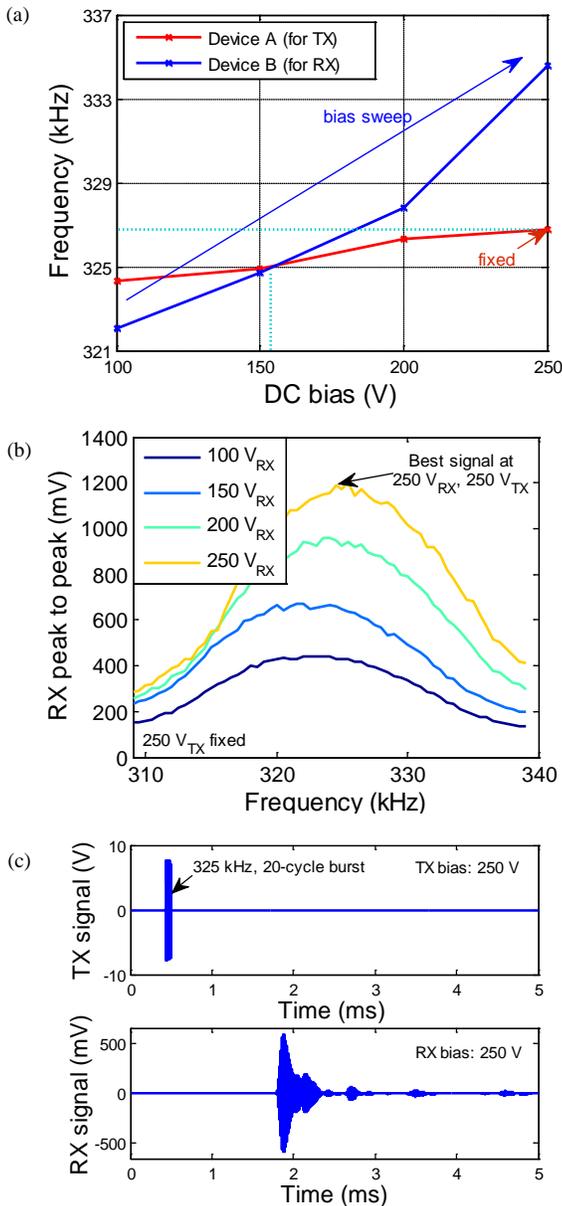


Fig. 6: Pitch-catch measurement result for a pair of devices at 7 atm: (a) shows the short circuit resonance for the transmitting Device A and the open circuit resonance for the receiving Device B; (b) shows the frequency response of peak-to-peak voltage for the received signal with the dc biasing scheme indicated in (a); (c) shows the time domain transmitting and received signals at the point of best signal as indicated in (b).

To validate our frequency matching method to determine the optimal biasing scheme for the pitch-catch devices, a series of pitch-catch measurements are performed as V_{TX} is fixed at 250 V, and V_{RX} sweeps from 175 to 250 V. For each dc bias combination, a 20-cycle sinusoidal burst signal with frequency sweeping over the range of interest is applied to the transmitting device. However, as can be seen in Fig. 5(c), even when the frequencies match, interference is still present in the received signal due to the reflections from the pressure chamber side walls. Considering the transit time difference over different paths inside the chamber, only the first 0.24 ms

of the receiving signal is considered in extracting the RX peak-to-peak value in Fig. 5(b).

As indicated in Fig. 5(b), the best signal occurs at $V_{TX} = 250$ V, and $V_{RX} = 225$ V [time-domain signals are shown in Fig. 5(c)], which is indeed where the frequencies match.

Similar results for the same pair of devices at 7 atm are summarized in Fig. 6. Nonetheless, with V_{TX} fixed at 250 V and V_{RX} sweeping from 100 to 250 V, the frequency matching point should occur at $V_{RX} \sim 185$ V, which is too low to provide good operating efficiency. Therefore, the best signal still occurs when both V_{TX} and V_{RX} are at 250 V.

In short, the optimal biasing scheme involves both tuning the individual dc biases to achieve matching frequency, as well as choosing higher dc bias for better coupling efficiency. Sometimes we can achieve both criteria, but other times when a matched frequency can only be attained by low dc bias voltages, the effect that higher biasing voltages give higher coupling efficiency will take over.

Note that even at 7 atm, we are able to obtain a received signal with good signal-to-noise ratio of 45 dB.

III. CONCLUSION

We successfully demonstrated that our CMUTs can handle elevated pressures up to 8 atm. Electrical impedance measured shows good agreement with the results of both the linear harmonic and the nonlinear modal analysis of ANSYS. Pitch-catch measurements validate our frequency matching method to determine the optimal biasing scheme for the device pair, and a received signal with good signal-to-noise ratio can be measured even at 7 atm.

For the next fabrication, we are working on improving the uniformity in the device gap height, and the mechanical strength of the CMUTs. Further characterization of the improved devices will be performed at even higher pressure up to 20 atm.

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