Air Coupled Through Transmission of Aluminum and other Recent Results Using MUTs

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Abstract—**The air-coupled transmission of 2.3 MHz longitudinal ultrasonic waves through aluminum is reported. Microfabricated ultrasonic transducers are used to emit and receive the ultrasonic tone burst. The signal at the receiver is 30 dB above the noise floor, which implies a dynamic range of approximately 110 dB. The dynamic range is independently verified, and transmission through steel is also demonstrated. Air-coupled NDE scans of lucite plates are presented. An optimized fabrication process, based on theoretical understanding of the transducers, enables the experiments. Significant progress in the fabrication of immersion MUTs is also in evidence. An insertion loss of 4 dB is reported and transmission experiments show 100 dB of dynamic range with 100% bandwidth.**

I. Introduction

Air-coupled and immersion capacitive ultrasonic transducers have existed for decades [1] [2]. Recent developments in microfabrication technology have spurred new versions of the devices [3][4][5][6][7]. The main motivational forces behind transducer development are applications in air-coupled nondestructive evaluation (NDE) and in 3-D immersion imaging using 2-D transducer matrices.

The use of airborne ultrasound in an NDE context is not new [8] [9], but recently various experiments demonstrating the practical feasibility of air-coupled NDE have been reported [10][11][12]. The main difficulty in air-coupled NDE is the large impedance mismatch between air and both the test sample material and the transducer material. Microfabricated capacitive transducers offer the most promise in overcoming the transducer impedance mismatch problem because they emit and receive sound through the vibration of a thin, light membrane and thus require no matching layers. The excitation of longitudinal waves in metallic solids with airborne ultrasound has been demonstrated with a broad-band, partially microfabricated transducer operating at frequencies below 1 MHz [13]. In this paper, we present experiments of air-coupled through transmission of solids using fully surface micromachined, narrow band devices operating at 2.3 MHz. These microfabricated ultrasonic transducers (MUTs) have a dynamic range of 110 dB, and are thus the only technology capable of air coupled through-transmission of longitudinal waves in metals at high frequencies different from the metal's longitudinal resonance.

This paper also presents results indicating that MUTs can transmit and receive in liquids with an insertion loss of 4 dB per transducer. The transducers have a fractional bandwidth of approximately 100% and a dynamic range in excess of 100 dB. Thus, they are a promising new alternative to piezoelectric devices in immersion applications. The advantages of MUTs are perhaps most applicable to 2-D transducer matrices because the elements can be lithographically defined (in contrast to the precise dicing required in piezoelectric devices) and because the fabrication techniques are compatible with standard CMOS processing. Thus, switching, multiplexing, and even signal processing may be integrated with the transducer elements.

II. Device Description and Fabrication

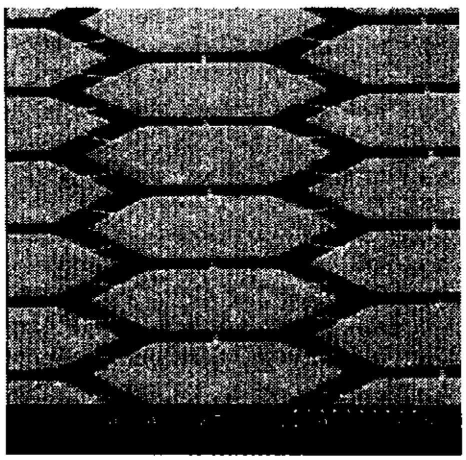

Fig. 1. SEM of a portion of a MUT

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A MUT consists of metalized silicon nitride membranes suspended above heavily doped silicon bulk. Details of device operation and fabrication are found in [14] [15]. A section of a MUT is shown in Figure 1. Critical to the improved performance of the new generation of MUTs is a fabrication process which allows for the precise lithographic control of MUT dimensions. A schematic of the fabrication process is shown in Figure 2. MUTs used for immersion applications have lateral dimensions on the order of 30 microns, as in Figure 1, while MUTs optimized for air-coupled operation have lateral dimensions on the order of 100 microns. A set of such devices, packaged by securing the chips onto a test pc board and wire bonding to the contact pads, is used to perform the experiments herein reported.

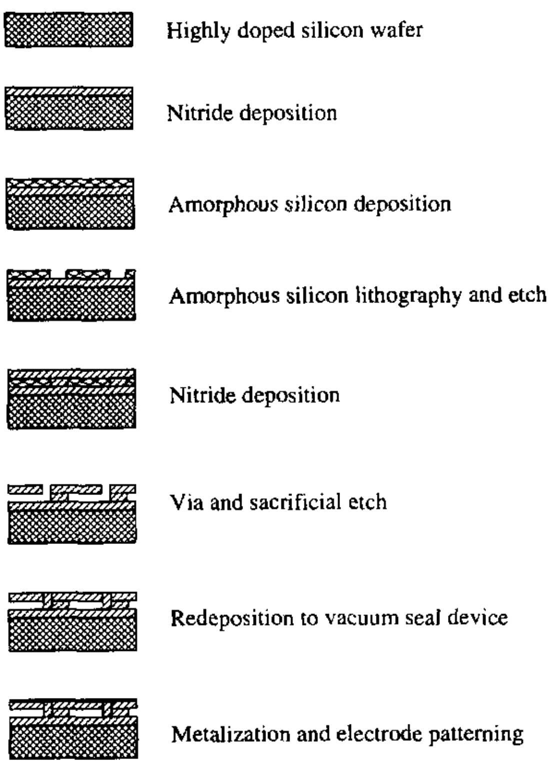

Fig. 2. MUT fabrication process.

III. Air Coupled Experiments

Experiments were performed with the setup shown in figure 3. First, with no sample in between the transducers, the lowest detectable signal was found to be generated by a 0.1 mV excitation tone burst (produced by placing a 40 dB of attenuation at the output of an HP function generator set to 10 mV). A DC bias of 30 V was applied to the transducers. The received voltage was observed

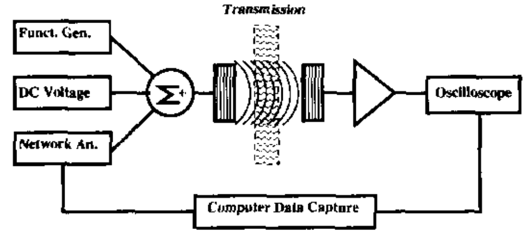

Fig. 3. Schematic of transmission experiment setup.

to vary linearly with excitation voltage. Thus, a 10 V driving burst would imply a dynamic range of 100 dB for the transmission setup. After accounting for attenuation in air and electrical impedance mismatch, the dynamic range of the transducers was found to be 110 dB.

The large dynamic range enables the transmission of sound through solids. The received signal from a 2.3 MHz, 16 volt, 20 cycle tone burst excitation through 1.9 mm of Aluminum is shown in figure 4. The received signal is not averaged. The SNR of

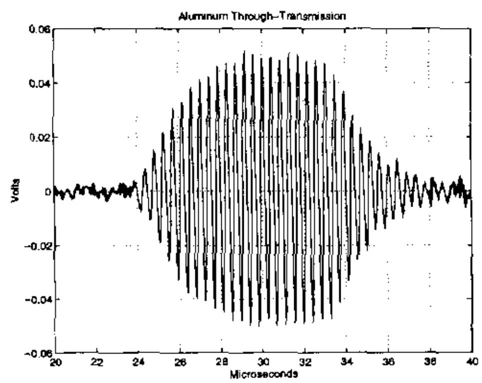

Fig. 4. Air-coupled aluminum through transmission.

the received signal is above 30 dB, implying that 110 dB of dynamic range is feasible. In order to further verify the dynamic range and the practical utility of MUTs, a 1.7 mm steel shim was placed in between the transducers. The expected loss of figure 5 is calculated with a transmission line model and material parameters found in [16]. From the figure, it is clear that a transmission system with a dynamic range of at least 105 dB is necessary. The received signal of air-coupled through transmission of steel is found in figure 6. The signal was averaged 16 times.

A proof of principle experiment was also performed to demonstrate MUTs ability to image defects in solids, using longitudinal through transmission. Images were constructed from the amplitude and phase of such transmission through a 6 mm slab

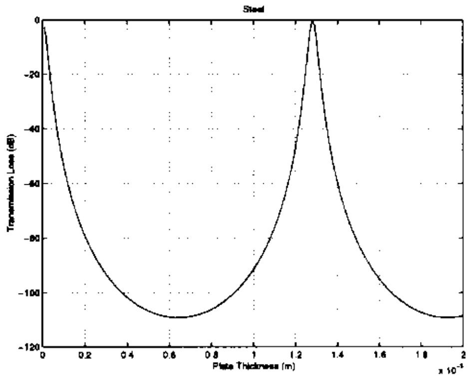

Fig. 5. Loss due to impedance mismatch of steel and air at 2.3 MHz.

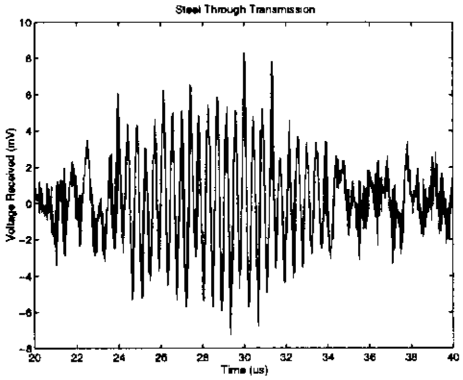

Fig. 6. Air-coupled through transmission of steel.

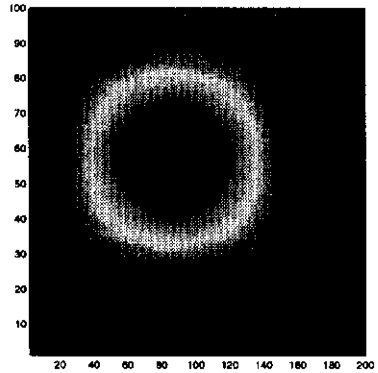

Fig. 7. Image of indentation in lucite.

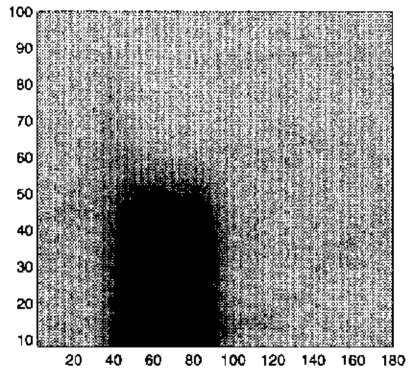

Fig. 8. Image of drilled void in lucite.

of lucite. The image of a circular indentation (5 mm diameter) is shown in figure 7. A 2 mm diameter void, formed by drilling into the side of the slab, is shown in figure 8. The units in the figure are 10 microns per unit on the horizontal axis, and 20 microns per unit on the vertical axis. The size of the imaged defect represents the convolution of the 5 mm transducer aperture and the defect. These experiments demonstrate the practical feasibility of MUTs in air-coupled NDE applications.

IV. Immersion Experiments

Immersion experiments were performed with vegetable oil to preclude any damage to the transducers' metalization from the effects of water. A suitable protective coating layer will eventually be applied to the transducers, but oil was used in the experiments due to time constraints. The real impedance of the immersion transducers is 50 Ohms at 4.5 MHz. The ratio of the imaginary to real impedance is found in figure 9. The ratio of approximately 5 is significant because it implies that tuned transducers of 20 % fractional bandwidth can be realized. If operated untuned, as in the experiments herein reported, the transducers' bandwidth is in excess of 100 % (see figure 10)[1]. Furthermore, when the effects of diffraction and impedance mismatch to the electronics are accounted for, figure 10 implies an insertion loss of only 4 dB per transducer.

The received signal from a 10 cycle, 1 Volt excitation at 4.5 MHz is shown in figure 11. The SNR at 1 V excitation was measured (by varying the oscilloscope scale) to be approximately 60 dB. Thus figures 10 and 11 demonstrate the broad bandwidth of the device and imply a dynamic range of at least 100 dB.

V. Conclusion

The experiments herein reported demonstrate the practical feasibility of using MUTs in air-coupled NDE applications. They also indicate that MUTs are an alternative to piezoelectric transducers in im-

[1]There is always a trade-off between efficiency and bandwidth, and the final design point is determined by the constraints of system design. The fluctuations in the trace are due to reflections during the CW measurement of the network analyzer

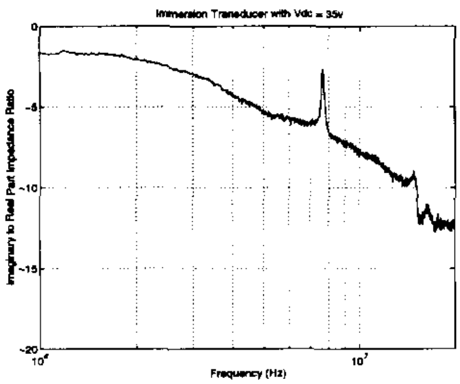

Fig. 9. Impedance ratio of an immersion MUT.

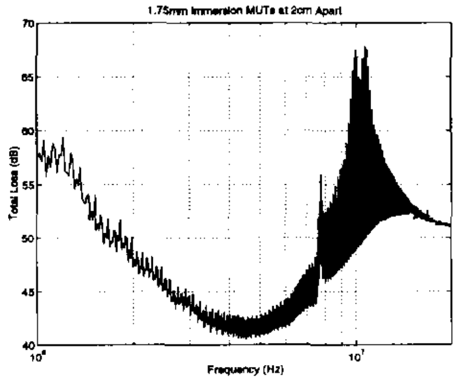

Fig. 10. Two-way insertion loss of untuned MUTs (CW measurement).

mersion applications.

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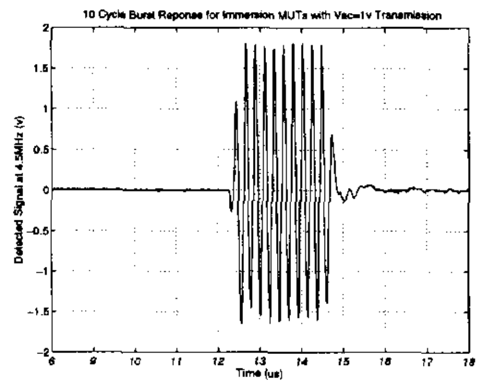

Fig. 11. Transmission of 10 cycle tone burst through oil using MUTs

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