Micromachinable Leaky Wave Air Transducers

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Abstract— **In this paper, ultrasonic air transducers which use the lowest order antisymmetric(A_0) mode Lamb waves in a thin plate as a means of efficient coupling of ultrasonic energy to air are discussed. For a silicon plate of 1μm thickness, the energy leak rates can go up to 0.6 dB per wavelength. At MHz frequencies the plate thickness should be in the range of 1-10 μm, which requires micromachined structures to be used. The radiation pattern of the transducers can be controlled by the geometry of the transducer, which can also be used for focusing. A theoretical model to calculate the efficiency and optimized transducer dimensions is presented. This model is applied to common micromachining materials such as silicon, silicon nitride and silicon dioxide. The analysis show that, with these transducers it is possible to achieve a conversion loss with a minimum of 8.7 dB and 78 % fractional bandwidth. Experimental results on transmission imaging are also presented using an implementation of the transducer operating around 580 kHz.**

I. Introduction

GENERATION and detection of ultrasound in air has a number of applications in non contact sensing, non destructive evaluation etc.[1]. Due to the large impedance mismatch conventional piezoelectric transducers are not very efficient sources of ultrasound in air. The efficiency can be increased using several matching layers which increases the losses and reduces the bandwidth of the system. Recently, several micromachined capacitive transducers have been developed. The devices made by stretching metallic membranes over micromachined grooves in silicon provide wide bandwidth, however their efficiency is low [2]. Efficient ultrasonic transmission up to 11 MHz is demonstrated using a resonant thin silicon nitride membrane over a sub-micron thick surface micromachined air gap [3], [4]. Ultrasonic wave transmission in air at 1 MHz using leaky waves has been demonstrated [5]. In this paper the leaky waves on micromachining materials are shown to be suitable for leaky wave air transducers. The transducer is analyzed and optimum dimensions and the bandwidth of the devices are derived. Finally, a conically focusing air transducer is used to show the potential of these devices for air ultrasound applications.

II. Leaky waves in thin plates

Any ultrasonic wave propagating on a solid surface radiates energy to the surrounding fluid medium if the phase velocity is larger than the velocity of sound in the fluid. The perturbation theory predicts the rate of this energy transfer very accurately for surface acoustic waves [6]. According to this approach the leak rate diverges to infinity when the phase velocity of the mode approaches to that of the fluid. More accurate models using the real part of the poles of the plane wave reflection coefficient can also be used to calculate the leak rate [5]. This approach is accurate as long as the fluid loading on the solid structure is small as in the case of air and it shows that the phase velocity of the mode should be close to the sound speed in air for high leak rates.

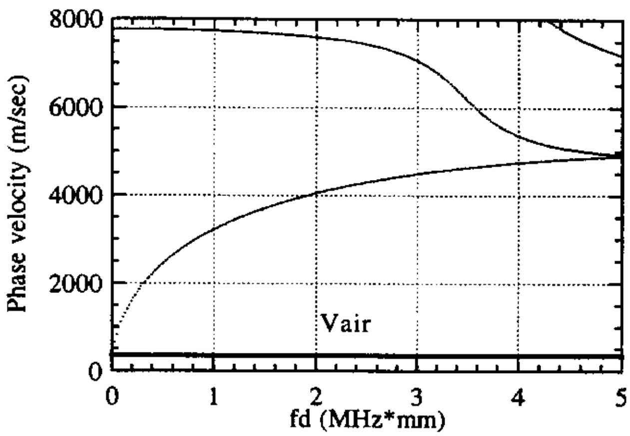

Fig. 1. Dispersion of the S_0 and A_0 mode Lamb waves in (001) cut silicon plate.

In Fig. 1, the phase velocity of the lowest order Lamb waves in a silicon plate with free boundaries is plotted as a function of the frequency thickness product (fd). It is observed that the phase velocity of the A_0 mode can be adjusted so that it is close to the sound speed in air (330 m/sec), which is shown on the graph. For example, a 1 μm thick silicon plate will have a phase velocity of 330 m/sec at 7 MHz. The phase velocity matching can be achieved using any solid with appropriate thickness. However, the leak rate of the ultrasonic energy is a function of the elastic properties of the plate and most dominantly determined by the density of the plate material. For example, high density materials such as brass and steel have much lower leak rates as compared to silicon and aluminum.

Since these thin plates are much easier to fabricate using micromachining techniques, common micromachined membrane materials are investigated as transducer materials. In Fig. 2, part of the A_0 mode dispersion curves for 1 μm thick silicon, silicon nitride and silicon dioxide plates are plotted, assuming that the films are not stressed. These film materials have already been used for Lamb wave devices [8]. The corresponding leak rates for these plates are

0-7803-4153-8/97/$10.00

plotted in Fig. 3. As expected, the leak rates have maxima when the phase velocity is close to 340 m/sec, and they go to zero when the wave in the plate is subsonic in air. These figures, given in units of dB-λ show that 50% of the power in the Lamb wave will be radiated to air in a distance of 5 λ for a 1 μm thick silicon plate at 7 MHz. Experiments confirm these theoretical leak rate calculations. So, once generated, the ultrasonic energy in the Lamb wave is transferred to air in a very short distance, providing a very efficient transduction mechanism. Since the micromachining materials have high leak rates, micromachining can be effectively used to fabricate these devices.

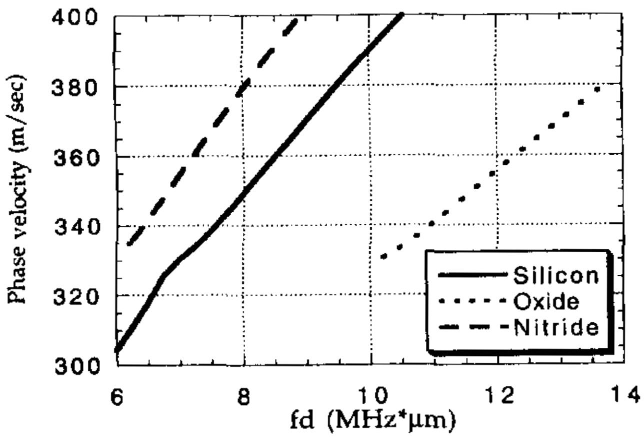

Fig. 2. Part of the A_0 mode dispersion curves of silicon, silicon nitride and silicon dioxide plates.

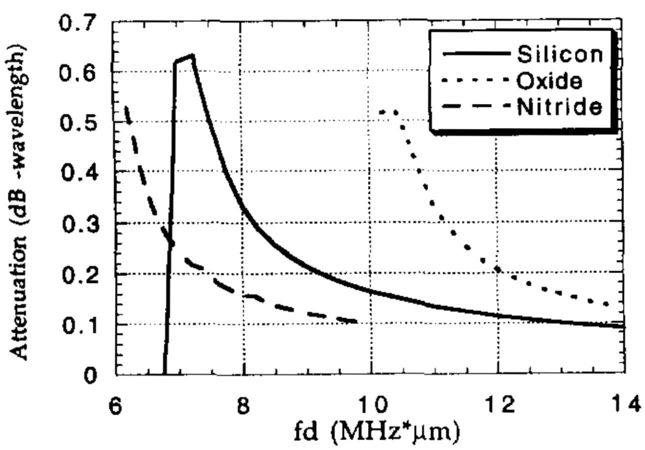

Fig. 3. Leak rates in dB-λ for the same materials in Fig. 2.

III. Analysis of the Leaky Wave Transducers

The purpose of this section is to find the characteristics of the leaky wave such as optimum dimensions, bandwidth etc. The energy transfer from the leaky wave to the ultrasonic wave in air is a mode conversion process. Hence it can be analyzed using the methodology developed for bulk mode to surface wave conversion with appropriate modifications [7].

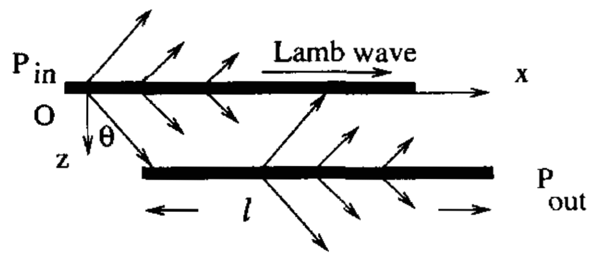

Fig. 4. Geometry and coordinates for theoretical analysis.

Referring to Fig. 4, assume that a Lamb wave propagating in the x direction with a phase velocity of $V_p = V_{air}/sin(\theta)$ in the transmitter plate. The radiated field is received by an identical transducer of length l. The total power radiated from the transmitter to the medium can be found as

$$P_{in} = \frac{|v_{iz}(0)|^2 Z_{air}}{2\alpha cos(\theta)} \tag{1}$$

where $v_{iz}(0)$ is the normal component of the incident particle velocity radiated from the transmitter at $x = 0$ and has a variation

$$v_{iz}(x) = v_{iz}(0)e^{-j\beta x}e^{-\alpha x}. \tag{2}$$

Z_{air} is the acoustic impedance of air and β and α are the real and imaginary part (i.e. the leak rate) of the the propagation constant in the x direction. It has to be noted that only half of the input power will reach the receiver since half of it is lost from the other side of the transmitter plate. This power loss can be prevented by using plate/gap/substrate structures, which will not be discussed in this paper. The Lamb wave amplitude at the receiving plate due to this incident field can be found using the normal mode theory. The expression for the normalized field amplitude at a distance x is given as

$$a_n(x) = \frac{e^{-j\beta x}e^{-\alpha x}}{2P_{nn}} \int_0^x e^{j\beta x'}e^{-\alpha x'}[v_{zt}^* T_{zt}(x') - v_{zb}^* T_{zb}(x')]dx'. \tag{3}$$

In this equation, the v_{zt} and v_{zb} are the normal component of particle velocity at the top and bottom surfaces of the plate. The incident normal stress field is denoted by $T_{zt}(x')$ and P_{nn} is the total power per unit width carried by the mode. Since for an antisymmetric mode

$$v_{zt} = v_{zb} \qquad T_{zt} = -T_{zb} \tag{4}$$

the mode amplitude of the Lamb wave at a distance l can be written as

$$a_n(l) = \frac{e^{-j\beta l}e^{-\alpha l} l v_{zt}^* v_{iz}(0) Z_{air}}{2P_{nn}cos(\theta)} \tag{5}$$

Using the relation between the mode amplitude and power the output power in the Lamb wave can be written as

$$P_{out}(l) = |a_n(l)|^2 P_{nn} = l^2 e^{-2\alpha l} \frac{|v_{zt}|^2 |v_{iz}(0)|^2 Z_{air}^2}{4P_{nn}cos(\theta)^2}. \tag{6}$$

Using the perturbation theory, the leak rate of a Lamb wave mode can be expressed in terms of the mode variables as

$$\alpha = \frac{|v_{zt}|^2 Z_{air}}{2P_{nn}cos(\theta)}. \quad (7)$$

Note that the leak rate is doubled as compared to a surface wave since the plate is perturbed by the fluid at both surfaces of the plate. Substituting this expression in Eq. 6, the output power can be found in terms of the transducer dimension and the leak rate

$$P_{out}(l) = \frac{\alpha l^2 e^{-2\alpha l} Z_{air}|v_{iz}(0)|^2}{2cos(\theta)}. \quad (8)$$

To find the optimum dimension of the transducer, the two-way efficiency is defined as the ratio of the output power to total input power. This results in the expression

$$\eta(\alpha l) = (\alpha l)^2 e^{-2\alpha l} \quad (9)$$

for the two-way efficiency of the transmitter-receiver system. Differentiating this expression with respect to αl, the maximum efficiency is found as

$$\eta_{max} = 0.135 \quad when \quad \alpha l = 1 \;\; (l = \frac{1}{\alpha}) \quad (10)$$

At this optimum value the two way insertion loss is about 8.7 dB, which shows the high efficiency of the transducer. The variation of efficiency as a function of transducer length is plotted in Fig. 5. The important conclusion is that the leak rate of the Lamb wave should be high enough so that the transducer has a feasible dimension with reasonable insertion loss levels. In case of a 1 μm thick silicon transducer the optimum dimension is about 14 λ (0.66 mm) at 7.5 MHz, which can be easily micromachined. The curve is very similar to the ones obtained for surface wave transducers and shows the importance of the transducer size for generic mode conversion based systems, a fact that is often ignored in Lamb wave applications.

Using the efficiency vs. transducer size and leak rate variation with frequency curves, one can find the bandwidth of a transducer for a given dimension. In Fig. 6 the insertion loss of a 1 μm thick silicon transducer is plotted as a function of frequency. The optimum dimension of 0.66 mm results in a 35% fractional bandwidth. Using a larger transducer one can achieve larger bandwidths due to shape of the efficiency curves and avoiding the low frequency cut-off in the subsonic regime. As an example, a 1.32 mm transducer can have a 78 % fractional bandwidth, which is appropriate for many pulse echo applications.

IV. Experimental results

A leaky wave transducer is constructed using an 18 μm thick (001) silicon plate which is epoxy bonded to a PZT-5H ring with 2.3 cm diameter as shown in Fig. 7. The transducer is polarized in the radial direction, has a thickness of 1.3 mm, and the coupling to the A_0 mode is achieved through the d_{31} coefficient. With this configuration the

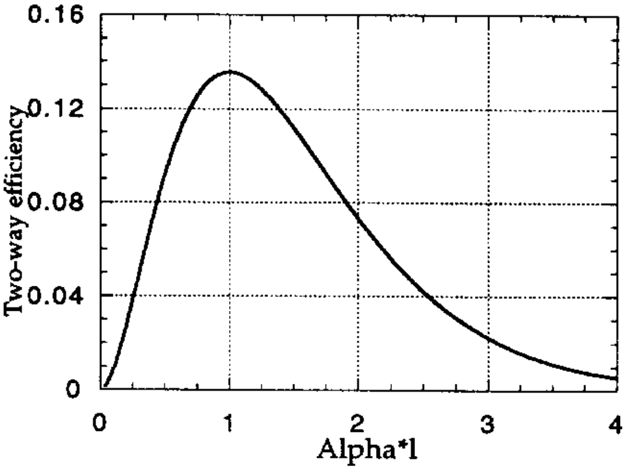

Fig. 5. Variation of the efficiency of the leaky wave transducer with transducer length-leak rate product.

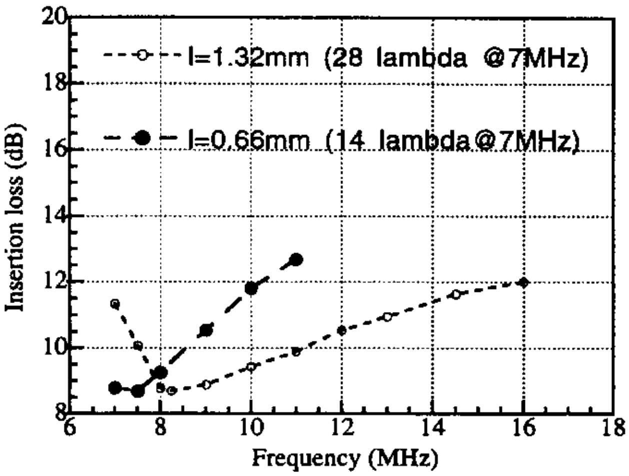

Fig. 6. The Lamb wave to Lamb wave insertion loss as a function of frequency calculated for two different transducer sizes.

device has 15% fractional bandwidth around 580 kHz. As depicted in Fig. 7 Lamb waves generated at the transducer-plate contact converge to the center of the plate while leaking ultrasonic waves to air. This results in a self line focusing device.

In Fig. 8, single shot digitized received signal is plotted when the transducers are facing each other. Total insertion loss is around 55 dB for these suboptimum devices. Although the dynamic range is not large, through transmission measurements can be done on a thin plate of steel (25 μm) and copy paper (100 μm). These experiments show transmission losses in the 40 dB range which is much smaller than the normal incidence experiments. This is the result of the mode conversion in these thin plates. When an 18 μm thick silicon plate is used in the experiment, the transmission loss is only 17 dB, since the plate is well phase matched to the leaky waves.

The focusing and imaging ability of the device is also

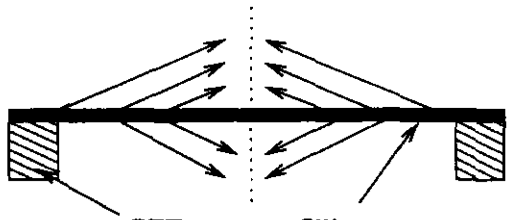

Fig. 7. Schematic of the self line focusing leaky wave transducer.

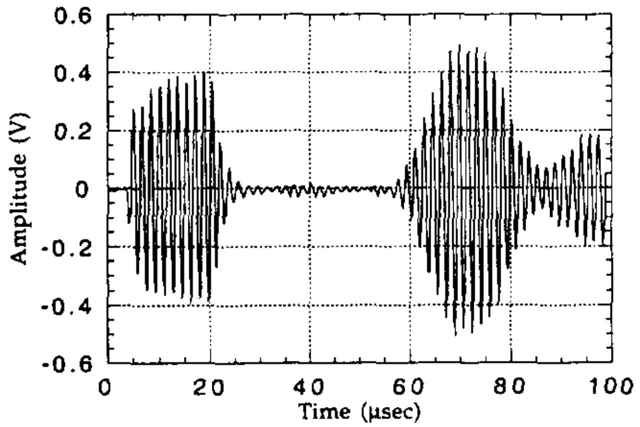

Fig. 8. Digitized transmitted signal with 9 mm separation between transducers.

measured using a scanning imaging system. Fig. 9 shows the amplitude variation of the received signal when a straight edge is scanned. The 3 dB resolution of the transducer is approximately 1 mm, which is less than 2 wavelengths in air. In Fig. 10, the transmission image through a 1 mm diameter hole in 25 μm thick steel plate is shown. The image size is 1 cm x 1 cm. The high resolution and the interference fringes of Lamb waves in the plate indicate the efficiency of mode conversion and high resolution imaging capability of the transducers.

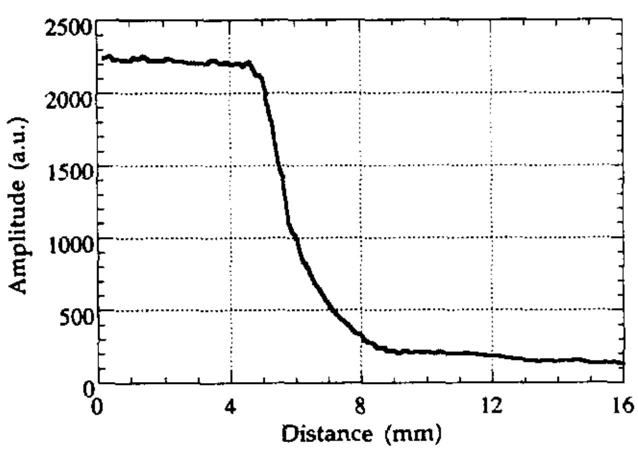

Fig. 9. Line scan of a straight edge between the transducers.

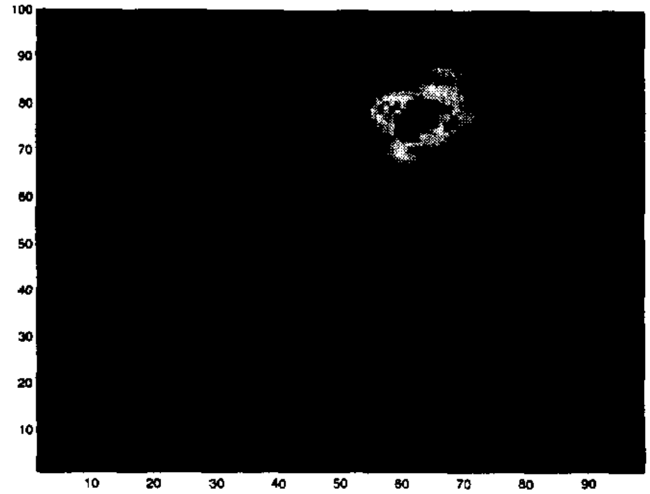

Fig. 10. Transmission image of a 1 mm diameter hole in 25 μm thick steel membrane.

V. Conclusion

Leaky Lamb waves in thin plates provide an efficient means to couple ultrasonic energy to air. The theoretical analysis presented in this paper shows that it is possible to achieve both high efficiency and wide bandwidth ultrasonic wave transduction using leaky wave air transducers. The analysis also shows that it feasible to fabricate these transducers using micromachining techniques. The experiments on large scale devices indicate that leaky wave transducers can be used in many ultrasound imaging and sensing applications in air in a wide frequency range.

VI. Acknowledgments

This work is supported by the US Office of Naval Research.

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