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Development of a Spherically Focused Capacitive-film Air-coupled Ultrasonic Transducer

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Abstract We have built a spherically focused, not using acoustic mirrors, capacitive micromachined air-coupled ultrasonic transducer. A flexible backplate of a copper/polyimide backplate is used, permitting it to conform to a spherically shaped substrate. The backplate is patterned with 40-μm depressions having 80-μm center-to-center spacing. A 6-μm thick aluminized Mylar film completing the transducer is deformed to allow it to conform to the spherical backplate. The device's frequency spectrum is centered at 805 kHz with -6 dB points at 440 and 1210 kHz.

Keywords: spherical, focused, air-coupled, capacitive, ultrasound transducer

1. Introduction

Air-coupled ultrasonic transducers are becoming more widely used in nondestructive evaluation because they are practical and efficient when the test article under inspection cannot be brought into contact with water. The unique characteristics of air as a coupling medium, such as short sound wavelength, have encouraged the development of more applications, despite the large signal-to-noise penalty typically associated with this form of ultrasonic inspection. Currently, most air-coupled ultrasonic inspection methods utilize either conventional piezoceramic transducers or capacitive film transducers. When a solid piezoceramic transducer is used to couple sound into air, the large acoustic impedance mismatch between the element and air renders broadband matching nearly impossible (Carr and Wykes, 1993). Although the piezoceramic transducers employ impedance matching layers, they are narrowband and operate in low frequency range. Recently, microfabrication techniques have been used to fabricate capacitive ultrasonic transducers (Haller and Khuri-Yakub, 1996, Suzuki et. al., 1999). Indeed, these techniques provide a means to fabricate the capacitive air-coupled transducers with low fabrication cost, high reliability, relatively high sensitivity, and reasonably wide bandwidth. Capacitive film transducers skirt the impedance mismatch problem by using a thin polymer film of low areal density as the vibrating element.

As interest in air-coupled ultrasonics has grown, much additional effort is being invested in the development of transducers suitable for air-coupled use, optimized for transducer sensitivity, as well as imaging resolution. One natural way to increase transducer sensitivity, often used with water-coupled devices, is to focus the transducer beam. So far, this goal has largely eluded investigators, except for the use of Fresnel zone plates (Schindel 1998), cylindrical focusing (Robertson et. al. 2002), or acoustic mirrors

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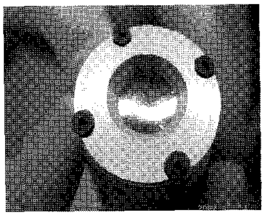
(Holland et. al. 2004). The Fresnel zone plate approach has low sensitivity and limited bandwidth, the cylindrical focusing leaves one dimension unfocused, and the acoustic mirrors suffer from incomplete focusing owing to diffraction effects. The challenge remains to fabricate a natively focused capacitive micro-machined transducer. Because brittle silicon wafers are typically used as one side of the capacitor, little progress has been made.

In this paper, we present the development of a spherically focused capacitive film air-coupled transducer, utilizing a spherically deformed backplate and conformal metalized polymer film in the shape of a spherical radiator.

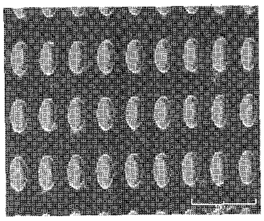
2. Transducer Fabrication

Our 10-mm spherically focused capacitive-film transducer is fabricated with a 25.4 mm geometric focal length and an active angular sensitivity of $\pm 15^\circ$ with respect to the normal axis. It is designed to excite a large range of plate wave modes when in normal incidence for low-density engineering materials, such as plastics, carbon or glass-fiber composites. A fully constructed spherically focused capacitive film transducer is shown in Figure 1(a). Our spherically focused capacitive-film air-coupled spherical transducer consists of a thin metalized polymer membrane, micro-machined flexible backplate, and spherically curved backing fixture. The metalized polymer membrane is constructed in two layers: one is a 6-μm thick Mylar, and the other is a 100-nm thick aluminum metallization. Instead of the brittle and inflexible silicon backplate, our backplate is fabricated using a flexible copper/polyimide substrate, commonly used for flexible printed circuit board designs. The flexible backplate consists of 17-μm thick copper layer and 13-μm thick polyimide substrate. The copper layer is patterned with circular depressions (40-μm in diameter and 80-μm center-to-center) fabricated by wet etching. As shown in a SEM image in Figure 1(b), the patterns are dimple shape as result of isotropic wet etching. The etched depth in the center of the dimple is found to be approximately 10-μm deep. Then, the backplate is carefully deformed to conform to a machined spherically curved backplate fixture, whose radius is the same as the desired geometric focal length of the transducer.

To assist the metalized Mylar film in conforming to the spherical backplate, we slightly stretch the Mylar film using a steel ball bearing. The radius of the ball bearing is approximately the same as the geometric focal length of the spherically focused capacitive transducer. After stretching the Mylar film, it assumes a spherical shape and can be fitted directly to the copper/polyimide backplate without wrinkling, when a bias voltage is also applied as in operation. This simple process completely suppresses all wrinkles, which might occur if we were to attempt to apply the Mylar film directly to the spherically curved backplate. Details of the conformal film fabrication are reported elsewhere (Jun-Ho Song, 2005).



(a)

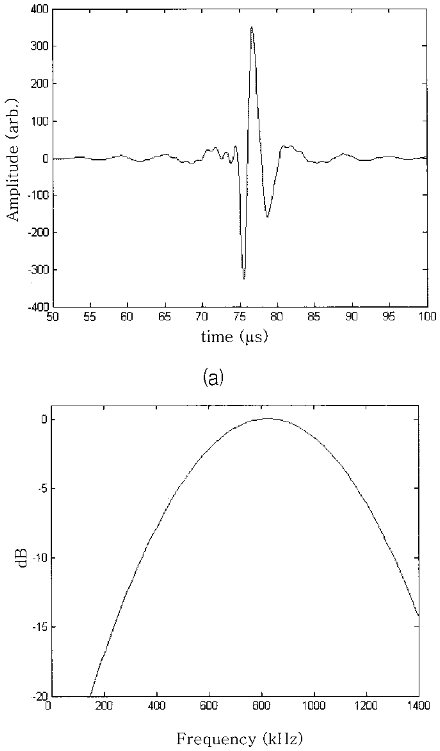


(b)

Fig. 1 (a) A photograph of a 5 mm radius, 25.4 mm focal length spherically focused capacitive micromachined air-coupled ultrasonic transducer. A white line on a 6 mm Mylar/Al film is the reflection of a light source. (b) A SEM image of a flexible copper/polyimide backplate.

3. Transducer Characterization

To study the characteristics of our transducer, the sound pressure fields are measured by scanning a 200 μm diameter quasi-point receiver and recording its output voltage versus position. We drive the quasi-pint receiver at 250 V using a broadband signal. Figure 2(a) shows the typical response of our spherically focused capacitive transducer, and Fig. 2(b) shows its corresponding frequency spectrum. The latter shows that the frequency spectrum is centered at 805 kHz with a 6 dB bandwidth of approximately 770 kHz, which is measured at a lower and upper frequency of approximately 440 and 1210 kHz, respectively.

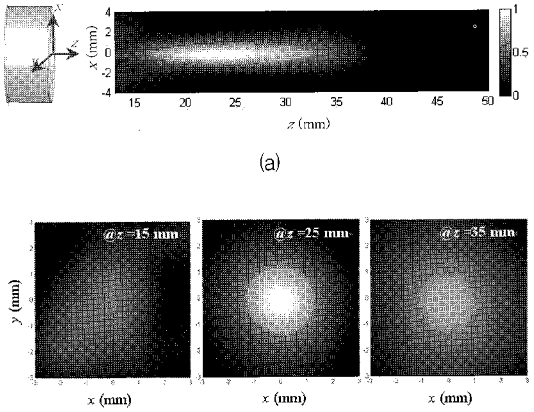


(a)

(b)

Fig. 2 Typical amplitude response and corresponding frequency spectrum: (a) normalized signal amplitude, and (b) corresponding frequency spectrum. The quasi-point receiver has a 200 Vdc bias, and the transmitter is driven by a broadband excitation at 250 V peak-to-peak.

Figure 3(a) shows the pressure fields for broadband excitation in the *x*-*z* plane at *y* = 0, radiated from the spherically focused capacitive air-coupled transducer whose geometric focal length is 25.4 mm. The sound field is scanned in the *x*-*z* plane with spatial resolutions of 0.1 mm and 0.2 mm in the *x*- and *z*-axis, respectively. The origin of the coordinate system is located at the center of the concave face of the spherical backplate in the spherically focused capacitive transducer. The figures show peak-to-peak sound field amplitudes at each point where brighter regions represent much stronger sound field amplitude than darker regions. The focal zone extends from 17.1 mm and 34.1 mm, respectively. The maximum amplitude is shown at *z* = 24.9 mm. Figure 3(b) shows the measured sound field for broadband signal in the *x*-*y* plane at *z* = 15 mm, 25 mm, and 35 mm. The figure clearly shows a point focusing performance of the transducer.



(a)

(b)

Fig. 3 Measured sound pressure fields radiated from a 5 mm radius, 25.4 mm focal length spherically focused air-coupled transducer driven by broadband transient signals: (a) sound pressure field in the x-z plane at y = 0, and (b) sound pressure fields in the x-y plane at z = 15, 25 and 35 mm. Brighter regions represent stronger sound pressure fields than darker regions.

To evaluate the focusing performance of our spherically focused transducer, we have compared its measured field with a theoretical prediction using the Rayleigh-Sommerfield model (Schmerr, 1998). Figure 4 shows the cross section of the focal region of the measured and theoretical sound pressure fields for a 10-cycle 800 kHz tone burst excitation, radiated from the spherically focused air-coupled transducer. The sound pressure from a focused piston radiator is

$$p(R_0,y,\omega)=-i\omega\rho v_0 a^2\left[\exp(ik\overline{R}_0)/\overline{R}_0\right]\left[J_1(kay/\overline{R}_0)/(kay/\overline{R}_0)\right] \tag{1}$$

where R_0 is the focal length, $\overline{R}_0=\sqrt{R_0^2+y^2}$, y is the radial distance, k is the wave number, ρ is the mass density of the medium, p is the radiating sound pressure, a is the radius of a piston transducer, v_0 is the piston velocity (assumed uniform over the face of the radiator), and J_1 is the first-order Bessel function. The calculation has no adjustable parameters except for the arbitrary amplitude. Our measurements are obtained at the focal zone for each excitation signal, which we have found in the x-z plane scan. The full width at half maximum (FWHM) value, or 6 dB drop-off point, is measured to be 1.38 mm, and its theoretical prediction is 1.37 mm. The theoretical prediction is sufficiently close to the experimental measurements for us to conclude that our device is operating like an ideal spherically focused piston radiator.

To show excellent imaging capabilities of our spherically focused transducer, we have scanned a 20 mm thick aluminum honeycomb and a 25 mm thick Balsa wood in through-transmission configuration with 1 mm step size. Figure 5 (a) shows the C-scan image of four bonded 38.1 mm diameter titanium inserts in the aluminum honeycomb panel. Figure 5(b) shows the C-scan image of a 25 mm thick Balsa wood. It clearly shows the defects, annual rings and burls on the Balsa wood.

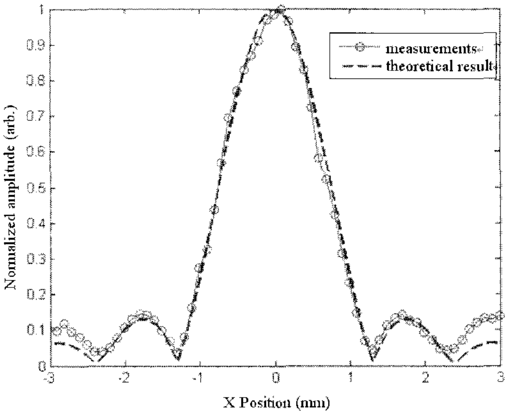
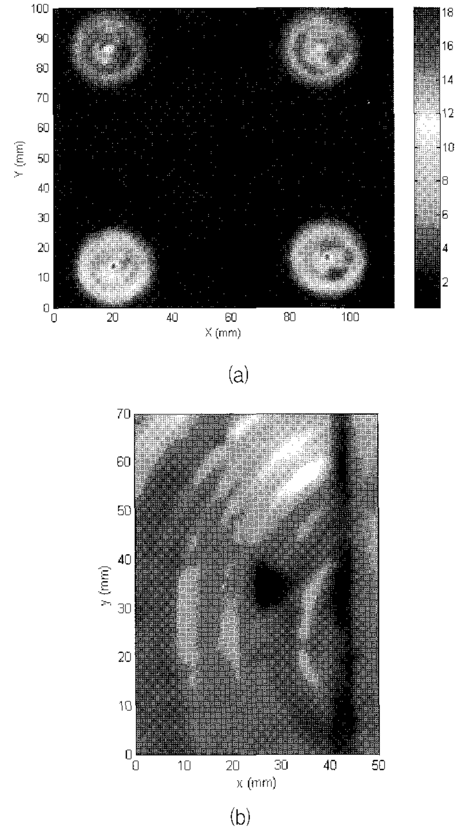


Fig. 4 Cross sections of the focal region of the measured and theoretical sound pressure fields radiated from a 10 mm diameter, 25.4 mm focal length, spherically focused air-coupled transducer when driven by an 800 kHz tone burst.



(a)

(b)

Fig. 5 C-scan images of (a) four bonded, 38.1 mm diameter titanium inserts in an aluminum honeycomb, and (b) A 25 mm thick Balsa wood

4. Summary

In summary, we have demonstrated a simple, yet reliable, fabrication method to produce natively focused micromachined capacitive air-coupled spherical ultrasonic transducers. By selecting a flexible substrate as a backplate, we eliminate one of the most difficult and unsolved problems in a curved backplate fabrication. Moreover, because our device is natively focused, this transducer eliminates the need for auxiliary devices, such as acoustic mirrors, to focus air-coupled acoustic beams. We have tested this device and demonstrated that it behaves accurately like a spherically focused piston radiator.

Acknowledgememts

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