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High Frequency (>30MHz) Flexible Broadband Transducers

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I. Motivation/Background

Ultrasonic techniques have been widely used for nondestructive evaluation and clinical diagnoses. General features desired for medical ultrasonic probes are broad bandwidth, efficient acoustic coupling to human body with safety, sufficient signal strength, high sensitivity and high signal-to-noise ratio. Piezoelectric lead zirconate titanate (PZT) are commonly used as ultrasonic transducer (UT) materials because of its superior electromechanical efficiency. In disk forms its ultrasonic frequencies lower than 20MHz are often used in conventional medical diagnostics. However, higher frequencies are desirable for high quality imaging of tissue microstructures. At higher frequencies thin disks become difficult to be fabricated due to its brittleness. On the other hand, piezoelectric polymers such as polyvinylidine fluoride (PVDF) become attractive UT materials because of its flexibility. In either material, backing materials need to be constructed onto one side of the UT in order to achieve the broadband width, which makes the probe bulky and non-flexible.

II. Statement of the Contribution/Methods

Flexible UT arrays consisting of a thin substrate, a bottom electrode if the substrate is an insulator, a piezoelectric composite ceramic layer and a top electrode with a total thickness less than 100μm have been produced. Polyimide film, aluminum foil and stainless steel foil were used as substrates. On top of polyimide film a thin (<1 μm thick) nickel alloy layer was coated as the bottom electrode by electroless plating. PZT ceramic film of less than 40μm thick was made by a sol-gel spray technique. The density and the thickness of the film were optimized so that high frequency ultrasound can be efficiently generated and received. The top electrodes were made by the colloidal silver spray. Each top electrode of the UT array had a size of 3mm by 3mm and this size may be varied with ease. Due to the porosity inside the film and thin substrate, high flexibility and broadband width is realized.

III. Results/Discussion

Ultrasonic measurements of these three types of flexible UT have shown that their frequency components may be higher than 30MHz and the 6dB bandwidth can reach 100%. In comparison to PVDF type of flexible transducers the receiving sensitivity of the developed flexible UTs is comparable, however, their signal strength, frequency bandwidth and signal to noise ratio in the pulse echo measurement are higher. The developed UTs can work up to 150°C and PVDF UT cannot. When another layer of polyimide was used to cover the PZT film side of the UT, such flexible UT can be used as a water immersion transducer. Theoretical calculations on coupling efficiency between these transducer substrates with respect to water and fat have been carried out and the polyimide flexible UT can transmit more energy into the human flesh than the two other types.

High Frequency (>30 MHz) Flexible Broadband Transducers

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***Abstract*—Flexible ultrasonic transducer (UT) arrays consisting of a thin substrate, a bottom electrode if the substrate is an insulator, a piezoelectric composite ceramic layer and a top electrode with a total thickness less than 100 µm have been produced. A stainless steel foil, aluminum foil and polyimide film were used as a substrate. On top of the polyimide film a thin (<1 µm thick) nickel alloy layer was coated as a bottom electrode by an electroless plating method. A lead zirconate titanate (PZT) ceramic film of 30 µm thick was made by a sol-gel spray technique. The density and thickness of the PZT film were optimized so that high frequency ultrasound can be efficiently generated and received. An array of top electrodes was made by a colloidal silver spray. Each top electrode of the UT array had a size of 3 mm by 3 mm and this size may be varied with ease. Due to the porosities inside the PZT film and thin substrate, high flexibility and broad bandwidth of the developed UTs have been realized. Ultrasonic measurements with these three types of flexible UTs have shown that their frequency components could be higher than 30 MHz and the 6-dB bandwidth can reach 80%. It is also shown that the polyimide film could be a suitable substrate material of the flexible UTs for ultrasonic measurements in tissue and tissue-like materials due to its good acoustic coupling to such materials. The presented flexible UT fabrication technique allows a selection of the substrate material (either polymer or metal) with a thickness suitable for the specimen to be characterized.**

Keywords-flexible ultrasonic transducers; array transducres; high frequency; thick piezoelectric ceramic film; polyimide; sol-gel air spray

I. INTRODUCTION

Ultrasonic techniques have been widely used for nondestructive evaluation and clinical diagnoses. General features desired for medical ultrasonic probes are broad bandwidth, efficient acoustic coupling to human body with safety, sufficient signal strength, high sensitivity and high signal-to-noise ratio. Piezoelectric lead zirconate titanate (PZT) is commonly used as ultrasonic transducer (UT) materials because of its superior electromechanical efficiency.

In disk forms, its ultrasonic frequencies lower than 20 MHz are often used in conventional medical diagnostics. However, higher frequencies are desirable for high quality imaging of tissue microstructures. At higher frequencies, thin disks become difficult to be fabricated due to its brittleness. On the other hand, piezoelectric polymers such as polyvinylidine fluoride (PVDF) become attractive UT materials because of its flexibility [1, 2]. In either material, backing materials often need to be constructed onto one side of the UT in order to achieve the broad bandwidth, which makes the probe bulky and non-flexible.

In this paper, flexible UT arrays consisting of a thin polymeric or metallic substrate, a bottom electrode if the substrate is an insulator (i.e. polymeric substrate), a piezoelectric composite ceramic layer and a top electrode with a total thickness less than 100 µm have been produced. The ultrasonic performance of the UTs developed is presented and an application for tissue and tissue-like material characterization is discussed.

II. TRANSDUCER FABRICATION

The fabrication process is based on a sol-gel composite spray method developed previously [3, 4]. The piezoelectric PZT powders were purchased with a particle size distribution of 1-3 µm. The powders were dispersed into a PZT sol-gel solution by a ball milling method to achieve the paint.

A 38-µm thick stainless steel (SS) foil, 22-µm thick aluminum (Al) foil and 50-µm thick polyimide (PI) film were chosen as a thin substrate assuring the flexibility of the transducer. The thickness of each material was chosen so that the substrate is flexible but stable enough during the UT fabrication. It is noted that substrates thinner than the presented ones are also applicable.

The SS and Al foils serve as both the substrate and bottom electrode, while on top of the PI film, a thin (<1 µm thick) nickel alloy layer was coated as the bottom electrode by an electroless plating method. Then, a PZT ceramic film was made by a sol-gel spray technique.

After each PZT layer spray, thermal treatments such as drying, firing and annealing were carried out. Each layer had a thickness of 5-15 µm and a few layers were made until the film reached the desired thickness. The final PZT composite film thickness was 30 µm measured by a micrometer. The film was then electrically poled using a corona discharging technique. The corona poling method was chosen because it could pole the piezoelectric film over a large area with different curvatures and with ease.

The longitudinal wave velocity and density of the sol-gel PZT composite film fabricated were measured and found to be 2230 m/s and 4370 kg/m^3, respectively. These values were

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about 40% smaller than those of the raw PZT material due to the porosities inside the film.

Finally, top electrodes were made by a colloidal silver spray. The thickness of the silver top electrode was about 1 μm. 3 x 4 array flexible UTs fabricated with substrates of a SS foil, an Al foil and a PI film are shown in Figs. 1 (a), (b) and (c), respectively. Each top electrode of the UT array had a size of 3 mm by 3 mm and this size may be varied with ease. The developed UTs can work up to 150°C. When another layer of a polyimide film is used to cover the PZT film side of the UTs, such flexible UTs can be used as a water immersion transducer.

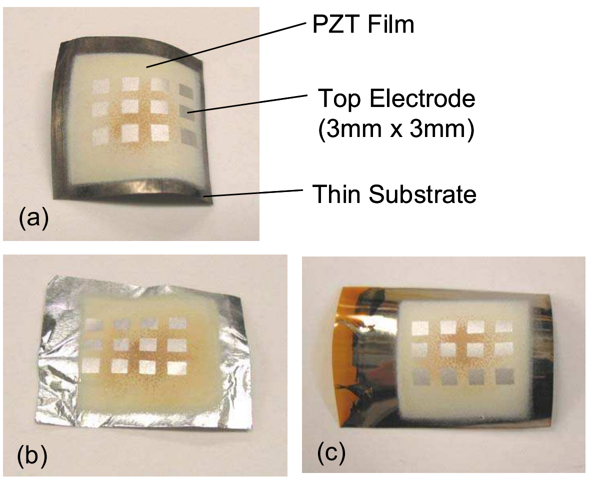

Figure 1. 3 x 4 array flexible UTs developed. Substrate: (a) 38-μm thick SS foil; (b) 22-μm thick Al foil; and (c) 50-μm thick PI film. The SS and Al foils serve as both the substrate and bottom electrode, while a nickel alloy layer (<1 μm thick) was deposited on the PI film substrate as a bottom eleoctrode.

III. ULTRASONIC PERFORMANCE

Pulse-echo measurements using developed flexible UTs were conducted to evaluate their ultrasonic performance with an 8-mm thick aluminum alloy plate as a sample. The experiments were carried out using a single UT arbitrary chosen among twelve UTs for each flexible UT in Fig. 1. Clear echoes (more than five round trip echoes) reflected from the bottom of the sample were observed. Figs. 2, 3 and 4 present the results of the first echo obtained with the SS, Al and PI flexible UTs, respectively, in the (a) time domain and (b) frequency domain.

The center frequency and 6-dB bandwidth were respectively 18 MHz and 12 MHz (67%) for the SS UT, 30 MHz and 14 MHz (47%) for the Al UT, and 36 MHz and 28 MHz (78%) for the PI UT. Reasonably broad bandwidths (50-80%) have been achieved with these UTs for pulse-echo measurements. The PI UT had the highest center frequency (36 MHz) and the widest bandwidth (78%) among the three UTs developed.

The center frequency varied depending on the substrate material as seen in Figs. 2-4 (b). This is probably due to the different resonant conditions determined by the UT configuration with multiple layers, and the acoustic impedance and thickness of each layer. It is noted that a half, a quarter and three quarter wavelength resonant frequencies of the 30-μm thick sol-gel PZT composite film are 37.2 MHz, 18.6 MHz and 55.8 MHz, respectively, assuming that the longitudinal wave velocity of the PZT film is 2230 m/s.

The center frequency of the PI UT (36 MHz) was close to a half wavelength resonant frequency (37.2 MHz) and that of the SS UT (18MHz) to a quarter wavelength resonance (18.6 MHz). The variations of the center frequency and bandwidth among the three UTs developed will be further discussed in the following section.

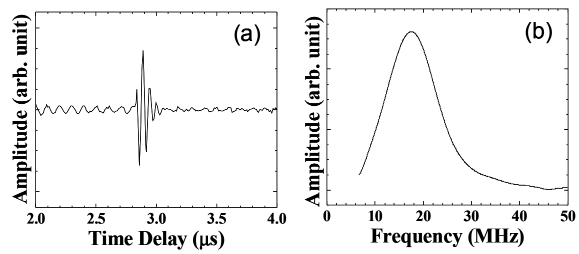

Figure 2. Ultrasonic performance of a flexible UT fabricated with a SS foil shown in Fig. 1 (a), measured with an 8-mm thick aluminum alloy plate in pulse-echo mode: (a) first round trip echo; and (b) frequency spectrum.

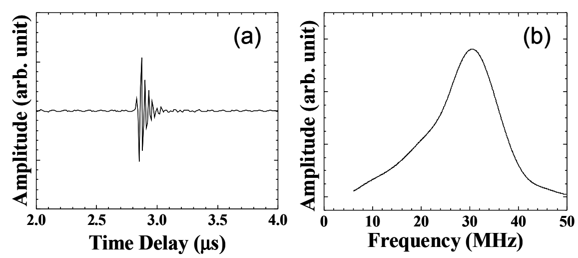

Figure 3. Ultrasonic performance of a flexible UT fabricated with an Al foil shown in Fig. 1 (b), measured with an 8-mm thick aluminum alloy plate in pulse-echo mode: (a) first round trip echo; and (b) frequency spectrum.

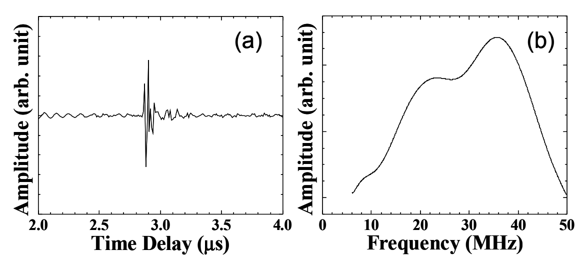

Figure 4. Ultrasonic performance of a flexible UT fabricated with a PI film shown in Fig. 1 (c), measured with an 8-mm thick aluminum alloy plate in pulse-echo mode: (a) first round trip echo; and (b) frequency spectrum.

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IV. Discussions

A. Frequency Spectrum

In order to investigate the frequency spectrum variations with the different substrate materials of the UTs presented in Figs. 2-4 (b), numerical calculations were carried out. We used the transfer matrix formulation [5] to calculate the resonant characteristics of multi-layered structures composed of a top electrode, a PZT composite film, a bottom electrode in case of a PI substrate, a substrate, and water couplant in contact with an aluminum sample. The technique is also useful to determine the ultrasonic response of multi-layered structures including lossy viscoelastic materials such as tissues and tissue-like materials.

Since the transfer matrix formulation does not consider the conversion loss of the UTs, calculated spectra outside of the resonant frequencies regions of the PZT film may not accurately reflect the experimental spectra. Therefore, we only discuss the resonant frequency regions of the 30-μm thick sol-gel PZT composite films fabricated on the SS, Al and PI substrates.

In the calculation, the longitudinal wave velocity of 2230 m/s and density of 4370 kg/m^3 for the sol-gel PZT composite film described above were used. The calculated transmission spectra for the SS, Al and PI UTs with an aluminum sample are presented in Figs. 5 (a), (b) and (c), respectively. A fairly good agreement of the tendency of the center frequency variations is found between the experimental (see Figs. 2-4 (b)) and calculated results.

However, the experimental spectra have wider bandwidth than the calculated results. In particular, the steep dip between 30 MHz and 40 MHz appearing in the calculated spectrum of the PI UT in Fig. 5 (c) is only shallow in the experimental result in Fig. 4 (b). We believe that this is due to the porosities inside and nonuniformity of the sol-gel PZT film, e.g. their impact in conversion loss, which were not considered in the calculations. This aspect will be further investigated with a more complete model and analysis in a near future.

B. Tissue Characterization

In order to study ultrasonic performance of developed flexible UTs for biomedical applications such as tissue characterization, pulse-echo measurements with a 1-mm thick silicone rubber as a sample were carried out using the SS, Al and PI UTs in Fig. 1. A first round trip echo and its frequency spectrum are shown in Fig. 6 (a) and (b), respectively, obtained using the PI UT.

Due to high ultrasonic attenuation in the silicon rubber and relatively large sample thickness, high frequency components excited by the PI UT were significantly attenuated, resulting in a center frequency of about 7 MHz for the first echo observed. In addition, echoes were not observed using the SS and Al UTs. This indicates that the PI UTs may be suitable for ultrasonic measurements in tissue and tissue-like materials due to its good acoustic coupling to such materials.

The PI film substrate could work as an acoustic impedance matching layer between the sol-gel PZT composite and tissue materials by choosing an appropriate thickness of the PI film. For instance, an acoustic impedance (Z_m) of the matching layer can be calculated by $Z_m = (Z_{PZT} \times Z_w)^{1/2} = 3.8 \times 10^6$ kg/m^{2}s, where Z_{PZT} (= 9.7×10^6 kg/m^{2}s) and Z_w (= 1.5×10^6 kg/m^{2}s) are the longitudinal wave acoustic impedances of the sol-gel PZT composite and water, respectively. The acoustic impedance of the PI film is 3.4×10^6 kg/m^{2}s, that is close to the Z_m, while those of the SS and Al foils are 46×10^6 kg/m^{2}s and 17×10^6 kg/m^{2}s, respectively [6].

The thickness (d_{PI}) of the PI substrate as a matching layer would be a quarter wavelength given by $d_{PI} = V_{PI}/4/f_0$, where V_{PI} is the longitudinal wave velocity of the PI film and f_0 is the center frequency of the UT. For instance, the d_{PI} is calculated to be 20 μm when f_0 = 30 MHz and V_{PI} = 2400 m/s.

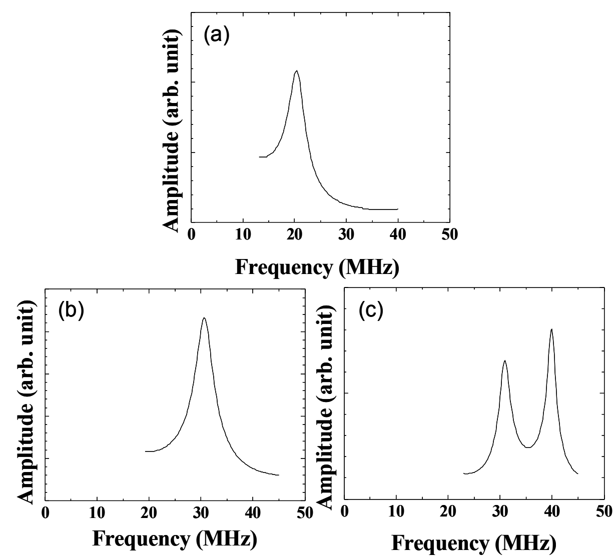

Figure 5. Calculated transmission spectra of flexible UTs with an aluminum sample: (a) SS UT; (b) Al UT; and (c) PI UT.

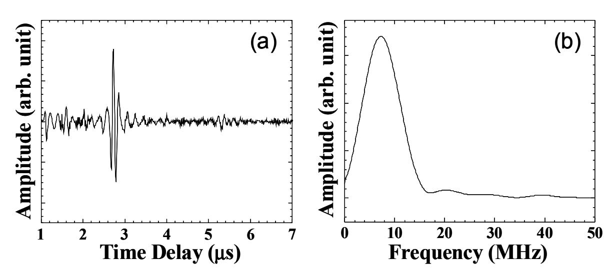

Figure 6. Result of a pulse-echo measurement with a 1-mm thick silicone rubber as a sample using the PI UT: (a) first round trip echo; and (b) frequency spectrum.

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V. Conclusions

Flexible UT arrays consisting of a thin substrate, a bottom electrode if the substrate is an insulator, a piezoelectric composite ceramic layer and a top electrode with a total thickness less than 100 µm have been produced. A 38-µm thick SS foil, 22-µm thick Al foil and 50-µm thick PI film were used as the substrate.

On top of the PI film, a thin (<1 µm thick) nickel alloy layer was coated as the bottom electrode by an electroless plating method. A sol-gel PZT ceramic film having 30-µm thickness was made by a sol-gel spray technique. A 3 x 4 array of top electrodes was made by a colloidal silver spray. Each top electrode of the UT array had a size of 3 mm by 3 mm and this size may be varied with ease. Due to the porosities inside the PZT film and thin substrate, high flexibility was realized. The developed UTs can work up to 150°C. When another PI film is used to cover the PZT film side of the UT, such flexible UT can be used as a water immersion transducer.

The center frequency and 6-dB bandwidth were respectively 18 MHz and 12 MHz (67%) for the SS UT, 30 MHz and 14 MHz (47%) for the Al UT, and 36 MHz and 28 MHz (78%) for the PI UTs. Reasonably broad bandwidths (50-80%) have been achieved with these UTs for pulse-echo measurements. The PI UT had the highest center frequency (36 MHz) and the widest bandwidth (78%) among the three UTs developed.

Theoretical calculations indicate that the variation of the center frequency among three UTs with different substrate materials was due to the different resonant conditions of each UT configuration. The broad bandwidth might be attained due to the porosities inside and nonuniformity of the PZT film.

It is also indicated that the PI film could be a suitable substrate material of the flexible UT for ultrasonic measurements in tissue and tissue-like materials due to its good acoustic coupling to such materials. The presented flexible UT fabrication technique allows a selection of the substrate material (either polymer or metal) with a thickness suitable for the specimen to be characterized.

In future work, we will combine the transfer matrix formulation technique with Mason [7-9] and/or KLM [10] model of UTs including the effect of the porosities inside sol-gel PZT composites to study the entire ultrasonic performance of flexible UTs applied for multi-layered viscoelastic material characterization in order to optimize the flexible UT design.

Acknowledgment

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