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Ultrasonic transducers with functionally graded piezoelectric ceramics

Noboru Ichinose*, Naohiko Miyamoto, Sadayuki Takahashi

School of Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555 Japan

Abstract

Ultrasonic transducers used for measurement systems are required having a capability of generating a short time waveform ultrasonic pulse, i.e., a broadband frequency spectrum. In order to obtain the broadband transducer, functionally graded piezoelectric ceramics with a ceramic backing are fabricated and their ultrasonic performances are examined. Gradient of the piezoelectric parameter is realized by sintering a layer-structured ceramic green body composed of piezoelectric ceramic calcined powder layers with various compositions or composed of green sheets containing calcined powder mixed with some organic materials. It has been found that the above transducer generates an ultrasonic wave with a broader frequency spectrum compared with that of the conventional one.

Keywords: Broadband frequency spectrum; Ceramic backing; Functionally graded piezoelectric ceramics; Green sheet technology; Ultrasonic transducers

1. Introduction

Ultrasonic transducers composed of a piezoelectric ceramic have been widely used in ultrasonic measurement systems such as nondestructive testing and medical diagnosis. Transducers are required having a capability of generating a short time waveform ultrasonic pulse, i.e., a broadband frequency spectrum, in order to achieve high resolution ultrasonic imaging. Conventional ultrasonic transducers are basically composed of a uniform piezoelectric ceramics plate and a backing which is bonded to the ceramic plate back face. The ultrasonic pulse time waveform of the conventional transducer, however, is not sufficiently short, because the transducer generates ultrasonic pulse at both surfaces of the ceramic plate upon impulse excitation and these pulses are repeatedly reflected between one face and the other.

Recently, Yamada et al., have succeeded in creating a functionally graded piezoelectric ceramics (FGM) plate by giving a temperature gradient in the thickness direction and have found that the FGM transducer with a ceramic matched backing, bonded together with an adhesive, generates a short time waveform ultrasonic pulse.[1]

In this study, FGM transducers with a ceramic matched backing are fabricated by sintering a layer-structured ceramic green body without using any adhesive materials.[2] Individual layer is a thin layer of piezoelectric ceramics calcined powder or a ceramic green sheet composed of the calcined powder with some organic binder, plasticizer and solvent. The composition of the calcined powder in every layer is different one another. Then, piezoelectric and ultrasonic wave generation characteristics are examined.

2. Experimental

2.1. Materials

Fig. 1 shows pseudo-ternary solid solution system of $(1-x)Pb(Ni_{1/3}Nb_{2/3})O_3-xPb(Zr_{0.3}Ti_{0.7})O_3$ ceramics with a composition of $x = 0.50$, 0.45, 0.40, 0.35 and 0.30 which were used for FGM transducers.

Fig. 2 indicates dielectric constant ϵ before poling, electromechanical coupling factor in radial vibration mode k_p and in thickness vibration mode k_t for an individual composition ceramic. The ceramic with

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* Corresponding author.

E-mail address: ichinose@waseda.jp (N. Ichinose).

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$x = 0.30$ shows no piezoelectricity at a room temperature. Values for k_t and k_p increase and ε decreases with x.

2.2. Transducer fabrication

Fig. 3 shows fabrication procedures for the FGM transducer with a ceramic backing. This procedure is almost the same as that of multilayer piezoelectric ceramic actuators.[3] Ceramic green sheets composed of ceramic calcined powder with some organic binder, plasticizer and solvent were laminated and pressed together. The part to be the FGM after sintering was consisted of green sheets with various composition x. The part to be the ceramic backing after sintering, however, was consisted only of the green sheets with $x = 0.30$. Ag/Pd metal paste layer to be internal electrode after sintering was inserted between the green sheets to be FGM and to be ceramic backing. This layer-structured ceramic green body containing a metal paste layer was co-fired.

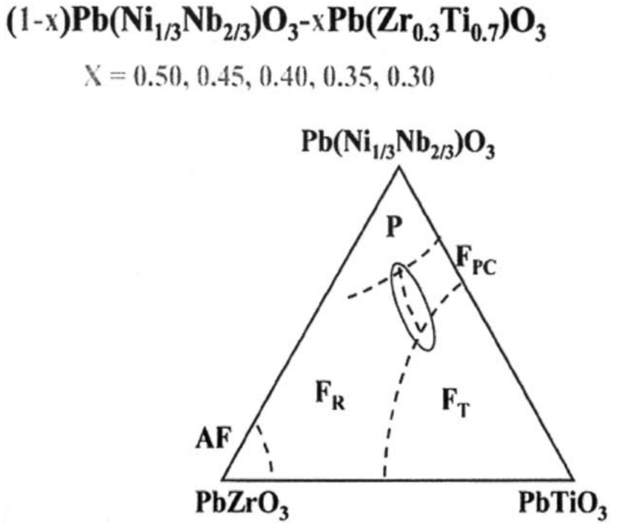


Fig. 1. Piezoelectric ceramic composition.

2.3. Ultrasound measurements

The experimental setup for the ultrasonic wave generation measurement is given in Fig. 4. The transducer was driven in water by applying a negative spike-shape pulse by a pulser-receiver (Panametrics 5800PR). The launched ultrasonic wave was received by a hydrophone probe (Specialty Engineering Associates PVDF-z44-100). The time waveform of ultrasound and its frequency spectrum were observed by a digital oscilloscope (Hewlett Packard HP54810A) equipped with a fast Fourier transform (FFT) function.

3. Results and discussion

3.1. Transducers with a tungsten-epoxy backing

Fig. 5 shows the gradients of Ti and Ni atom concentration in the thickness direction for the FGM

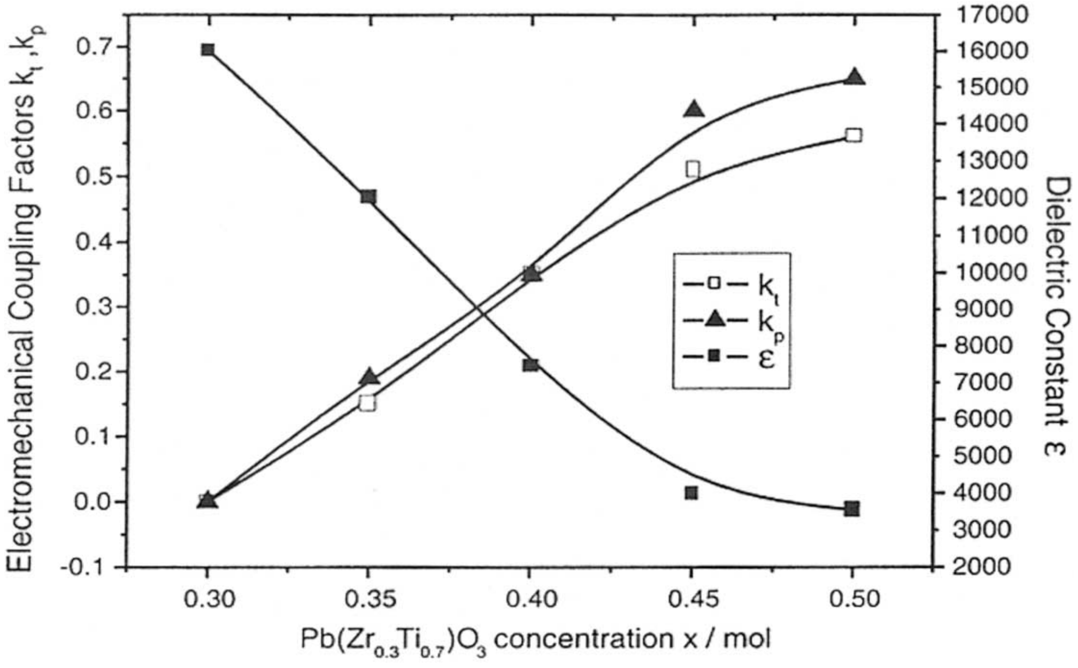
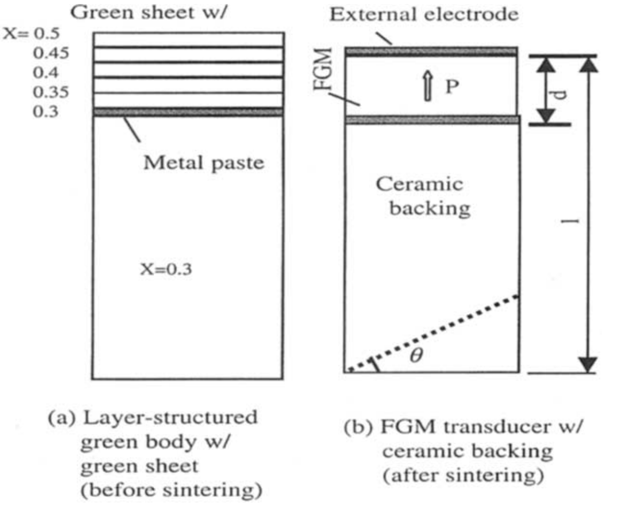


Fig. 2. Values for k_t k_p and ε as a function of x.



(a) Layer-structured green body w/ green sheet (before sintering)

(b) FGM transducer w/ ceramic backing (after sintering)

Fig. 3. Fabrication procedure of a ceramic backing FGM transducer.

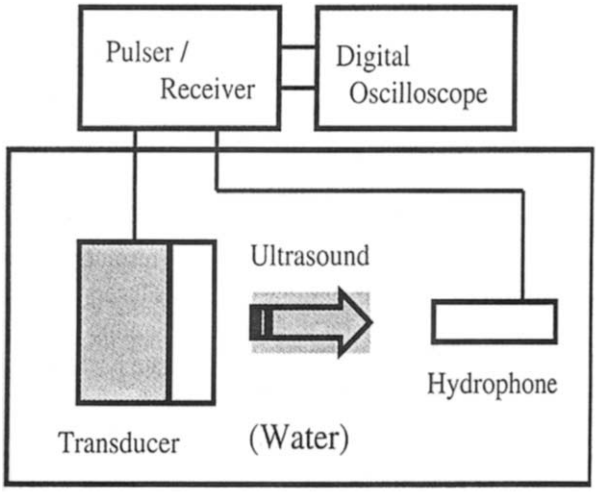


Fig. 4. Setup for the wave generation test.

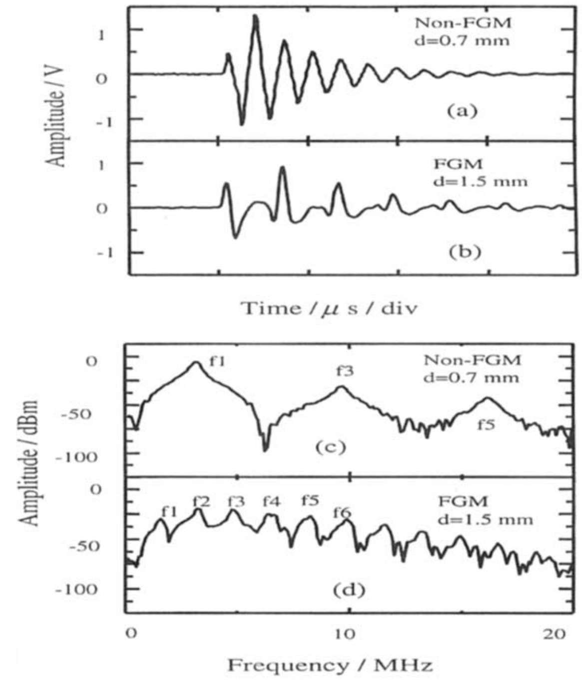


Fig. 5. Gradients of Ni and Ti concentration in the thickness direction for FGM plate.

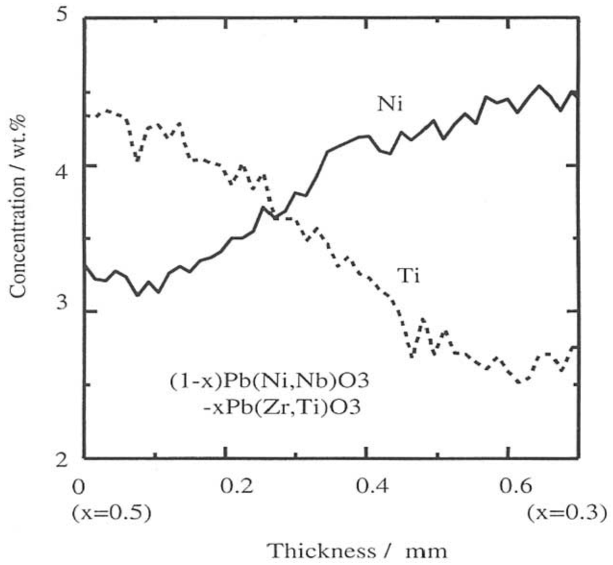


Fig. 6. Admittance characteristics for non-FGM (a) and FGM plate (b).

plate with a thickness $d = 0.7$ mm. This plate is made of the layer-structured ceramic green body composed of calcined powder. The measurement was carried out using EPMA. The Ti concentration monotonously decreases and Ni increases from the face of $x = 0.5$ toward $x = 0.3$, respectively. That is, these atom concentrations continuously and smoothly vary in the thickness direction. The degree of the gradient could be controlled by changing the composition x and the thickness of the calcined powder layer.

Fig. 6(a) and (b) shows the electrical admittance characteristics focused on the thickness vibration modes for the uniform piezoelectric ceramic (non-FGM) plate with $x = 0.50$ and $d = 0.7$ mm, and for the FGM plate with $d = 0.7$ mm, respectively. As is well-known, the resonant responses for the even order vibration mode appear in the non-FGM. It is noted, however, that both the even and odd order mode resonant responses appear in the FGM.[4] This result indicates that the FGM plate examined here has a gradient in the thickness direction not only for the ceramic composition but also for the piezoelectric parameter.

The time waveform and frequency spectrum for the non-FGM transducer with a tungsten-epoxy mismatched

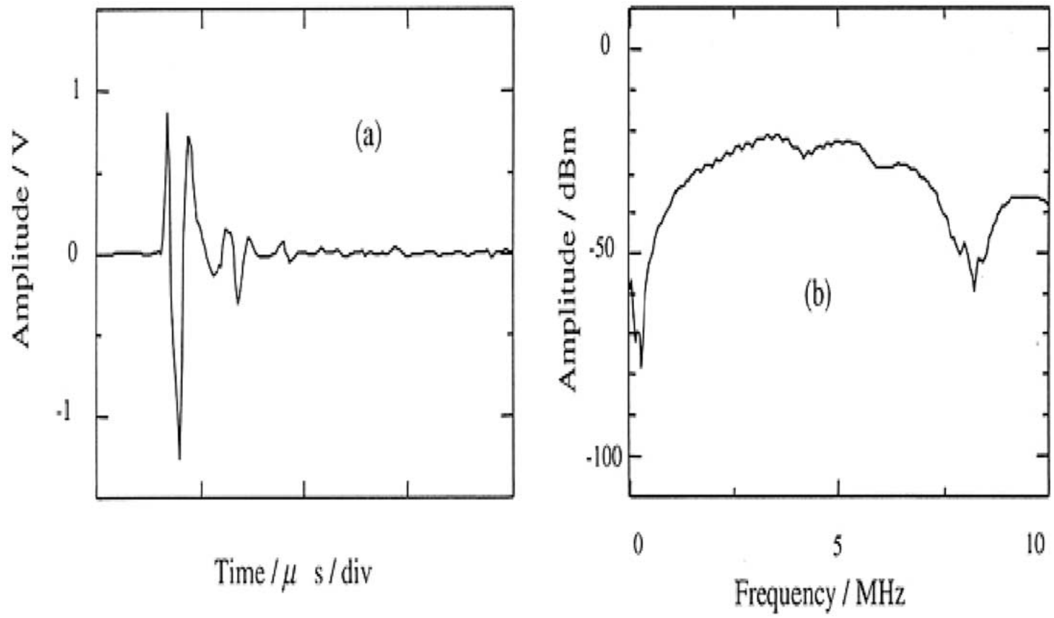


Fig. 7. Time waveform for non-FGM (a) and FGM transducer (b), and respective frequency spectrum (c) and (d).

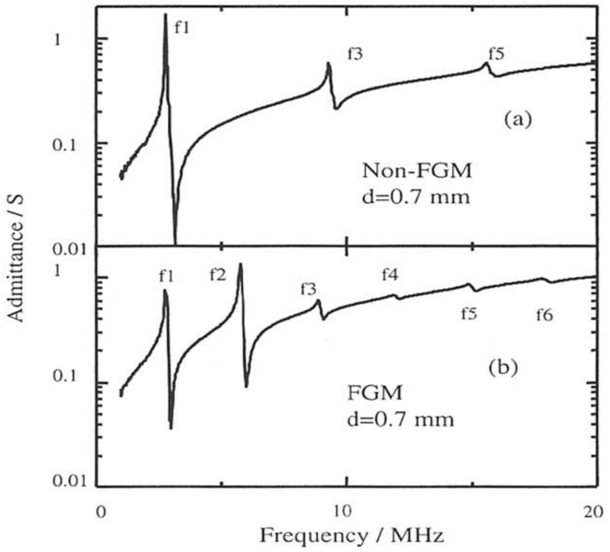


Fig. 8. Time waveforms for ceramics backing non-FGM transducers with $d=0.5$ (a), 1.0 (b) and 2.0 mm (c), and respective frequency spectra (d)–(f).

backing are shown in Fig. 7(a) and (c). Thickness of the non-FGM plate is 0.7 mm. The time waveform shows the long trailing pulses and the amplitude of frequency spectrum indicates its maximum only at the resonant frequencies for the even order vibration mode. Fig. 7(b) and (d) show the results relating to the FGM transducer with a tungsten-epoxy backing. Thickness of the FGM plate is 1.5 mm. The trailing pulse number appeared in the time waveform is markedly reduced compared with that of the non-FGM transducer. The time length of the trailing, however, is unimproved because the reflection pulses inside the FGM plate are still present. The amplitude of the frequency spectrum shows the maximum at the resonant frequencies for both the even and odd order vibration modes. This spectrum is quite different from that of the non-FGM transducer.

3.2. Transducer with a ceramic backing

The time waveform and frequency spectrum for the non-FGM transducer with a ceramic matched backing are shown in Fig. 8(a)–(c), and in Fig. 8(d)–(f), respectively. Thickness of the non-FGM part varies from $d=2$ to 0.5 mm, while length of the ceramic backing is kept constant (l–$d=18$ mm). The first two pulses of opposite polarity as shown in (b) and (c), are those generated at the front and back faces of the non-FGM part, respectively. Therefore, the time interval between these two pulses decreases with decrease in d and these pulses partially overlap each other when $d=0.5$ mm as in (a). It is clear that the reflection pulses inside the non-FGM part are absent, though the reflection from the tail end of the ceramic backing does not diminish yet. The frequency spectrum changes with the resonant frequency which depends on the thickness of the non-FGM part.

Fig. 9(a) and (b) show the time waveform and frequency spectrum for the FGM transducer with a ceramic matched backing. Thickness of the FGM part $d=0.7$ mm and length of the ceramic backing

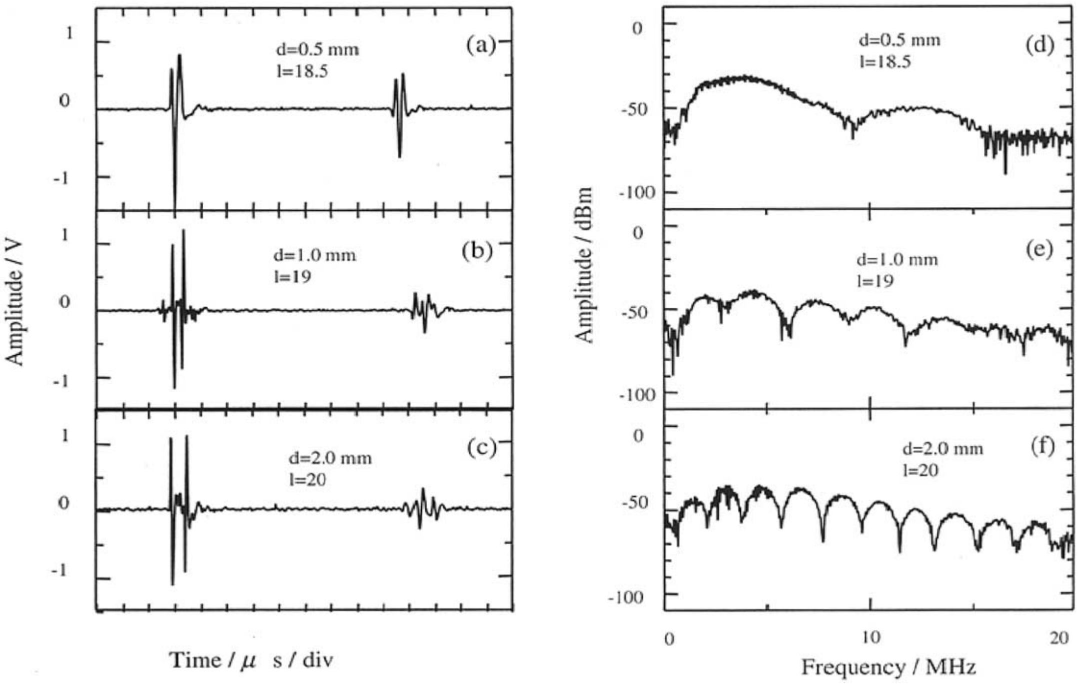


Fig. 9. Time waveform (a) and frequency spectrum (b) for ceramic backing FGM transducer.

$(l–d) = 9.3$ mm for this transducer. Although the reflection wave from the boundary between FGM part and ceramic backing part is not sufficiently suppressed yet in this transducer, it is clear that the pulse length is shorter and the frequency spectrum is smoother compared to those of the non-FGM transducer with a tungsten-epoxy mismatched backing (Fig. 7 (a) and (c)).

4. Conclusions

1. Functionally graded piezoelectric ceramics (FGM) are fabricated using ceramics green sheet technologies.
2. Compositional and piezoelectric gradients are confirmed by EPMA and admittance analyses.
3. FGM ceramic backing transducer has a capability to generate a short time waveform and a broadband frequency spectrum ultrasonic pulse compared with conventional one.

Acknowledgements

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