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A quarter-wavelength vibration mode transducer using clamped boundary backing layer

*Seunghee Lee, Kwangyun Choi, Kyungho Lee,
Youngshin Kim and Sungsik Park

Siemens Ltd., Seoul; H CP US / SUSKO Division, Pohang 790-834, Korea
seunghee.lee@siemens.com

ABSTRACT

Most conventional ultrasonic transducer designs are based on a structure using a half-wavelength vibration mode piezoelectric resonator. We introduce a new structure of the ultrasonic transducer which is a quarter-wavelength vibration mode transducer. It is expected to improve sensitivity as well as short pulse length. To generate quarter-wavelength vibration mode of the piezoelectric material, the clamped boundary condition is realized using a quarter-wavelength thickness tungsten carbide layer. In this work, a feasibility study on the quarter-wavelength mode transducer is presented. First, the simulation was performed for the new structure by KLM equivalent analysis method. Next, a quarter-wavelength mode ultrasonic transducer was fabricated and evaluated compared to a conventional transducer. Finally, the performance of the new transducer was verified in an ultrasonic imaging system.

1. INTRODUCTION

Medical imaging diagnostic ultrasonic transducers have been developed since the 1950's. Linear arrays, phased arrays, extending the number of channels, harmonic imaging, Doppler mode imaging and 2D arrays have been proven to acquire high quality ultrasound images. In addition, research for new materials such as piezoelectric material and elastic material for acoustic lens, matching layer and backing material have been studied as well. In recent years, the studies to make broader bandwidth in ultrasonic transducers have been carried out using piezoelectric composite materials and single crystals such as PMN-PT and PZN-PT. However, although those materials have outstanding characteristics, there is a trade-off among the performances. Therefore, it is important to select proper materials for a specific purpose.

In this study, we introduce the structure of a quarter-wavelength vibration mode transducer to improve both sensitivity and bandwidth using a clamped boundary backing layer. We verified the feasibility of the transducer by comparing simulated and measured acoustic performances.

2. THEORY AND SIMULATION

In this study, we theoretically explained the structure of the quarter-wavelength vibration mode transducer using a clamped backing layer. And the acoustic performance improvement of the transducer was verified by simulation.

2.1. Theory

In general, thickness of the piezoelectric material in a conventional ultrasonic transducer is a half wavelength, while the suggested transducer has a quarter wavelength thickness piezoelectric material. Fig. 1 shows geometric and acoustic differences between half-wavelength and quarter-wavelength resonators. A conventional ultrasonic transducer has a backing block with high attenuation coefficient to absorb the propagated wave toward the backside. On the other hand, the suggested transducer has an advantage in terms of energy efficiency compared to the conventional one, because it generates ultrasonic wave toward one side only. Moreover, it results in better electrical impedance matching. A half thickness of the PZT makes decrease of the electrical capacitance. Thus, improved performance will be expected. However, it is difficult to build up the clamped boundary condition on the back side of the PZT in order to generate quarter wavelength vibration.

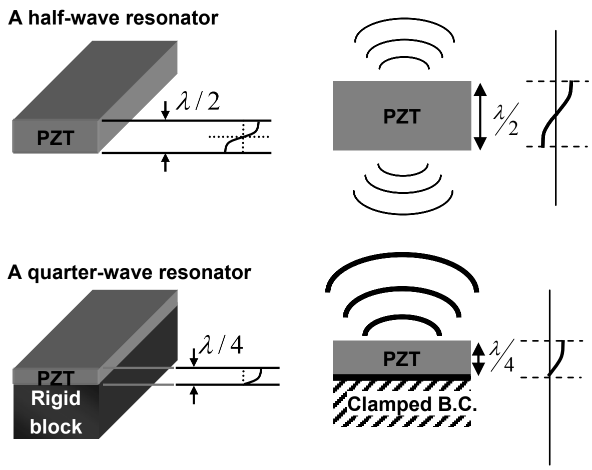

Fig. 1 Normal modes of resonators according to boundary conditions

The condition is able to be realized by inserting a rigid material between the PZT and the backing block as shown in Fig. 2. The material has very high acoustic impedance and a quarter-wavelength thickness.

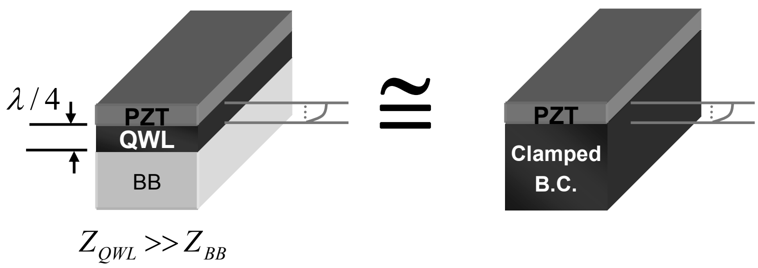

Fig. 2 Principle of a quarter-wave clamped boundary condition

The effective acoustic impedance of the backing block, Z_{eff}, which is combination of the rigid quarter-wavelength layer and backing block is derived as Eq. (1).

$$Z_{eff} = Z_{QWL}^{\ 2} / Z_{BB} \tag{1}$$

Here, Z_{QWL} is acoustic impedance of the quarter-wavelength layer and Z_{BB} is that of a backing block in Fig. 2.

In other words, if Z_{QWL} is much higher than Z_{BB}, then Z_{eff} is also much higher than Z_{PZT}. Therefore, this structure becomes almost clamped boundary condition. In this work, we applied tungsten carbide material which has very high acoustic impedance as a quarter-wavelength layer. For example, when the acoustic impedance of tungsten carbide, Z_{QWL} is 95 Mrayl and that of epoxy backing block, Z_{BB} is 3 Mrayl, Z_{eff} reaches a very large value, over 3,000 Mrayl, assuming that the Z_{PZT} is 33 Mrayl, the reflection coefficient, R from the piezoelectric material to the backing block is calculated as 97.8% from Eq. (2). Thus, the structure can be almost clamped boundary condition.

$$R = \frac{Z_{eff} - Z_{PZT}}{Z_{eff} + Z_{PZT}} \tag{2}$$

2.2. Simulation result

KLM equivalent circuit model, which is a simulator to analyze piezoelectric transducers, is applied to simulate the structure. The new structure has improved results compared to the conventional structure as shown in Fig. 3. The simulation result shows that overall sensitivity and bandwidth have improved.

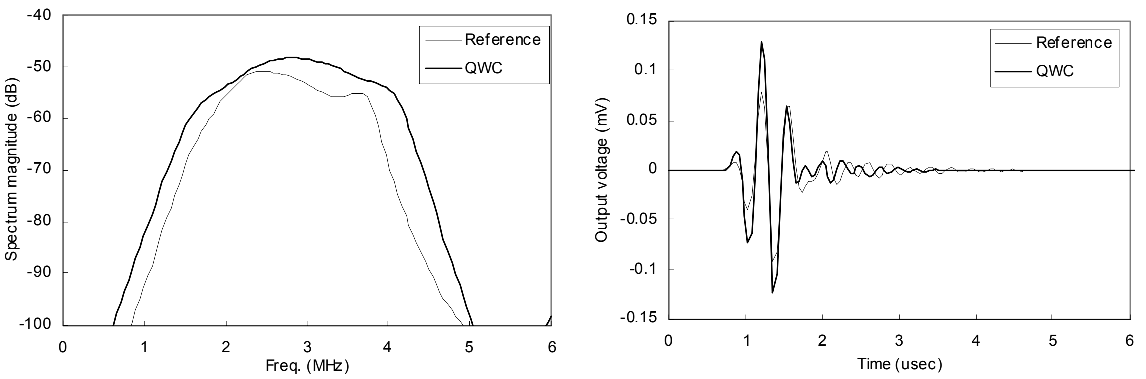

Fig. 3 Comparison of transducer performances between the conventional and new design structures

Additionally, a critical factor in this structure is investigated. We found that thickness of the bonding layer between the PZT and the tungsten carbide layers is a very significant factor in the structure by simulation. In general, it uses an epoxy material as the bonding layer and is controlled within 3 um to satisfy acceptable bonding strength. Especially, in the new structure, a thick bonding layer results in a significant decrease of bandwidth at the high frequency as shown in Fig. 4. Therefore, the thickness of the bonding layer between the PZT and the tungsten carbide needs to be controlled within 1 um. Otherwise, it should be introduced in such a way that it bonds directly without an adhesive layer if possible.

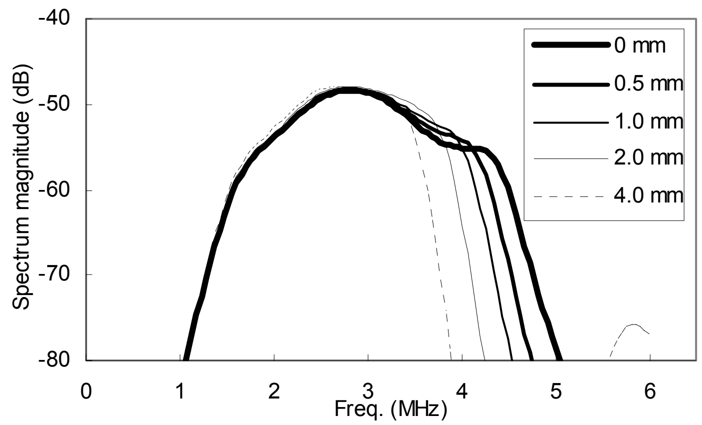

Fig. 4 Performance decrease according to the thickness of the epoxy adhesive layer

The signal flexible circuit is usually attached on the bottom surface of the PZT. But, in this structure, it should be positioned between the tungsten carbide and the backing block to minimize degradation of acoustic performance as shown in Fig. 5. Fortunately, there is no problem in electrical property because tungsten carbide has low electrical resistance.

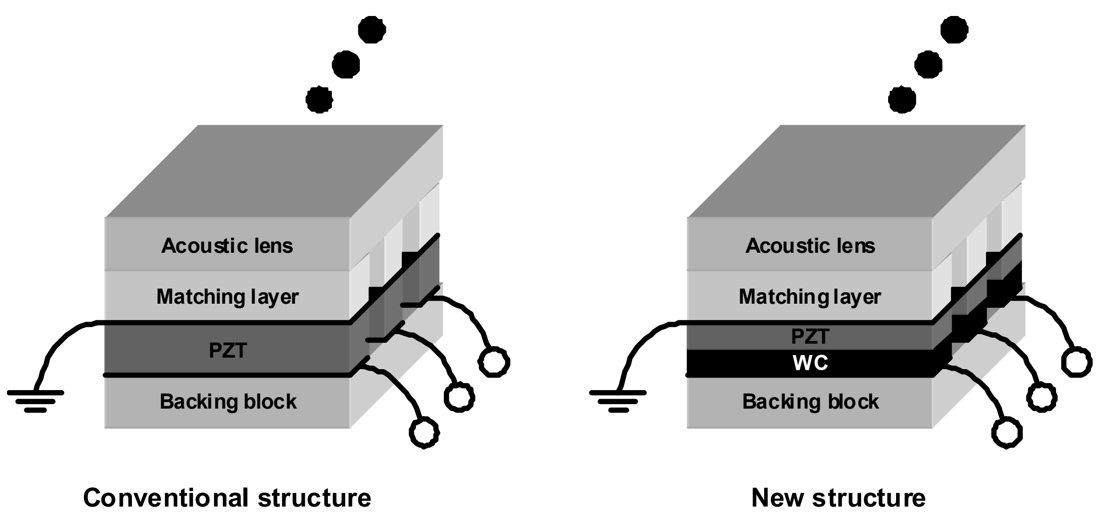

Fig. 5 Array structure of the conventional and new designs

3. EXPERIMENTAL RESULT

Two types of transducers were fabricated in this study. One is the conventional type and the other is the new structure. The thickness of the epoxy adhesive layer between the PZT and the tungsten carbide layer constructed within 1 um in Fig. 6.

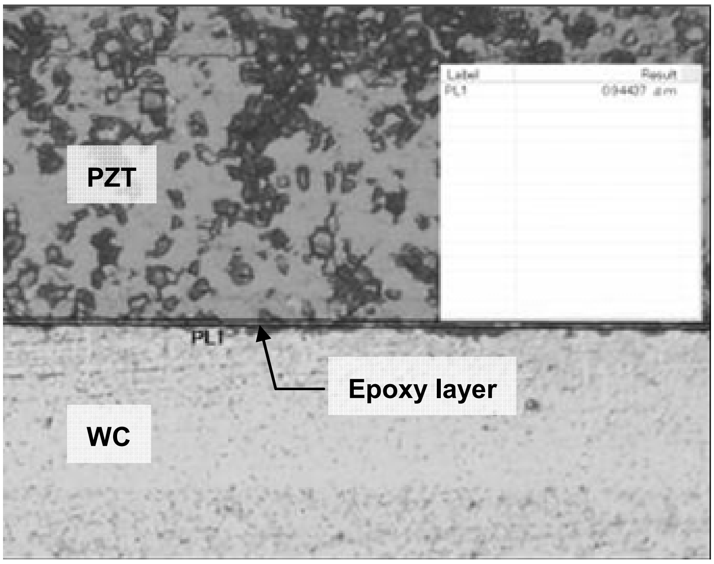

Fig. 6 Section image of epoxy bonding layer between the PZT and the tungsten carbide

3.1. Transducer level experimental result

The result which compares acoustic performance of the fabricated transducers is shown in Fig. 7. The results show that the new transducer with a quarter-wavelength thickness PZT and tungsten carbide has remarkable acoustic performance improvement than the conventional transducer. The experimental result shows that overall sensitivity improvement was found and -6dB fractional bandwidth has been increased by 15 %.

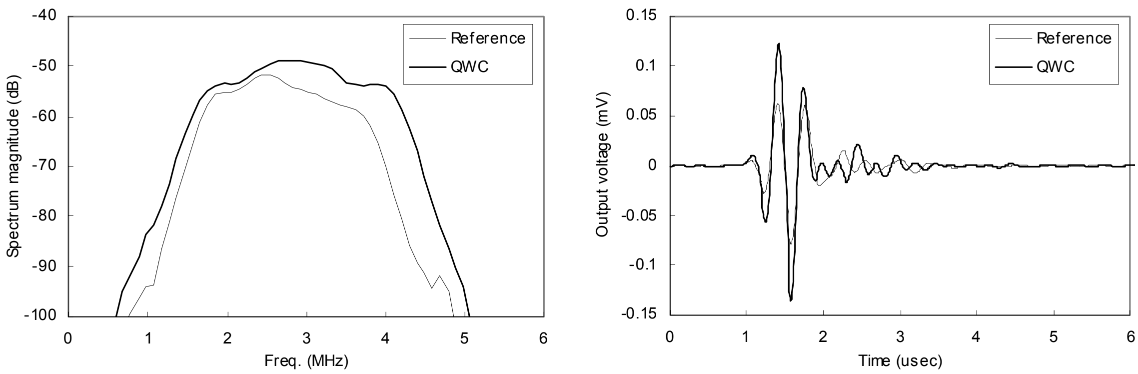

Fig. 7 Experimental result of the conventional and new transducers

3.2. System image level test result

The ultrasonic images are acquired from the fabricated transducers. Fig. 8 shows the comparison between the new and the conventional transducers. The new transducer has distinguished contrast resolution on the image and penetration at the far field zone.

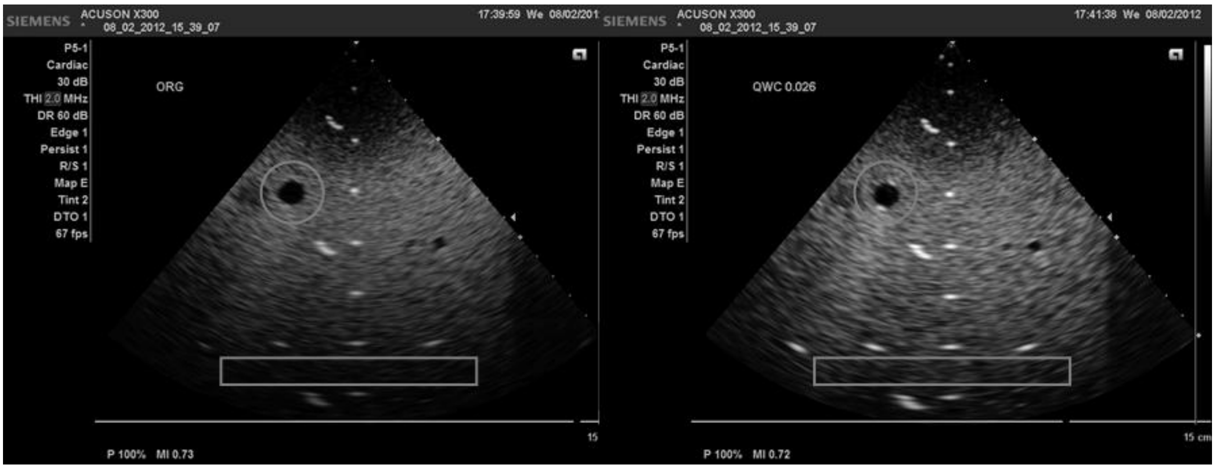

Fig. 8 Comparison of system level image between the conventional and new transducers

CONCLUSION

This paper shows structure of a transducer which uses a quarter-wavelength vibration mode and verifies the feasibility to improve acoustic and image performance by simulation and experiment. Also it is confirmed by simulation that thickness of the bonding layer between PZT and tungsten carbide must be a critical design factor in the transducer. It is experimentally verified that the new transducer has overall sensitivity improvement and 15% increase in -6dB bandwidth compared to a conventional transducer. The new structure is an innovative technology that can contribute to acoustic performance improvement of ultrasonic transducers, combined with other technologies. It also can be applied to various acoustic devices.

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