Low Voltage Power Supply Incorporating Ceramic Transformer

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Abstract

A low voltage power supply provides the regulated output voltage of 1 V from the supply voltage around 48 V. The low voltage power supply incorporates a ceramic transformer which utilizes piezoelectric effect to convert voltage. The ceramic transformer isolates the secondary from the primary, thus providing the ground isolation between the supply and the output voltages. The ceramic transformer takes the place of the conventional magnetic transformer. The ceramic transformer is constructed from a ceramic bar and does not include any magnetic material. So the low voltage power supply can operate under a magnetic field.

The output voltage is stabilized by feedback. A feedback loop consists of an error amplifier, a voltage controlled oscillator and a driver circuit. The amplitude ratio of the transformer has dependence on the frequency, which is utilized to stabilize the output voltage.

The low voltage power supply is investigated on the analogy of the high voltage power supply similarly incorporating the ceramic transformer. Stability of the power supplies is studied from the theoretical viewpoint of the stability. It is shown that the compensation, which has been applied to the high voltage ceramic transformer, could work similarly for the low voltage power supply.

I. INTRODUCTION

In Japan, many companies have competed in development of the low voltage power supply based on the ceramic transformers. Main objective of the development is miniaturization of power supplies. The competition has been severe due to a large market of power supplies miniaturized in size. The first target is the power supply of a laptop computer that is so far a small box placed outside the computer. The people engaged in the development have wanted to replace the box with the card that can be inserted into the slot of the laptop computer. Yet such the card-size power supply has been not yet available so far.

The ceramic transformer reduces the power supply in size mainly for the following two reasons. Firstly power density of the ceramic transformer is more than five times larger than that of the conventional electric transformer. Secondly the ceramic transformer can be operated efficiently at high frequencies where the conventional transformer increases in loss. For example, a newly developed ceramic transformer 14 mm x 14 mm x 6 mm in size delivers 30 W with the efficiency better than 95 % at the operating temperature less than 22 degrees Centigrade. The companies emulate ceramic transformers in composition of material, process of manufacturing and the mode of vibration.

From the viewpoint of the power supply operating in a strong magnetic field, the size of the ceramic transformer is not so important. To moderate the requirement for size brings large freedom to the design of the ceramic transformer. Following experts of ceramic transformers, further studies are unnecessary to manufacture the low voltage ceramic transformer operating in the magnetic field. They are ready to supply such the ceramic transformers if there is enough demand.

II. GROUND ISOLATION

The ceramic transformer utilizes piezoelectric effect to convert voltage. The ceramic transformer is made of the primary, the secondary and the intermediate as shown schematically in Fig. 1. At the primary, the piezoelectric effect converts the electrical energy to mechanical vibration. The vibration travels through the intermediate to the secondary where the piezoelectric effect converts the vibration, restoring the electric energy. The intermediate conducts the vibration, isolating electricity. The intermediate isolates the secondary from the primary electrically, thus providing the ground isolation between the supply and the output voltages.

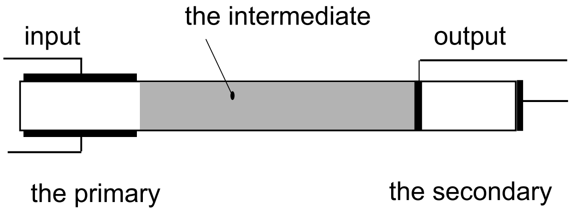

Figure 1: Schematic Structure of Ceramic Transformer

A. *Inductance*

When energy is stored in inductance L loaded with resistance R, the time constant is L/R. To maintain voltage across the resistance, energy is injected into the inductor by switching at time intervals roughly equal to the time constant. Accordingly, a large resistance increases the switching frequency. Since the load resistance of power supply tends to be small, the inductance is a good energy reservoir for the low voltage power supply. It might be difficult to implement the ground isolation between the supply and the output voltage without the magnetic transformer. Yet the magnetic transformer cannot work in a magnetic field.

B. *Capacitance*

When energy is stored in capacitance C loaded with resistance R, the time constant is RC. The time intervals for switching required maintaining the voltage becomes longer as R increases in resistance. The capacitance is therefore a good energy reservoir for large resistance and for the high voltage power supply. The ceramic transformer reserves energy as mechanical vibration, with energy dissipation at the load decaying the vibration. The ceramic transformer is similar to capacitance in that the time constant of the decay is proportional to load resistance. In this sense, the low voltage power supply incorporating the ceramic transformer is similar to the charge-pump power supply. But it is difficult for the charge pump power supply to implement the ground isolation, which the ceramic transformer provides generically.

III. CERAMIC TRANSFORMER

The ceramic transformer includes an internal resonance circuit. The carrier is converted in amplitude by the transformer. The amplitude of the carrier at the input is changed at the output, with the input to output voltage ratio of the amplitude being an amplitude ratio that shows a resonance as a function of the driving frequency: the frequency of the carrier. Fig. 2 plots the amplitude ratio against the driving frequency. The amplitude ratio depends on the driving frequency. Feedback utilizes the dependence for stabilization. Controlling the driving frequency, the feedback adjusts the amplitude ratio so as to stabilize the output voltage.

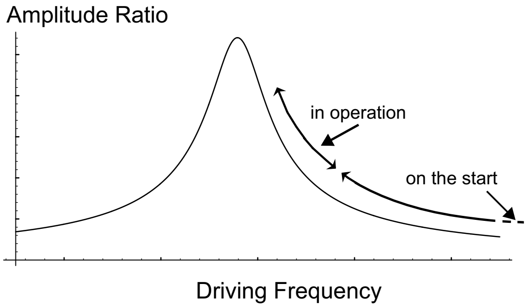

Figure 2: Resonance Shown by Amplitude Ratio

A. *Range of Driving Frequency*

There are alternatives of the driving frequency higher or lower than the resonance frequency of the transformer. When the driving frequency ranges below the resonance frequency, the amplitude of the carrier at the output increases as the increase of the driving frequency. The driving frequency ranging above the resonance frequency makes the amplitude decrease as the increase of the driving frequency. Usually the ceramic transformer is driven for the sake of efficiency by the driving frequency higher than the resonance frequency.

B. *Breakdown of Feedback*

The range of the driving frequency is designed to be higher than the resonance frequency as shown in Fig. 2. So the feedback increases the driving frequency when the output voltage is higher than a reference voltage. Similarly the driving frequency decreases when output voltage is lower than the reference voltage.

If the output current falls within the limit of allowance, the driving frequency is maintained higher than the resonance frequency such that the feedback is negative as designed. The limit for the output current is sufficient in most cases, but it cannot cover, for example, short-circuiting the output voltage to ground. When the output current deviates beyond the limit, the driving frequency may decrease below the resonance frequency; a condition that will not provide the required negative feedback, i.e., positive feedback locks the circuit such that it is independent of the output current. In order to recover the negative feedback, the driving frequency must be reset externally in addition to removing the cause of the feedback breakdown.

C. *Protection*

The output current deviated beyond the limit causes the breakdown of feedback decreasing the driving frequency beyond the resonance frequency. Such decrease of the driving frequency, accompanied with the breakdown of the feedback, lowers the output voltage. Thus the breakdown of feedback works as protection against, for example, short-circuiting the output voltage to ground.

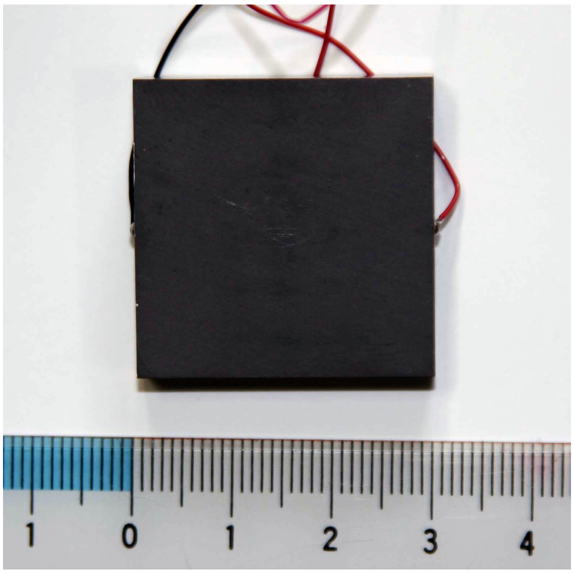

Figure 3: Picture of Stepdown Ceramic Transformer

IV. AN EQUIVALENT CIRCUIT

V. STEPDOWN CERAMIC TRANSFORMER

Stepdown ceramic transformers are provided by Tokin Corp (Fig. 3). The stepdown transformer makes the carrier stepdown. The carrier at the input is reduced in amplitude at the output. The ceramic transformer, driven by the carrier with a maximum amplitude, maintain the amplitude at the output to be 17 V up to 2 A, where the driving frequency moves to the resonance frequency as the increase of the output current. The rating of the transformer is estimated at 34 W. Tokin Corp. has demonstrated the feasibility of the stepdown DC-DC convertor utilizing the ceramic transformer, where the transformer can deliver output current up to 2 A at an output voltage of 17 V with the supply voltage of 380 V. Based on the wattage of the transformer, the DC-DC converter employing the ceramic transformer could supply output current up to 34 A with the output voltage of 1 V, if the converter were supplied with dc 380 V.

The analysis of the ceramic transformer is most easily arrived by the use of an electrical equivalent circuit. Rosen derived the equivalent circuit [4]. Rosen's representation of the equivalent circuit is extended in the form of lumped resistance, inductance, and capacitance especially at frequencies around resonance. An equivalent circuit is developed to an lumped element circuit as shown in Fig. 4, where the parameters of the stepdown ceramic transformer are given.

It can be seen in the figure that the input resistance of the ceramic transformer is rather large. So the driving frequency higher than the resonance frequency is favorable for the efficiency.

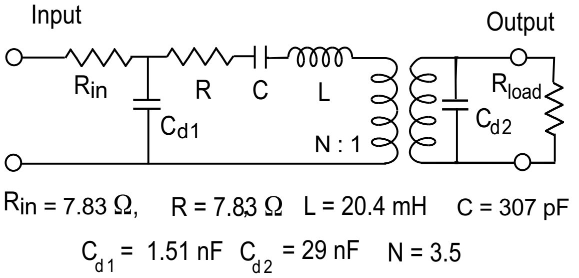

Figure 4: Equivalent Circuit for Tokin's Ceramic Transformer

VI. STEPDOWN DC-DC CONVERTER

We have designed a stepdown DC-DC converter based on the stepdown ceramic transformer. Performances of the converter are extensively simulated, and the implementation is now in progress. The DC-DC converter transforms the dc supply voltage of 48 V to the dc output voltage of 1 V. The output current supplied by the converter amounts to more than 3 A.

Since the wattage of the transformer is 34 W, the output current could amount to 34 A if the converter were supplied with 380 V. Assumed that the amplitude ratio does not depends on the supply voltage, the converter supplied with 48 V reduces the amount of output current roughly in the proportion of 380 to 48.

The converter is composed of a reference voltage, an error amplifier, compensation circuits, a driver circuit, the ceramic transformer and a circuit for rectification and smoothing (which is called a RS circuit hereafter) (See Fig. 5).

The output voltage of the converter is stabilized by feedback, i.e., it is fed back to the error amplifier to be compared with the reference voltage. The voltage difference between the input of the error amplifier is supplied to the compensation circuits and then fed to the driver circuit where the carrier driving the ceramic transformer is produced. The carrier is modulated by the output of the error amplifier.

The carrier is converted in voltage at the ceramic transformer, and the converted voltage induced between the output terminals of the ceramic transformer is rectified and smoothed in the RS circuit. The RS circuit is composed of a diode bridge for rectification and a capacitor for smoothing. The RS circuit is found in Fig. 6. The output of the RS circuit is the output of the stepdown converter. The output voltage is supplied to the error amplifier for the feedback.

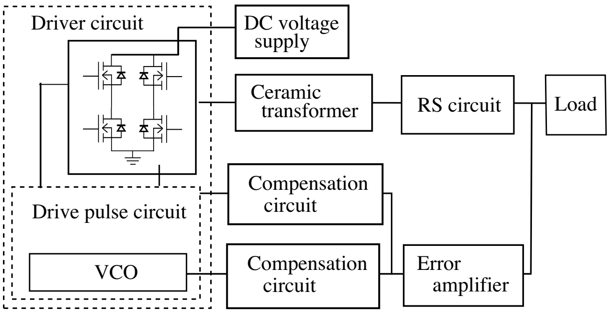

Figure 5: Block Diagram of Stepdown Converter

A. Frequency Modulation

The driver circuit includes a voltage controlled oscillator (VCO) to which the output of the error amplifier is supplied through the compensation circuit. The VCO generates the driving frequency. Then the carrier which drives the ceramic transformer is modulated in frequency by the output of the error amplifier. The ceramic transformer convert the modulation from frequency modulation at the input to amplitude modulation at the output. Then the carrier at the output is modulated distortedly in amplitude by the output of the error amplifier. The RS circuit demodulates the output of the ceramic transformer with rectification and smoothing, restoring the output of the error amplifier. So the output of the RS circuit is the distorted output of the error amplifier.

B. Amplitude Modulation

The output of the error amplifier is transmitted to the driver circuit through the compensation circuit which cancels the delay caused by the RS circuit. At the driver circuit, the output of the error amplifier controls the amplitude of the carrier produced by the driver circuit. The amplitude of the carrier is adjusted so as to reduce the output of the error amplifier.

VII. DRIVER CIRCUIT

The driver circuit includes a field-effective transistor (FET) H-bridge. The H-bridge is comprised of a pair of half-bridges. The half bridge consists of a pair of FETs which is turned on and off alternatively. The pair of FETs in the half-bridge is controlled individually by a pair of gate pulses. The gate pulses are nearly complimentary and the duty ratio of the gate pulses is close to 50 %. Operation of the FETs is involved with delays. Then, being strictly complementary, the gates pulses may turn on both the FETs simultaneously. So the gate pulses are provided with time intervals during which both the FETs are turned off simultaneously, where the time interval is called dead time.

The half-bridge is associated with a pair of gate pulses. The H-bridge is operated by two pairs of gate pulses. Each pair of gate pulses is nearly complementary. Two pairs of gate pulses share the same frequency equal to the driving frequency which is generated by the VCO. There is phase difference between the pairs of the gate pulses. Namely, the H-bridge is operated in a phase shift mode. The phase difference between the pairs control the amplitude of the carrier. The output of the error amplifier, transmitted through the compensation circuit, controls the phase difference between the pairs.

A reactance element, which is included in the driver circuit, is also needed to obtain efficient voltage conversion, being implemented by an air-core coil that can operate under a strong magnetic field.

VIII. SIMULATION

Performances of the stepdown converter are extensively simulated. The resonance shape of the ceramic transformer is simulated by circuits shown in Fig. 6 which includes simulation circuits for the driver circuit and the RS circuit.

A. Simulation of Driver Circuit

As for the driver circuit, FETs are simulated by voltage-controlled switch in the simulation circuit. Conduction of the switch is controlled by the control input. The switch makes while the voltage between the control input is higher than 1 V. Otherwise the switch breaks.

One half-bridge is composed of S1 and S2. The other half-bridge is made of S3 and S4. ABM13 and ABM19 generate individual sinusoidal waves of the same frequency equal to the driving frequency. ABM14 and ABM15 are supplied by ABM13. The gate pulses generated by ABM14 and ABM15 make one pair. ABM17 and ABM18 are supplied by ABM19. The gate pulses generated by ABM17 and ABM18 make the other pair. The input terminal 1 of ABM19 controls phase difference between the sinusoidal waves and then the phase difference between the pair. The driving frequency depends on the output of ABM12. ABM12 is an integrator, integrating the input with the integration at the output.

The simulation circuit is independent of practical implementation of the driver circuit. The simulation circuit, functionally equivalent to the driver circuit, is based on mathematical relation and composed so as to shorten simulation time.

B. Resonance Shape of Ceramic Transformer

The output voltage from V5 controls the driving frequency. The driving frequency in terms of kHz is equal to the voltage in terms of V as is seen in Fig. 6. The voltage spanned across R76 is plotted against the driving frequency with the increment of 100 Hz from 60 kHz to 65 kHz.

R76 works as load. The load is varied, stepping 200 mΩ from 1Ω to 200 mΩ, which corresponds to the plots from A to E in Fig. 7 respectively.

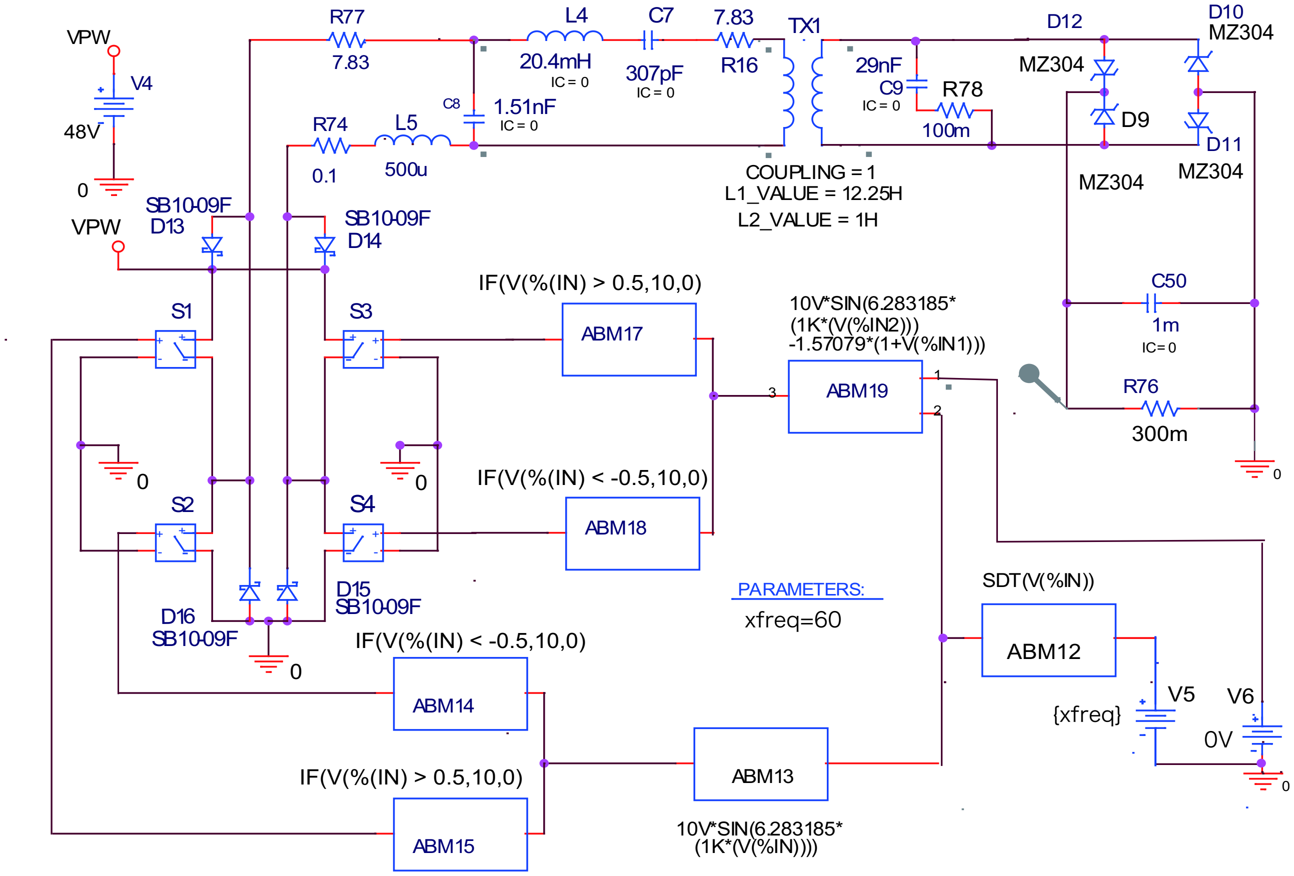

Figure 6: Simulation Circuit for Resonance Shape

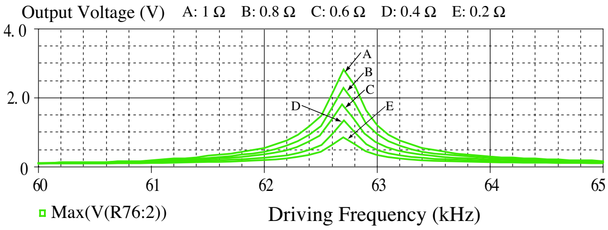

Figure 7: Resonance Shape

VPW in Fig. 6 being supplied with 380 V instead of 48 V, the voltage spanned across R76 might be multiplied roughly eight times. Then the voltage might exceed 1 V so far as the load is larger than 50 mΩ.

IX. TRANSIENT RESPONSES

Transient responses of the output voltage are important for power supplies. As for the the stepdown converter, the shifts of the output voltage are simulated in details. Fig. 8 shows the shift of the output voltage when the pulsed load current adds to the stationary load current of 1 A, where the magnitude of the pulsed load current is 500 mA and its duration is 100 msec. The output of the error amplifier and the input to the VCO are shown together with the output voltage of the converter in Fig. 8.

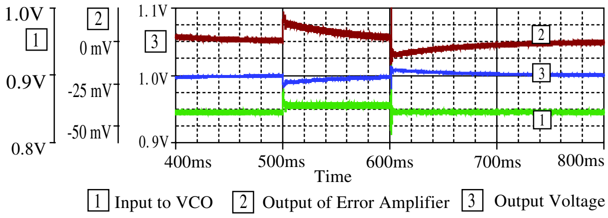

Figure 8: Shift of Output Voltage

The transient responses are unsatisfactory so far when the stationary load current is so small as 10 mA for example. The transient responses in these cases remains to be studied.

X. DISCUSSIONS

It is essential to develop such the ceramic transformer that is optimized for the stepdown DC-DC converter supplied with dc 48 V. The driving frequency concerns the magnitude of inductance in the driver circuit and the capacitance in the RS circuit. The driving frequency being ten times higher, the inductance and the capacitance could be reduced by a factor of ten.

The bandwidth for feedback is roughly proportional to δ, where δ is HWHM of the resonance defined as $\delta = \omega_r/2Q$ for Q value Q and the angular velocity at the resonance ω_r. Assumed that Q value of the resonance is independent of the resonance frequency, the resonance frequency being higher makes the bandwidth wider, which improves the frequency response of the converter. A few hundred kilohertz might be appropriate resonance frequency, then the size of the ceramic transformer could be reduced largely.

It is important to reduce the capacitance between the primary and the secondary. The capacitance need to be less than 100 pF for good isolation. Such the ceramic transformer could be available soon hopefully.

XI. ACKNOWLEDGMENT

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REFERENCES

[1] M. Imori, N. Matsui, M. Ishino, T. Kimura, T. Mieno, S. Imada and M. Katsuno, In 11th Workshop on Electronics for LHC Experiments – LECC 2005: Heidelberg, Germany, 12–15 Sep 2005.

[2] M. Imori, T. Taniguchi, T. Kimura and S. Imada, In 10th Workshop on Electronics for LHC Experiments and Future Experiments– LECC 2004: Boston, USA, 13–17 September 2004.

[3] M. Imori, T. Taniguchi, T. Kimura and S. Imada, In 9th Workshop on Electronics for LHC Experiments – LECC 2003: Amsterdam, The Netherlands, 29 Sep - 03 Oct 2003 / Ed. by Claude, Sandra - Geneva, CERN, 2003. [CERN–2003–006; LHCC–G–061; CERN–LHCC–2003–055] pp.420-424.

[4] C.A. Rosen, Proc. of Electric Component Symposium, 1959, pp.205–211.

[5] M. Imori, H. Matsumoto, Y. Shikaze, H. Fuke, T. Taniguchi, and S. Imada, Colmar, France, 9–13 September 2002.

[6] Y. Shikaze, M. Imori, H. Fuke, H. Matsumoto and T. Taniguchi, Proc. of the sixth Workshop on Electronics for LHC Experiments, Krakow, Poland, 11–15 September 2000.

[7] Y. Shikaze, M. Imori, H. Fuke, H. Matsumoto and T. Taniguchi, IEEE Transactions on Nuclear Science, Volume: 48, June 2001, pp. 535 -540.

[8] M. Imori, T. Taniguchi and H. Matsumoto, IEEE Transactions on Nuclear Science, Volume: 47, Dec. 2000, pp. 2045 -2049.

[9] M. Imori, T. Taniguchi and H. Matsumoto, IEEE Transactions on Nuclear Science, Volume: 45, June 1998, pp. 777 -781.

[10] M. Imori, T. Taniguchi, H. Matsumoto and T. Sakai, IEEE Transactions on Nuclear Science, Volume: 43, June 1996, pp.1427 –1431.

[11] S. Kawasima, O. Ohnishi, H. Hakamata *et. al.*, IEEE Ultrasonic Sympo., Nov., 1994, Cannes, France. pp.525–530.

[12] O. Onishi, Y. Sasaki, T. Zaitsu *et. al.*, IEICE Trans. Fundamentals. Vol. E77–A, No. 12 December 1994. pp. 2098–2105.