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Improvement of High Voltage Staircase Drive Circuit Waveform for High-Intensity Therapeutic Ultrasound
超音波治療用階段状送信波形の改良

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1. Introduction

A high-intensity therapeutic ultrasound (HITU) has been largely expected as a means to treat tumors less-invasively. Breast cancer is the highest prevalence in the diseases potentially causing death to women[1)]. One-day HITU therapy without surgical operation while maintaining the cosmesis of breast would reduce the physical burden on a patient, and should contribute to reduce the medical costs.

We have developed HITU systems to ensure such a therapeutic method, and tested them in experimental high-intensity focused ultrasound (HIFU) treatment of tumor-implanted animals.

Two designs have been invesitagted for the circuit to drive an array transducer generating HIFU. One design uses transformers, whose size and cost make those of the whole circuit large. It also has the problem of large power loss in the amplitude modulation mode.

The other design was a staircase voltage driver[2-5)] using a number of metal-oxide semiconductor field-effect transistors (MOSFETs). The size and cost of the circuit is smaller for this design. This circuit was used for a "triggered HIFU" transmission mode[5)], requiring amplitude modulation. It uses short and extremely high voltage ultrasound transmission pulses, in order to generate cavitation bubbles in the target tissue. The bubbles can accelerate HIFU heating of the tissue.

However, the drive voltage waveform tends to have ringing due to the inductive load. If the spike exceeds the MOSFET rating, there is a possibility of damage to MOSFETs by avalanche breakdown. Furthermore, the excessive voltage and current of the ringing may cause the heat dissipation of MOSFETs and increase the power consumption of the whole circuit.

Based in the latter design, a HIFU transmission circuit having high device safety, low power consumption, a small circuit size, and low cost is examined in this study.

2. Method

2.1 Pre-existing circuit

We already reported a four-level staircase HIFU transmission circuit using MOSFETs. This circuit includes two-level positive supply voltages and two-level negative supply voltages, a pseudo sinusoidal transmit waves are generated by switching these supply voltage using MOSFETs in time series. When a HIFU transducer (Imasonic 11350 A101) was driven by ±20V(DC) and ±7.9V(DC) using a circuit shown in Fig. 1, the voltage waveform had significant ringing and overshoot and resembled a rectangular wave as shown in Fig. 2. The temperature of MOSFET rose up to 30.9°C as shown in Table I. In a long duration at a high voltage, damage of the MOSFET by the avalanche breakdown is suggested.

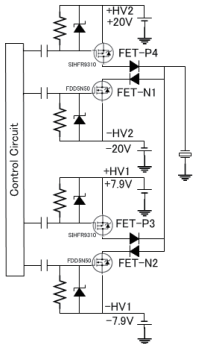

Fig. 1. Schematic of pre-existing HIFU driver circuit.

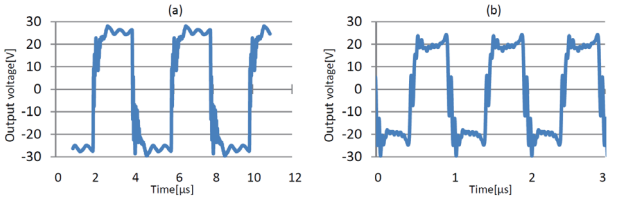

Fig. 2. Output voltage waveform of pre-existing HIFU circuit. (a) 250KHz and (b) 1.0MHz transmit.

Table I. Pre-existing circuit power consumption and MOSFET temperature rise.

Power supply voltage	(V)	-20	-7.9	+7.9	+20
MOSFET		FET-N1	FET-N2	FET-P3	FET-P4
Power consumption	(W)	1.00	0.55	0.47	1.20
MOSFET temperature rise	(°C)	9.7	13.6	30.9	16.4

Avalanche breakdown is a typical failure mode of a power MOSFET. When the flyback voltage exceeds

the rating of drain-source voltage (V_{DSS}) of the MOSFET, avalanche breakdown will occur. The flyback voltage at the switching operation of MOSFET. To prevent such avalanche breakdown, we should select a large avalanche tolerance MOSFET and reduce the parasitic capacity and parasitic inductance in circuit implementation, which is difficult in practice.

2.2 Proposed circuit

We examined how to return the charge of the surge pulse voltage to the power supply in the circuit. Proposed circuit detail is shown in Fig. 3. Here, FET-P1 and FET-N4 are held ON during the ultrasonic transmission. In this circuit, if a spike exceeds the supply voltage, +HV2 or -HV2, its charge will be fed back to the power source through FET-P1 or FET-N4, respectively. Since the actual on-resistance of the MOSFET is not zero ohm, the spike voltage pulses will not completely be supressed, but it may settle around the supply voltage level in tens of ns. This circuit operation will serve to prevent the breakdown of the MOSFET.

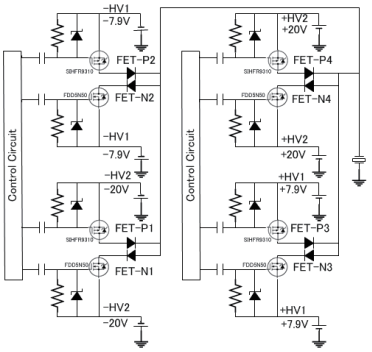

Fig. 3. Proposed schematic of HIFU driver circuit.

3. Results and discussion

The voltage waveform of this proposed circuit in experiment is shown in Fig. 4. At both 250 KHz and 1 MHz, the spike pulses excessig the supply voltage had converged in a short period of time of about 30 ns. Power consumption and the device temperature rise in this configuration are shown in Table II. The power consumption is suppressed to 73% compared to the pre-exisiting circuit, the maximum temperature rise of MOSFET was 16.4°C.

From these results, the proposed circuit should be useful for supressing excessive spike voltage, in the triggered HIFU mode at a high transmission voltage. Moreover, since the power consumption was greately reduced from the pre-exsiting circuit, an excessive temperature rise of MOSFETs will be avoided, in continuous wave transmission in the heating-waves mode. Consequently, the avalanche breakdown will be prevented

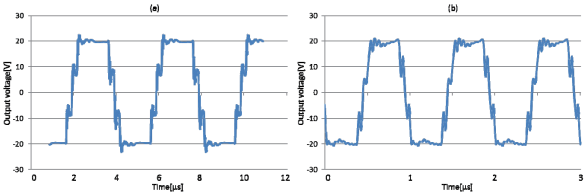

Fig. 4. Output voltage waveform of proposed HIFU circuit. (a) 250KHz and (b) 1MHz transmit.

Table II. Proposed circuit power consumption and MOSFET temperature rise.

Power supply voltage	(V)	-20		-7.9	
MOSFET		FET-N1	FET-P1	FET-N2	FET-P2
Power consumption	(W)	1.00		0.08	
MOSFET temperature rise	(°C)	9.3	6.0	8.3	11.7
Power supply voltage	(V)	+7.9		+20	
MOSFET		FET-N3	FET-P3	FET-N4	FET-P4
Power consumption	(W)	0.08		1.20	
MOSFET temperature rise	(°C)	14.6	16.4	6.4	13.8

4. Conclusion

We proposed a novel high voltage staircase drive circuit for a high-intensity therapeutic ultrasound system. This circuit suppresses excessive spike voltage in the waveform and reduces power consumption. It may avoid MOSFETs reaching the avalanche breakdown mode.

We are planning to build a HITU system using more than one hundred channels of the proposed circuit, and perform actual ultrasonic irradiation experiments in the near future.

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