Novel power circulation methods for a surface acoustic wave motor

Katsuhiko Asai
Matsushita Research Institute Tokyo, Inc., 3-10-1 Higashimita, Tama-ku, Kawasaki 214-8501, Japan
Minoru Kuribayashi Kurosawa
Tokyo Institute of Technology, Department of Advanced Applied Electronics, 4259 Nagatutamati, Midori-ku, Yokohama 226-8502, Japan
Toshiro Higuchi
The University of Tokyo, Department of Precision Machinery Engineering, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan

Abstract—This paper describes two novel power circulation methods which can increase the efficiency of surface acoustic wave (SAW) motors by 7 times. One method requires two driving interdigital transducers (IDTs) and two unidirectional IDTs to circulate power mechanically in a piezoelectric substrate. Another method requires two unidirectional IDTs and an electrical combiner to circulate power electrically. A traveling wave has been successfully excited at the driving frequency of 14.5 MHz by these two methods. The experimental result shows that the driving performance of the SAW motors with the power circulation methods was equivalent to the conventional non-circulation method. As the input power is one seventh, the efficiency of the SAW motor has been increased by 7 times by using the power circulation methods.

INTRODUCTION

Surface acoustic wave (SAW) motors have the advantages of high output force, high speed, high precision positioning, and high energy density. The maximum output force of 3.5 N, no-load velocity of 1.1 m/sec and step motion of 40 nm were obtained at 10MHz in the past researches [1], [2]. However, since the input power of 100 W or more were required to achieve such performance, the calculated efficiency (mechanical output per electrical input) of SAW motors was less than 1 %. Therefore, it is necessary to improve the efficiency to attain a practical SAW motor.

The efficiency of a SAW motor is split into two parts. The first part is mechanical output per vibration amplitude. The second part is vibration amplitude of a SAW per electrical input. The first part depends on the contact surface form of a slider and the contact conditions. Enlarging the contact area between a slider and a stator, and optimizing the pressing force (pre-load) are effective to increase the mechanical output [3], [4]. The second part depends on the design of a stator transducer. On a SAW motor without circulating power, only a part of input power is used for driving a slider, and the remaining power is dissipated into absorbers. In order to use most of input power for driving a slider, the power should be circulated in the device.

Tojo et al. [5] reported a SAW motor using a circulation method. The stator transducer consists of two substrates, and requires two driving interdigital transducers (IDTs) and four unidirectional IDTs for circulation. The traveling wave (standing wave ratio 1.6) was excited by putting in the signals whose phase difference was 90 degrees. However, driving a slider using a circulation method has never been demonstrated.

In this paper, we investigates two novel power circulation methods for a surface acoustic wave motor. The SAW motors using the power circulation methods were fabricated and those driving characteristics were measured.

PRINCIPLE OF SAW MOTOR

The schema of a conventional SAW motor using the conventional non-circulation method is shown in Fig. 1. The stator transducer is a SAW device made of LiNbO₃. The Rayleigh wave is excited by the IDT with a high frequency electrical power source. The traveling waves are propagated toward the both ends of the stator transducer. While the Rayleigh wave is propagated, each particle of the stator transducer moves elliptically, as shown in Fig. 2. A driving friction force is obtained by pressing the slider against the stator transducer. The direction of the driving force is opposite to the traveling wave propagation. At both ends of the stator transducer, the traveling wave is consumed in absorbers.
NEW METHODS

For high efficiency driving, two novel power circulation methods have been developed. The first method circulates the power mechanically in a piezoelectric substrate. The second method circulates the power electrically using an electrical combiner.

The structure of the stator transducer using the first power circulation method is shown in Fig. 3. In this method, two driving IDTs and two unidirectional IDTs are required. The unidirectional IDTs are connected electrically. The excited traveling wave is received by one unidirectional IDT, and converted into electric energy. Using this electric energy, another unidirectional IDT excites a circulated traveling wave. The circulated wave is propagated, and received by the initial unidirectional IDT again. Each unidirectional IDT is placed in a certain distance so that the excited wave and the circulated wave can overlap each other.

The driving IDT excites two traveling waves propagated toward the both ends of the stator transducer. The traveling waves displacement $y_+, y_-$ at position $x$ and time $t$ is expressed as follows:

\begin{align}
    y_+ &= \alpha \sin \left( \omega t - \frac{\omega}{v_0} x \right) \\
    y_- &= \alpha \sin \left( \omega t + \frac{\omega}{v_0} x \right)
\end{align}

where $\alpha$ is the vibration amplitude and $v_0$ is the propagation velocity of the traveling wave. These two waves are circulated by the unidirectional IDTs placed at the both ends of the stator transducer. Therefore, the standing wave is excited as:

$$y_s = y_+ + y_- = 2\alpha \sin \left( \omega t \right) \cos \left( \frac{\omega}{v_0} x \right).$$

Two driving IDTs are placed at an interval of $\lambda/4 (= \pi v_0/2\omega) + n\lambda$. A sine signal and a cosine signal are put into the driving IDTs respectively. Each driving IDT excites the standing wave as follows:

\begin{align}
    y_{sin} &= 2\alpha \sin \left( \omega t \right) \cos \left( \frac{\omega}{v_0} x \right) \\
    y_{cos} &= 2\alpha \sin \left( \omega t - \frac{\pi}{2} \right) \cos \left( \frac{\omega}{v_0} x - \frac{\pi}{2} \right)
\end{align}

The traveling wave is excited by adding these two standing waves as:

$$y_t = y_{sin} + y_{cos} = 2\alpha \sin \left( \omega t - \frac{\omega}{v_0} x \right).$$

The traveling wave propagated in the opposite direction can be excited by swapping input signals.

The structure of the stator transducer using the second power circulation method is shown in Fig. 4. In this method, two unidirectional IDTs and an electrical combiner are required. The output port of the electrical combiner is connected to one unidirectional IDT. The input ports are connected to another unidirectional IDT and a high frequency electrical power source. A traveling wave is converted into
TABLE I

<table>
<thead>
<tr>
<th>Dimensions of the Unidirectional IDT.</th>
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<tbody>
<tr>
<td>Transducer</td>
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<tr>
<td>Periodic length</td>
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<tr>
<td>Electrode strip width</td>
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<tr>
<td>Aperture size</td>
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<td>Strip electrodes pairs</td>
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electric energy by the unidirectional IDT, and is put into the combiner. This electric energy and the energy from the power source are combined and used for exciting a circulated wave.

The electrical combiner mixes the input energy and the circulated energy unequally. The larger a circulated-to-input ratio is, the higher the efficiency becomes. The limit of this ratio depends on the loss in the circulation.

**DESIGN**

A substrate of 128 degrees rotated y-cut x-propagating LiNbO₃ was used for the stator transducer material. The same unidirectional IDTs were used for both of the first and second methods, and they consisted of the IDT as a transducer and the IDT as a reflector. The unidirectional IDT was designed as shown in Table I so that the impedance at the driving frequency is 50 Ω. The transducer IDT and the reflector IDT were placed at an interval of 603 µm. The driving frequency was 14.5 MHz.

In the first power circulation method, two driving IDTs are required. The dimensions of the driving IDT were 272 µm pitch, 68 µm electrode strip width and 8 mm aperture size. The driving IDT was composed of 10 strip electrode pairs. The two driving IDTs were placed at an interval 462 µm apart. The distances between the driving IDTs and each unidirectional IDT were 0.500 mm and 12.104 mm, respectively.

In the second power circulation method, an electrical combiner is required. The circulated-to-input power ratio at the electrical combiner was designed to be 4. The excessive power is consumed by an electrical resistance so that the ratio is 4. The two unidirectional IDTs were placed at an interval of 18.560 mm.

**CHARACTERISTICS OF STATOR TRANSDUCER**

The stator transducer using the first circulation method was fabricated according to the prescribed design. The traveling SAW was excited by putting in two signals to move the slider. The total input power was 0.4 W. The vibration amplitude of the normal direction to the surface was measured directly using a laser Doppler vibrometer. Fig. 5 shows the vibration distribution. In this figure, the positive direction means that the SAW is propagated toward the farther unidirectional IDT. It is obvious that the traveling SAWs propagated in the positive and negative directions were both excited. The standing wave ratio was 1.2.

The stator transducer using the second circulation method and the electrical combiner were fabricated in the same manner. The traveling SAW was excited at the input power of 0.7 W. Fig. 6 shows the vibration distribution. The standing wave ratio was 1.4 and the traveling SAW was excited.

The input power to excite the traveling SAW was measured. Fig. 7 shows the input power against the normal vibration amplitude. In this figure, the non-circulation method means that the SAW was excited by the IDT as a transducer of the unidirectional IDT (shown in the left part of Table I). This figure shows that the two kinds of input power to excite the traveling wave of 20 nm vibration amplitude were 14 W by the first power circulation method and 11 W by the second power circulation method. While the input power by the non-circulation method was 81 W. Therefore, the input power was decreased to 1/6 and 1/7 of the non-circulation method, respectively.
Driving a Slider

The driving performance of a slider was experimented by using the fabricated stator transducers. The setup for the experiments is shown in Fig. 8. The stator transducer was placed on the iron plate. The dimensions of the slider made of silicon were 4x4x0.3 mm³. There were many projections of pillar form on the contact surface of the silicon slider. The diameter of each projection was 20 µm. The projections were formed every 30 µm directly by the dry etching. A permanent magnet was fixed on the slider. The mass of the slider with the permanent magnet was 1.32 g. The slider was pressed against the stator transducer by the force of 0.86 N.

The motion of the slider was observed by using a laser Doppler vibrometer. The maximum output power was calculated from the transient response and the weight of the slider. Fig. 9 shows the maximum output power against the normal vibration amplitude. The maximum output power using the first or second power circulation method was equal to that using non-circulation method under the same vibration amplitude. Under the vibration amplitude of 20 nm, the no-load velocity and the maximum output force were 0.27 m/sec and 0.09 N, so that the maximum output power was about 6 mW.

Conclusion

Two novel methods for power circulation have been developed. SAW motors with using these methods were fabricated and a traveling wave was excited on these motors. The input power to excite a traveling SAW was decreased to 1/6 and 1/7 of the non-circulation method, respectively in the two methods. It was also experimentally observed that the driving performance of the SAW motor using the power circulation method was equivalent to that of using the non-circulation method. Therefore, the efficiency of a SAW motor has been increased by 7 times by using the developed power circulation method. The power circulation is significant to realize practical SAW motors.

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References