XY Surface Acoustic Wave Motor with Nanometer Resolution

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Abstract

An in-plane two-dimensional ultrasonic motor using surface acoustic wave (SAW)---2-D SAW motor---is reported. The motor utilizes traveling Rayleigh wave, a kind of SAW, for friction drive. To independently drive a slider in X- or Y-direction, four interdigital transducers (IDTs) were fabricated on ends of a stator plane to excite X- or Y-propagating Rayleigh wave. The operation area of the motor, namely the inside area surrounded by the four IDTs, was 14x14 mm². Since both the stator and slider are made of surface polished crystal substrates, the operational plane of the slider is flat and smooth on nanometer scale. The XY SAW motor performed less than 10 nm stepping motion every 0.2 ms for both directions. The motor also exhibited high speed, up to 0.5 m/s and 0.15 m/s for X- and Y-direction, respectively. The XY SAW motor showed excellent features for 2-D precise positioning actuator.

Keywords: ultrasonic motor, piezo actuator, friction drive, 2-D, nanometer resolution

1 INTRODUCTION

High-performances of a surface acoustic wave (SAW) linear motor has been reported, such as 1.5 m/s no-load speed and 13 N output force, even though that the linear motor consists of small devices; they are a 14x62x1 mm³ stator and 5x5x0.5 mm³ slider [1]. Moreover, the motor could perform 0.5 nm stepping motions [2].

The SAW linear motor is an ultrasonic motor, which utilizes the Rayleigh wave, a kind of SAW, for friction drive. Since the Rayleigh wave can propagate to the orthogonal direction of the stator, the SAW linear motor could easily expand to XY motor [3]. However, this XY SAW motor has not yet evaluated. The in-plane 2-D high-resolution motion is being essential for precise 2-D positioning applications. We, therefore, discuss the XY SAW motor in this paper.

2 PRINCIPLE

The XY SAW motor utilizes a SAW device for a stator to drive a slider, as illustrated in Figure 1. A SAW device is made of a piezoelectric crystal substrate, which has four interdigital transducers (IDTs) at its ends. RF electric power, approximately 20 MHz, in this report, is transduced to the Rayleigh wave at the IDT. The propagating Rayleigh wave power is transmitted to the slider motion by means of frictional coupling of the vibration [4]. By applying electric power to an IDT, the slider moves toward the IDT. The use of four IDTs, thereby, enables an arbitrary 2-D motion in plane.

Details of the friction drive mechanism are illustrated in Figure 2. Surface particles of the stator move in elliptical motion when the Rayleigh wave propagates. The rotating surface particles contact the slider surface at its wave crests. The particle motion, then, drives the slider through frictional force. The Rayleigh wave amplitude on the stator was from 8 to 15 nanometers in this report and the wavelength was 200 μm.

Owing to the use of small amplitude vibration for friction drive, the SAW motor exhibits sub-nanometer level high resolution [2,5], whereas the contact condition between the stator and the slider is crucial. To control the contact condition and to efficiently obtain the output power, a surface microfabricated silicon substrate element has been used as the slider [1]. A preload to the slider enlarges the output force of the motor due to the enlarged frictional force.
3 EXPERIMENTAL SETUP

The experimental SAW motor is indicated in Figure 3. The 31x31x0.5 mm³ stator was placed on a steel plate. Lead wires were attached to bus bars of the IDTs. The 2x2x0.5 mm³ slider was glued by a piece of double-sided stick tape to the φ3x3 mm³ neodymium magnet for the preload; the magnetic force between the magnet and the steel plate mainly yielded the preload. The magnetic force measured 60 mN. A φ3.6x2 mm³ steel bolt head was attached on the top of the magnet by the magnetic force. The bolt head was only used to add the height of this moving part in order to measure the slider motion. This is because a laser beam of the measurement equipment, the laser Doppler interferometer, was not able to position to the side of the magnet due to interference of a stator holder. The moving part weighted 0.206 g. The preload was the sum of the magnetic force and the weight of the moving part, namely 62 mN.

The stator was a square plate of 128° y-rotated x-propagation LiNbO₃ substrate. At the ends of the stator, IDTs were fabricated by means of vacuum deposition. The electrode materials were chromium and aluminmum. The dimensions of the IDT were 200 μm in pitch, 50 μm in electrode strip width, 50 μm in electrode strip gap and 11 mm in aperture. Each IDT was composed of 20 strip electrode pairs. The operation area on the stator was 14x14 mm². The LiNbO₃ is an anisotropic material so that the material constants are different in x-propagation direction and the orthogonal direction, which are hereafter referred to as X- and Y-direction. That results difference in propagation velocity and voltage to vibration amplitude ratio etc., however the Rayleigh wave propagates in both directions. The resonance frequencies of the IDTs for the Rayleigh wave propagation were 19.2 MHz and 18.2 MHz in X- and Y-direction, respectively.

The slider was made of a square plate of silicon substrate. The slider had microlens shaped projections—5-μm in diameter, 2-μm in height and arranged at 50-μm pitch—on its friction surface. The total number of the projections was 1600. The microlens projections were fabricated by means of thermal reflow of resist resin and dry etching. The microlens projections were employed to reduce contact area so as to obtain high contact pressure, since high-pressure contact condition ranging from 10 MPa to 100 MPa is required for ultrasonic friction drive.

4 TRANSIENT RESPONSES

The transient responses in X- and Y-directions are indicated in Figures 4 and 5. The driving voltage was applied from 0 ms, and the number of driving waves was 200,000 cycles. Namely, the durations that driving voltage was applied were approximately 10 ms in X-direction and 11 ms in Y-direction.

As indicated in Figure 4, maximum speed of 0.5 m/s was recorded on the condition of 60 Vₚₑᵃᵏ driving voltage in X-direction. The minimum driving voltage was 30 Vₚₑᵃᵏ; on this condition the motor performed 0.05 m/s traveling speed. The measurement data showed a typical transient response of ultrasonic motors; the speed rises as a first-order lag system (its step response has a form of [1-exp(-αt)] and falls linearly by kinetic frictional force.

The transient responses in Y-direction exhibited different property, as shown in Figure 5. More than 100 Vₚₑᵃᵏ driving voltage allowed the motor to function. On the condition of 140 Vₚₑᵃᵏ driving voltage, maximum speed of 0.15 m/s was obtained.
5 STEPPING DRIVES

Periodical 0.2 ms burst driving voltage was applied to each one of the IDTs both in X- and Y-direction to drive the XY SAW motor in a stepping motion. Figures 6 and 7 show examples of stepping motions in X- and Y-direction. The stepping motion indicated in Figure 6 was demonstrated on the condition of 40 V peak driving voltage and 120 cycles of driving waves. The motion indicated in Figure 7 was obtained on the condition of 100 V peak driving voltage and 120 cycles of driving waves. The duration while the burst driving voltage was applied was approximately 7 μs on each condition. This duration was very short compared to the 200 μs burst period, as shown in the indicated illustration of driving voltage in the figures. The moving part responded at low frequency to the voltage input.

Frictional driving force was acting on the slider only while the Rayleigh wave was underneath the slider. The slider, thus,
Figure 8. Step size in relation to the number of driving waves in X-direction; the driving voltage was 40, 50 and 60 V\textsubscript{peak}. 

Figure 9. Step size in relation to the number of driving waves in Y-direction; the driving voltage was 100, 120 and 140 V\textsubscript{peak}.  

principally moved while it was on the wave. The motion of the slider drove the magnet of the moving part through elastic coupling of the double-sided stick tape. Then the magnet drove the bolt head through magnetic coupling, likewise. The stepping motions in the figures were the motions of the bolt head of the moving part. The motion of the bolt head was the output of the spring-mass system so that it responded slowly [5].

The step sizes in relation to the number of driving waves in X- and Y-direction are depicted in Figures 8 and 9. The step sizes on any driving voltage conditions seem to increase as linear functions of the number of driving waves. The step sizes generally increased in keeping with the driving voltage. From the investigations of the stepping motions of SAW linear motor, however it is understood that the step sizes in nanometer scale are the quadratic function of the number of the driving waves or the driving voltage [4]. The preload was small in this experimental setup, hence it resulted inconstant contact condition and/or the vertical position variance of the moving part. This small preload would be the reason why the step size did not show the typical relationship to the driving conditions.

6 CONCLUSION

The XY SAW motor demonstrated less than 10 nm stepping motion in both directions along with high-speed motion; the maximum speed was 0.5 or 0.15 m/s in X- or Y-direction. Taking account of the study of the SAW linear motor, these performances can be improved. Designing an adequate mechanical structure will get the best performance of the XY SAW motor.

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