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Piezoelectric actuator for mobile auto focus camera applications

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Abstract Recently, various multimedia devices such as MP3 player, camera and even TV are integrated into a mobile phone. Consumer demands image cameras in mobile phone to have similar quality and performance as those of dedicated digital cameras. For a good image quality, increasing of resolution requires optical auto focusing, where a small lens group needs to be moved in a limited volume. Due to the efforts for reducing the size of each component in mobile phone, many types of motors have been investigated to achieve AF or zooming functions. However, a motor should be able to provide high controllability and performance to perform auto-focus (AF) camera function. One of the important features that piezoelectric motors have is the ability to maintain moving element position when the motor is not electrically excited. For mobile device application where power consumption is critical, this feature is fitting very well for lens positioning application in phone cameras. In this paper, we have applied our own development of piezoelectric motor for auto focus phone cameras. During auto focusing, we have measured total motor operating time that is less than one percent of total auto focusing time. Average instantaneous power, which is about 65 mWatts, is consumed only when the motor operates, which make piezoelectric motors to be superior over electromagnetic counterparts in terms of energy efficiency.

Keywords Piezoelectric · Actuator · Auto focusing · Camera module

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1 Introduction

Piezoelectric motors, which use accumulation of small displacements at high frequency through frictional contact, have features that make them a promising solution for lens moving mechanism. These features are high resolution of displacement, no power consumption when actuator is not moving due to frictional locking and no electromagnetic noise generation due to solid-state nature [2–6]. However, requirement of precise machining make these motor to be costly for large volume applications [2–5]. Additional constrains are manufacturability of piezoelectric vibrator and assembly in a small volume such as holding vibrators from their nodal position and robust driving methods to overcome environmental changes on piezoelectric ceramic body.

Regarding theoretical principal, piezoelectric ultrasonic motors have a long history. In 1942, a motor structure using vibratory motion of a rectangular bar was proposed by Williams and Brown [1]. In 60s we have seen many studies in former Soviet Union countries proposing motor structures using vibratory motions [2]. In 80's study of piezoelectric motors in Japan initiated to fulfill a technological need that is high precise positioners for semiconductor industry [3–5]. Therefore, as a technology, piezoelectric motors are available and the companies already manufacturing piezoelectric motors for high precision positioning application, basically high cost-small quantity applications [8–11].

We have developed such a piezoelectric motor where a multilayered piezoelectric actuator is used as the vibrating element [7].

Our aim in this project is to find a small, low cost and low power consumption actuator for lens moving mechanism by solving aforementioned issues of piezoelectric motors.

Basic operating principal and structure of the designed motor is described in the next section. Characteristics of the motor are given in Section III. In section IV, we present performance of this piezoelectric motor in an auto focusing camera module.

2 Design of mixed mode excitation type piezoelectric motor

The motor proposed in this study is a multi mode excitation type. The basic structure has 3 layers of piezoelectric ceramics plates, as shown in Fig. 1; top electrode are divided by 2 sections to form channel 1 (Ch1) and channel 2 (Ch2). Bottom electrode is uniform and mutual ground (GRN) to channel 1 and channel 2. The corresponding internal electrodes are connected to top and bottom electrodes through two side electrodes and one end electrode.

When, channel 1 is driven with an electrical signal, top left side, middle and bottom right sides of the piezoelectric ceramic layers are excited. Similarly, when channel 2 is driven, top right side, middle and bottom left sides of the piezoelectric ceramic layers of the stator are excited. The dimension of the stator is designed so that two orthogonal modes, which are first longitudinal (L1) and the second thickness bending (B2) mode resonance frequencies to be equal. The reason for using L1 and B2 modes is because nodal positions of these modes are overlap at the center of the actuator which is preferred for wire attachment and mechanical holding reasons.

After fixing the width and length of the stator as 1.5 and 5 mm, respectively, to match the first longitudinal mode into second bending mode, the thickness of the stator was varied. Calculated (using ATILA FEM program) and measured L1 and B2 mode resonance frequencies of the stator are shown in Fig. 2. While the first longitudinal mode is almost independent from the thickness of the stator, dependency of second bending mode is roughly square root of the thickness. For the specified length and width, the first longitudinal and second bending mode resonance frequencies are becoming close when the thickness is about 1.45 mm.

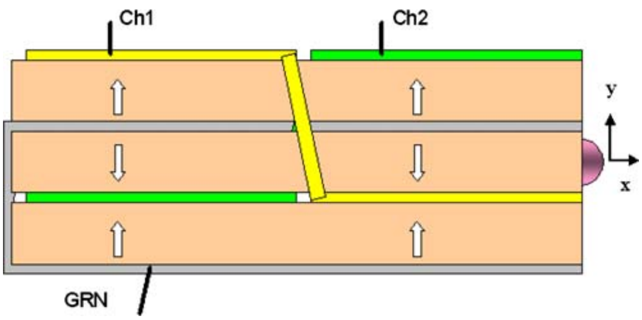


Fig. 1 Cross-sectional view of the stator that has 3 terminals (Ch1, Ch2 and Ground)

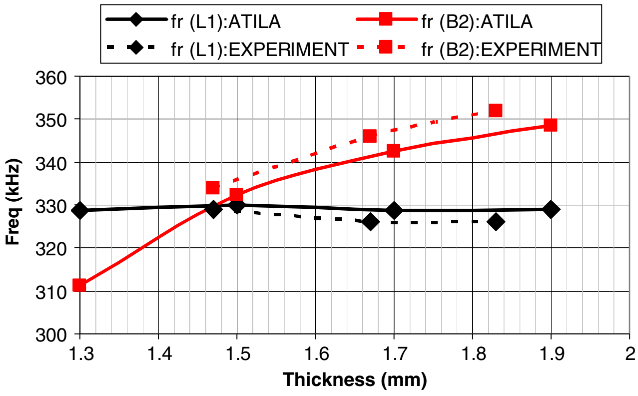


Fig. 2 Dependency of 1st longitudinal and 2nd bending mode resonance frequencies on actuator thickness for a length of 5 mm and a width of 1.5 mm. Dashed curves are experimental and solid curves are calculated using ATILA FEM program results

In order to increase manufacturability and decrease driving voltage of the motor, we made these actuators using co-firing multilayer actuator manufacturing technique. When making the stator elements of the motor with co-firing multilayer actuator manufacturing technique in an array form, we designed a unique electrode configuration. The electrodes for active channels (channel 1 and channel 2) are identical to ground channels except, ground channels electrodes are rotated by 180 degrees on the alternating layers in multilayer stator element. As can be seen in Fig. 3, the active electrodes of bottom M layers on the left side are connected to active electrodes of top N layers on the right side through one side electrode. Similarly the active electrodes of bottom M layers on the right side are connected to active electrodes of N

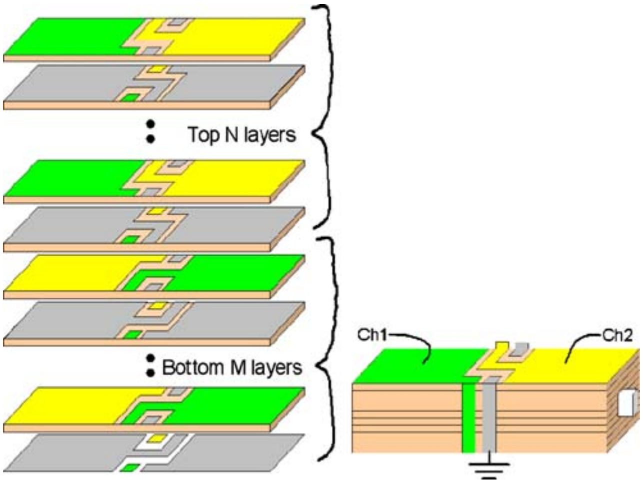


Fig. 3 Exploded perspective view shows in detail structure of the internal electrodes connectivity to termination side electrodes. Note that all electrodes (Ch1, Ch2 and Ground) on the bottom M layers are connected to the top N layers on the opposite sides through side electrodes

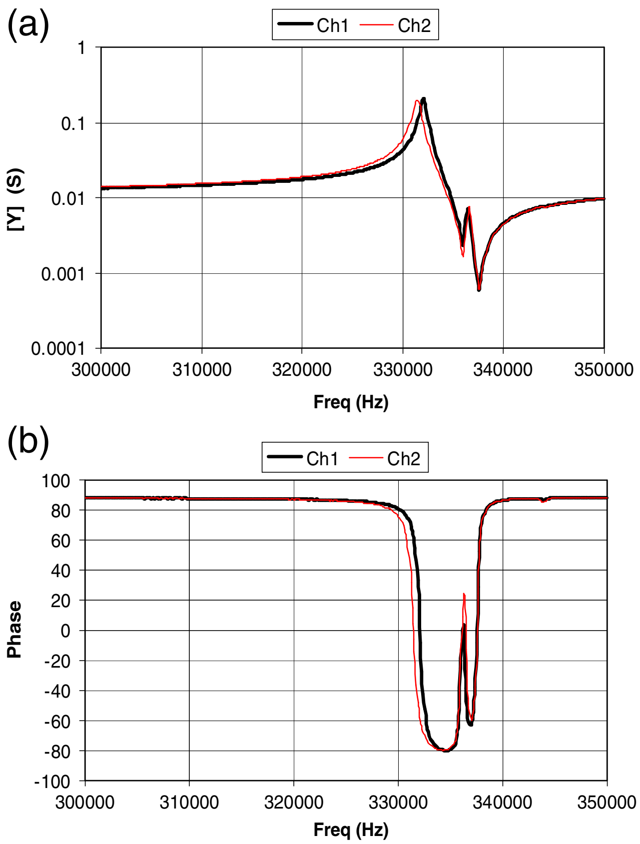


Fig. 4 Admittance (**a**) and Phase (**b**) spectra of a free stator for channel 1 and channel 2. Having identical admittance spectra means same lens moving speed which is important for lens position control during auto focusing time

layers on the left side through another side electrode. Two ground side electrodes are connecting ground internal electrodes that are placed on every other layer of thin piezoelectric plates.

Even though multilayer stator would be more costly compare to bulk stators, the proposed internal electrode structure let us to manufacture an array of multilayer stators at the same time making each stator unit to have a low cost.

The final stator has a dimension of 5.0 mm in length, 1.5 mm in width and 1.45 mm in thickness. The polarization directions of the layers are same as uniformly electroded piezoelectric actuators; every layer has opposite polarization to top and bottom neighboring layers.

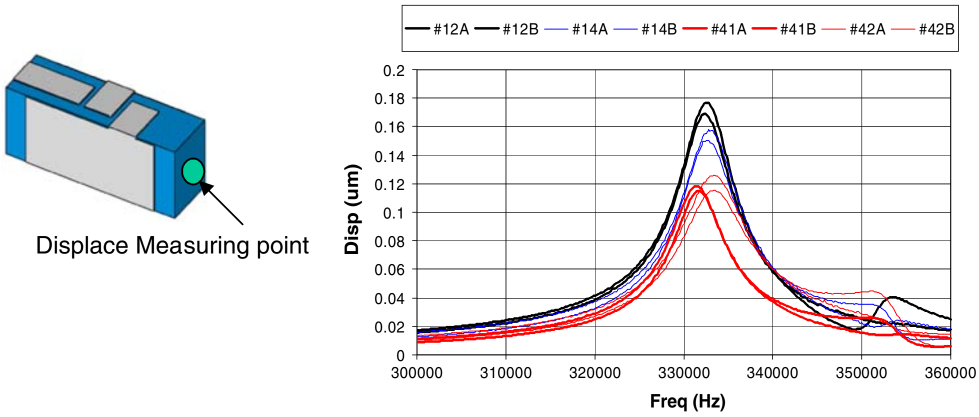
Excitation of co-fired multilayered stator is as follow. When channel 1 is excited; right side of the bottom M layers and the left side of the top N layers are excited. When channel 2 is excited; the left side of the bottom M layers and the right side of the top N layers are excited. By simultaneously changing channel 1 or channel 2 excitation direction of sliding element, in our application sliding element is a lens barrel is controlled.

3 Characteristics of piezoelectric stator

Figure 4 shows a typical admittance magnitude and phase spectra of the manufactured actuators, where the two resonance modes are seen for both channel 1 and channel 2. The main peak on Fig. 4a at 332 kHz is first longitudinal mode resonance frequency and the second peak at 336.5 kHz is the second bending mode resonance frequency of the free actuator. The second bending mode is in between first longitudinal resonance and anti-resonance frequencies. When one channel is driven with an electrical signal at a frequency in between the first longitudinal (L1) and the second thickness bending (B2) mode resonance frequencies, the two resonance modes are excited at the same time causing the end part of the piezoelectric stator to make an elliptical motion. The elliptical motion is then transferred to slider through frictional force.

Figure 5 shows displacement magnitude in longitudinal direction at one end of free stator as a function of frequency. The measurement was made by using Laser Doppler Vibrometer (LDV). As can be seen on the figure the peak displacement when actuator is excited at 2.8 V is in the range of 0.1 to 0.16 micrometers.

Fig. 5 Typical displacement magnitudes in longitudinal direction at one end of several stators as a function of frequency. Actuator numbers are arbitrarily selected. Letter “A” and “B” after the numbers are the measurements for channel 1 (Ch1) and channel 2 (Ch2), respectively



When making large quantity of actuators, an important criteria is to obtain identical performance from different stators in a narrow frequency range. As we can see on Fig. 5, peak displacement values in longitudinal directions at one end of the actuators are located in a narrow frequency range. In addition frequency and displacement values at peak point for channel 1 and channel 2 for the same actuator are almost equal to each other. Having identical peak displacement values in a narrow frequency range is critical because identical electrical driving circuitry can drive the motor and control lens position without component change with short adjustment time.

4 Af module using piezoelectric motor

The developed piezoelectric motor was applied for optic auto focusing in a camera module for mobile phones [7]. The multi mode vibration generated by piezoelectric stator element is transferred to the slider through a guiding mechanism. The tip attached to the stator and the slider has a high friction low wear contact. The stator is hold from its nodal positions and a spring applies a stress to the stator to increase force transfer to the slider on which lens is attached. A pair of roller creates a frictionless movement to the lens barrel for an efficient transfer of vibration force from stator to the lens barrel. Figure 6 shows auto focus camera module that has a size of 10×9.8×5.6 t (in mm);

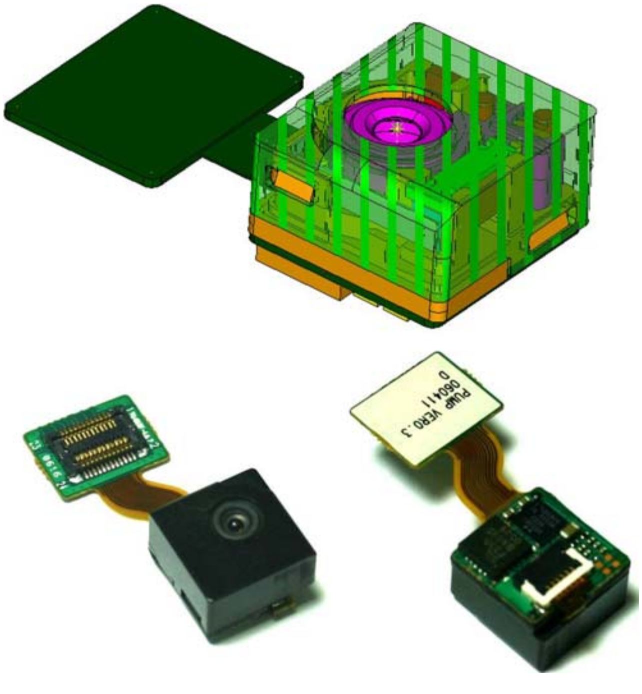


Fig. 6 Perspective views of 3D Drawing and Photo of the Camera module with a size of 10×9.8×5.6 t

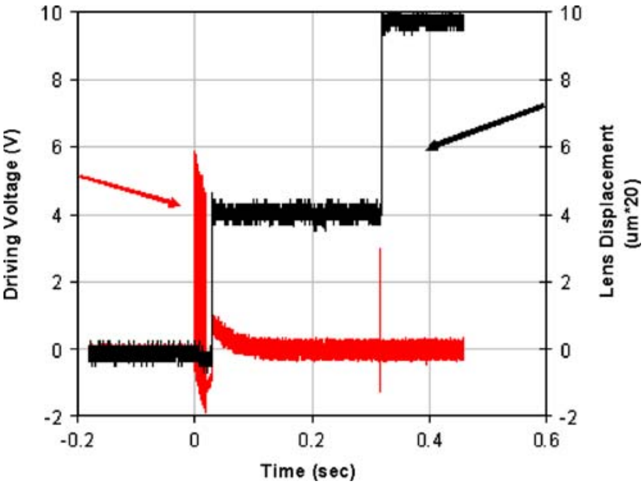


Fig. 7 Lens Position is maintained when input electrical signal is turned off

An important future of piezoelectric motors for portable device application is the ability of maintaining position without energy supply due to holding torque.

Figure 7 shows that lens position is maintained when the actuator is not electrically excited. First actuator was driven for 5000 pulses (15 milliseconds) at the driving frequency of the motor to move the lens to its initial position. Then the actuator was driven two times with 100 pulses. While at the first step lens was moved about 80 micrometers, however at the second step, it was moved about 110 micrometers. As we can see on the figure for large step motion, displacement for each step varies, which could make positioning accuracy to be unacceptable for auto focusing algorithm.

In order to overcome this problem we have applied two approaches. The first one was; embedding a reflective type

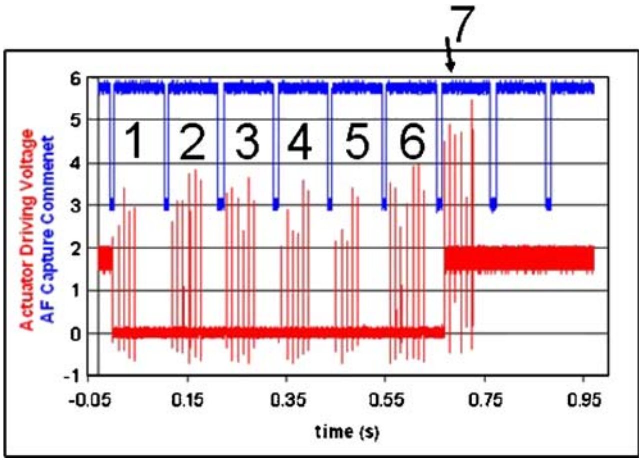
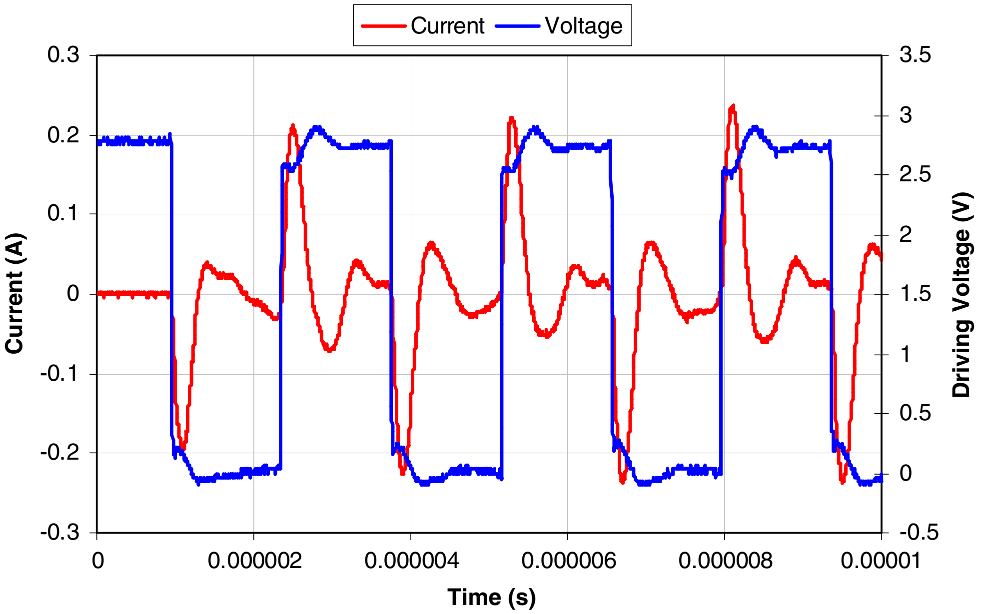


Fig. 8 Motor driving during auto focus searching time; each spike has about 30 packages of pulses; the driving time of the actuator for this example is 3.6 milliseconds. Total motor driving time is always less than 1% of auto focus searching time that is about 1 second

Fig. 9 Motor driving current and voltage waveforms when the motor is operating

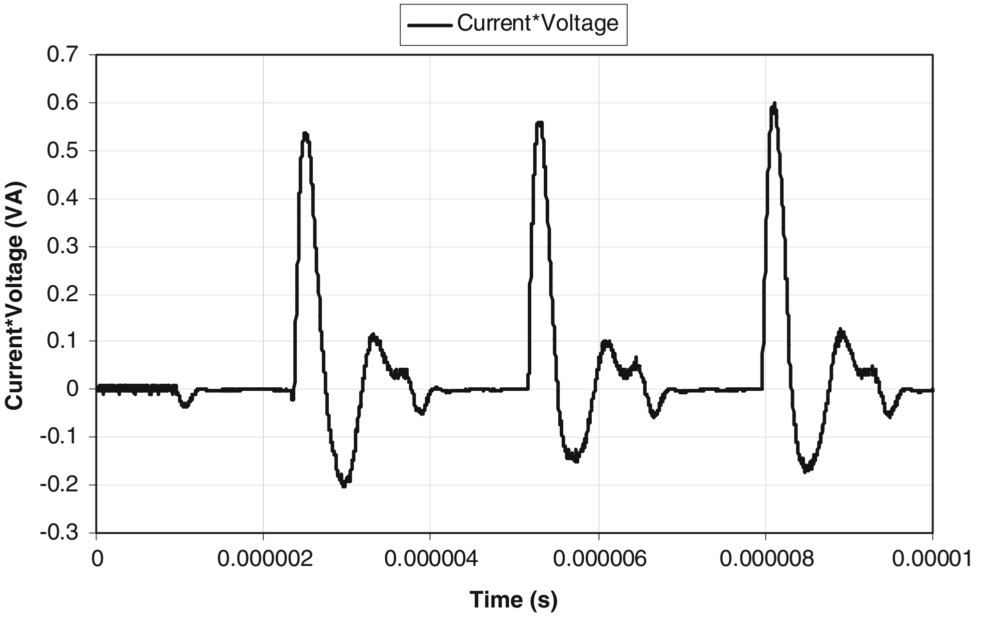


position sensor in to the camera module on the side of the lens barrel to obtain a lens position feedback for auto focusing algorithm. The other one was, exciting the actuator at small number of pulses to move the lens in small steps so that differences between each step to be small. As we can see on Fig. 8 which shows the driving voltage applied on actuator during auto focusing time, lens was moved at several small steps to reach a target displacement at each auto focus capture time.

Auto focus capture comment signal which is seen on the same figure is generated by image sensor. After each auto focus capture comment, auto focus algorithm checks the auto focus value created by image sensor. The task of auto focus algorithm is to maximize auto focus value. During auto focusing period which was seen in Fig. 8, lens was moved to a target position for each time auto focus capture comment was received. In each step AF value was measured. At first 5 steps because auto focus values were increasing, lens was moved at certain amount. At step 6, however, because auto focus values started to decrease, the lens was moved to the point where AF was at maximum by driving the piezoelectric motor in reverse direction. This was done during step 7.

In every step when lens is moving, the stator is electrically excited about 0.03 milliseconds. During total best focus point searching time, which is about 1 second or less, the lens is moved 10 to 15 times that makes the total motor operation time at most 0.5 milliseconds, which is less

Fig. 10 Current and voltage waveforms are multiplied to find instantaneous power when the motor is electrically excited



than 1% of total AF time. With this feature, piezoelectric motors are providing extremely energy efficient lens moving actuator solution as compare to electromagnetic counterparts.

We have also measure power consumption when the motor is electrically excited by measuring driving voltage and the current on the excited channel of the stator. Figure 9 shows the driving voltage and current waveforms on the excited channel. The actuator is driven at its operating frequency with a square wave changing from 0 to 2.8 Volt.

As can be seen on the figure current is drawn to the actuator during transient time of the driving voltage and it reaches a maximum value of about 0.2 A. Negative value of the current means stored current on the actuator returned to driver when voltage value is decreasing to 0V from 2.8 V.

When the current and voltage waveform during motor operation is multiplied to each other we obtained curve shown in Fig. 10. What is shown in this curve is instantaneous power that piezoelectric motor spend during operating time which make an RMS value of the power consumed by the motor is about 65 mWatts. Note that this power is consumed only when the motor operates which is less than 1 percent of total auto focus searching time that is less than 1 seconds. In other words average power consumption of the piezoelectric motor is about 6.5 mWatts during auto focus searching time. Therefore piezoelectric motors are extremely energy efficient lens positioning actuators for phone camera application.

5 Conclusions

In this study, we have introduced our own development of piezoelectric motor for lens moving mechanism. The motor is using a bar type multilayer piezoelectric actuator as the vibrating element (stator). The 1st longitudinal and 2nd bending modes are superimposed to generate a circular motion. This motion is then transferred to guided slider through frictional contact.

Piezoelectric multilayered stators were manufactured in a size of 5 mm in length, 1.5 mm in width and 1.45 mm in thickness and applied for lens moving mechanism in an auto focusing (AF) camera module with a size of $10\times9.8\times5.6\ \text{mm}^3$.

Due to existence of pre-stress between vibrating element and moving element, piezoelectric motors are providing extremely energy efficient lens positioning actuations for portable devices. Motor operating time is only one percent of total auto focusing time (~1 second) and during operating time, actuator consumes about 65 mWatts of power.

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