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A low-working-field (2 kV/mm), large-strain (>0.5%) piezoelectric multilayer actuator based on periodically orthogonal poled PZT ceramics

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ABSTRACT

In this work, we proposed a special designed multilayer actuator based on the periodically orthogonal poled (POP) PZT ceramics. Only the in-plane poled regions of the neighboring PZT layers were bonded together thus the large reversible switching strain in these regions can always be employed. A six-layer actuator was fabricated and testing results show that it can output actuation strains over 0.5% under a low field of 2 kV/mm at 0.1 Hz, about 3.5 times of that in conventional PZT actuators which is less than 0.15% under the same field. Furthermore, the output large strain is fairly uniform, which varies from 0.50% to 0.53% along the period direction, in comparison with that varying from 0.35% to 0.59% in a single-layer POP PZT. The large actuation strain drops quickly with the increasing frequency, and stabilized at about 0.2% under 2 kV/mm at or above 1 Hz. The low-frequency large strain is very stable and keeps unchanged after 20 k cycles of operation. To solve the charge accumulation problem during successive unipolar loading/unloading, an asymmetric bipolar field from −300 V/mm to 2 kV/mm is applied and meanwhile the actuation strain turns to be more uniform, only varying from 0.51% to 0.52% at 2 kV/mm. The low driving field, large strain of the proposed actuator makes it very promising in low-frequency, large strain/displacement actuation areas.

1. Introduction

Actuators have been playing an important role in modern industries as positioners, fuel injectors, scanners, etc. Currently used industrial actuators are mostly based on piezoelectrics, magnetics or shape memory alloys (SMA). Piezoelectric actuators, which are based on linear piezoelectric effect, have been dominant in the actuation area in the past decades [1]. Magnetic actuators are based on magnetostriction, which is not linear but quadratic effect of the applied magnetic field [2,3]. SMA actuators are based on the two-way shape memory effect (SME), which is usually achieved after thermal/mechanical training [4]. An ideal actuator should be electric driven, with large strain, good linearity, small hysteresis, quick responses and large blocking force. The typical performances of these three types of actuators were listed in Table 1, from which it can be seen that piezoelectric actuators are superior to magnetic and SMA actuators except for the small output strain, typically 0.1–0.15%.

In the past two decades, various efforts had been taken to enhance the actuation strain of piezoelectrics. The main approaches can be classified into four types: 1) Developing relaxor ferroelectric single crystals [5,6]. The actuation strain can reach over 1% via electric field induced phase transformation. However, the high cost of ferroelectric single crystals and the quick drop of the actuation strain upon applying a moderate prestress make this type of materials not suitable for industrial applications [7,8]. 2) Developing lead-free piezoelectric ceramics [9,10]. The actuation strain in a non-textured BNT-based ceramics can reach over 0.6% with very large hysteresis under a high field of 5 kV/mm [11]. While under a low field of 2 kV/mm (which is the typical field for piezoelectric actuators), the maximum strain is about 0.2% [12], only comparable to PZT. 3) Developing textured piezoelectric ceramics [13]. The actuation strains can be enhanced to 0.3–0.4% at 5 kV/mm for the textured lead-based PMN-PT ceramics via template grain growth [13,14], but it is only about 0.2% at 2 kV/mm, also showing no obvious advantage compared to PZT. For lead-free ceramics, the textured sample usually shows increased electros-

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Table 1
Comparison of typical performances of three types industrial actuators [1–4].

Performance	Actuation Type		
	Piezoelectric	Magnetics	SMA
Driving field	Electric	Magnetic	Thermal
Typical strain	0.1–0.15%	0.1–0.2%	2–5%
Linearity	Good	Poor	Poor
Hysteresis	Small	Small	Large
Frequency	>kHz	>kHz	<10 Hz
Blocking force	Large	Large	Large

train but the hysteresis is also larger compared to the non-textured ones [15]. 4) Realizing reversible non-180° domain switching via electromechanical loading or point-defect mediating [16–21]. The large actuation strain can reach up to 0.93% in BaTiO3 crystals and 0.66% in PMN-PT crystals via electromechanical loading[17]. With a prestress of 56MPa, the actuation strain in a soft PZT can be enhanced to be 0.2% at 2 kV/mm and 0.35% at 3 kV/mm via partial reversible domain switching [18]. However, the required prestress obviously limited the applications of this method. As to the point-defecting mediating method [19], the electrostrain dropped quickly after cycles of operation [20,21], which is due to the relaxation of the internal bias field generated during the aging process.

Recently, Li et al proposed a novel periodically orthogonal poling (POP) method and realized local actuation strain nearly 0.6% at 2 kV/mm in PZT ceramics via reversible domain switching [22], which is about four times of the actuation strain in conventional PZT ceramics. Such a large strain realized in PZT is very promising and had been thought to open the door to next-generation large-strain actuators [23]. However, the actuation strain in the POP PZT ceramics is strongly non-uniform along the period direction, varying from about 0.35% to 0.58% at 2 kV/mm, which is not suitable for actuator applications.

In this work, we designed a special piezoelectric multilayer actuator based on the POP PZT ceramics in which only the in-plane poled region of the adjacent layers were bonded together. In this way, the actuation strain of the actuator could become more uniform with the increasing number of layers. Large actuation strain varying from 0.50% to 0.53% were realized in a six-layer actuator under a unipolar field of 2 kV/mm at 0.1 Hz. The large actuation strain is very stable after 20 k cycles of operations, but drops quickly with the increasing frequency. To solve the charge accumulation problem under unipolar loading, a bipolar field from −300 V/mm to 2 kV/mm was also used to drive the actuator. It was found that the actuation strain under asymmetric bipolar field is more uniform (0.51–0.52%) and the charge accumulation is not severe any more. The proposed piezoelectric multilayer actuator based on POP PZT ceramics could be very useful in a variety of actuation areas due to its giant actuation strain over 0.5% under a low field of 2 kV/mm.

2. Experimental

In a periodically orthogonal poled (POP) piezoelectric ceramics [22], the originally thickness poled region is denoted as Region C and the subsequently in-plane poled region is denoted as Region A, as shown in Fig. 1(a). The material used is the well-known soft PZT-5H. The initial poling along the thickness is conducted with the electric field applied above the Curie temperature of 190 °C, the sample was gradually cooled to room temperature with the applied field on. The subsequent in-plane poling was conducted at about 80 °C on Region A. Under a unipolar field of 2 kV/mm at 0.1 Hz, the maximum strain in Region A can reach 0.57%, while the minimum strain in Region C is only 0.35% [22]. The large strain in Region A is mostly contributed by the non-180° domain switching from the in-plane poled state to the vertically poled state. In comparison, Region C is originally vertically poled but may be partially depolarized during the in-plane poling of adjacent Region A. So the relative small strain in Region C should be caused by the piezoelectric effect and partial domain switching. Nevertheless, the actuation strain in the POP PZT is strongly non-uniform along the period direction, which is not suitable for actuator applications.

To realize uniform actuation strain based on the POP PZT ceramics, a special multi-layer actuator was designed as shown in Fig. 1(a) where only Region A (in-plane poling region) of the neighboring layers were bonded together. In this way, the large actuation strain in Region A of all the layers will be employed. The relatively smaller strain in Region C will not be employed except for the top (or bottom) layer. Obviously, the output strain of such a designed actuator will turn to be more uniform with the increasing number of layers. For the industrial manufacture, a specially designed automatic bonding device with controlled movement and glue printing could realize the periodic bonding accurately as long as the period of the poling is large enough (say over 1mm).

In this work, a six-layer actuator based on the POP PZT-5H ceramics was fabricated using the proposed partially bonded method. Each layer is 10 mm long, 5 mm wide and 2 mm thick, thus the height of the whole actuator is about 12 mm. The large layer thickness of 2 mm were used here because each layer is periodically orthogonal poled separately and a smaller thickness would make the in-plane poling more difficult. The period of the POP is 2mm along the 10mm direction, i.e., five regions (CACAC) were formed in each layer, as seen in Fig. 1(a). The poling directions in Region C of the neighboring layers were opposite thus all the neighboring layers can share a common electrode. Here thin cooper sheets with the thickness of 40μm were inserted between the neighboring layers to serve as the common electrodes. The photography of the fabricated six-layer actuator were shown in Fig. 1(b).

The actuation performances of the six-layer actuator were then systematically measured. The testing setup is shown in Fig. 2. A uni-polar triangular signal generated by a function generator (Agilent 33220A) was amplified by a high-voltage amplifier (TREK 609B,

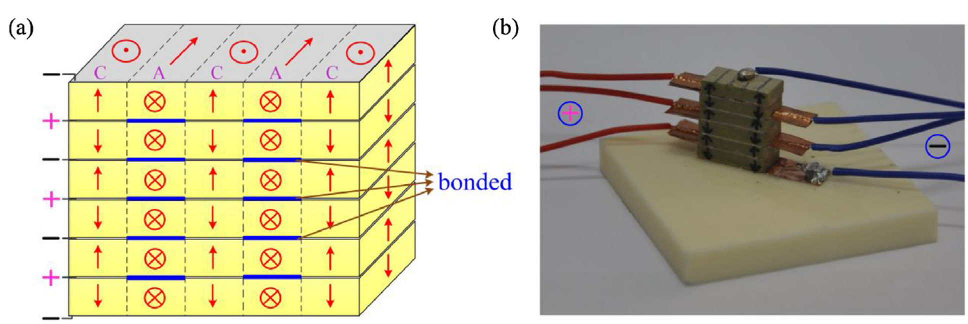

Fig. 1. A six-layer actuator made up of periodically orthogonal poled PZT ceramics in which only the in-plane poled regions (Region A) of neighboring layers are bonded together. (a) schematics (b) photograph.

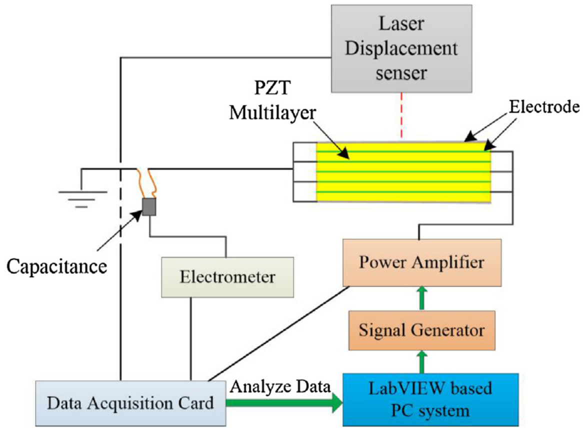

Fig. 2. Testing setup for measuring the actuation strain of the piezoelectric multilayer actuator.

voltage up to 10 kV, current limit of 2 mA) and then applied to the multilayer actuator. The displacement of the actuator was measured by using a laser displacement meter (LK-G30), and the charge was measured using a high-impedance (10^{12} Ω) electrometer (EST 103). The voltage signal, displacement signal, and charge signal are all collected by a USB data acquisition card (NI USB-6341), where the latter two signals are converted into strain and polarization. All the measurements are controlled by a home-made LabVIEW program and monitored by a computer.

3. Results and discussions

Fig. 3(a) shows the actuation strain curves measured in Region A and Region C of the POP PZT based six-layer actuator under a unipolar field of 2000 V/mm at 0.1 Hz. For comparison, the actuation strain curve of a conventional poled PZT-5H ceramics is also plotted in Fig. 3(a). It can be seen that there is slight differences between the strain curves of Region A and Region C, indicating the validity of the proposed actuator design. The actuation strain (in both Region A and Region C) of the six-layer actuator is over 0.5% under a relatively low field of 2 kV/mm, which is about 3.5 times of that in conventional PZT ceramics under the same field (about 0.145% at 2 kV/mm). From Fig. 3(a), it can also be seen that the linearity of the large actuation strain is fairly good. The degree of strain hysteresis, which is defined by the ratio of the strain deviation during field loading and unloading at half of the maximum electric field

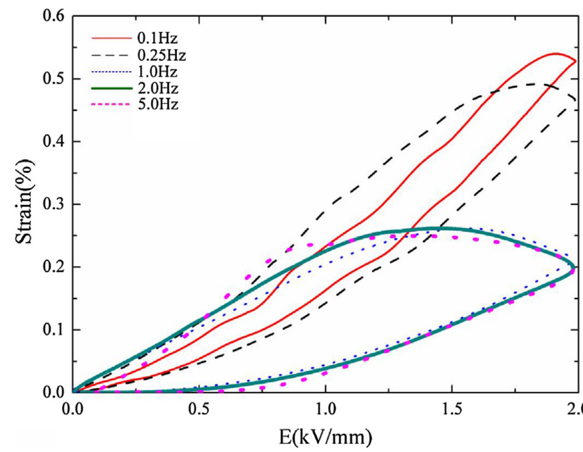

Fig. 4. Frequency dependent actuation strains curves of the six-layer POP PZT based actuator under a field of 2 kV/mm.

(ΔS_{hyst}) to the maximum strain at the maximum field (S_{max}) [1], is about 18% for both regions, larger than that in the single layer POP PZT which is below 10% [22]. Note that in Fig. 3(a), the maximum strain in Region A is not realized at the maximum field during loading, but at the early stage during field unloading. This is due to the fact that domain switching is a gradual process and shows obvious creep under a moderate electric field [24].

The maximum strain profile of the six-layer actuator along the period direction (10 mm) under 2 kV/mm at 0.1 Hz were plotted in Fig. 3(b), where the strain profiles of a single layer and a four-layer actuator were also presented for comparison. It can be seen that for a single layer POP PZT, the actuation strain varies from 0.35% in Region C to 0.59% in Region A. For a four-layer actuator, the strain turns to be fairly uniform, from 0.50% in Region C to 0.55% in Region A. In the six-layer actuator, the actuation strain becomes more uniform, just varies from 0.50% to 0.53%. It can be expected that the strain in such a designed actuator with more layers of POP PZT would become very uniform.

The frequency dependent actuation behavior of the six-layer actuator was also measured and the results were shown in Fig. 4. It can be seen that the actuation strain drops quickly with the increasing frequency. The maximum strain (in Region A) under 2 kV/mm is 0.53% at 0.1 Hz, it drops to 0.46% at 0.25 Hz, and stabilized at about 0.2% above 1 Hz. The strain hysteresis turns to be very large (about 100%) at or above 1Hz, which may indicates that domain

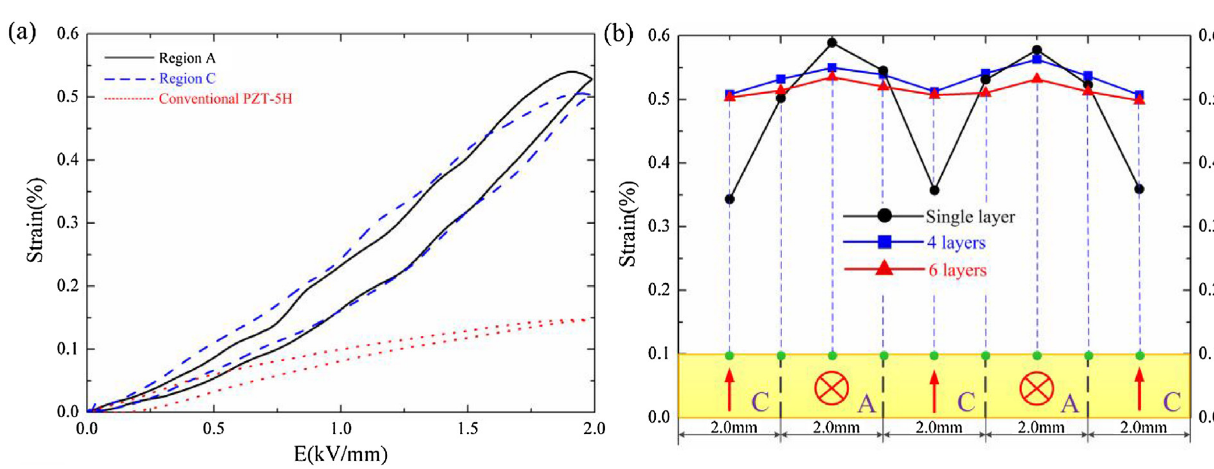

Fig. 3. Actuation testing results on the POP PZT based actuator under a unipolar field of 2 kV/mm at 0.1 Hz. (a) Comparison of actuating strain in different regions of a six-layer actuator and that of a conventional poled PZT ceramics; (b) maximum actuation strain profile along the period direction (10 mm) in actuators with different layers of POP PZT.

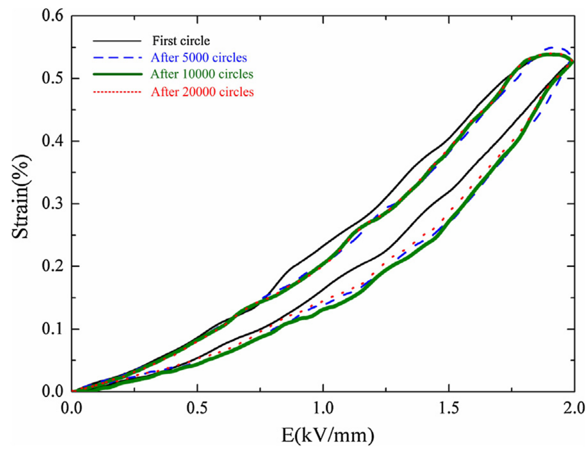

Fig. 5. The actuation strain curves of the six-layer POP PZT based actuator after different cycles of electric loading/unloading under 2 kV/mm at 0.1 Hz.

switching lags behind the applied field and cannot accomplish completely under quick loading. Note that the stabilized strain of 0.2% is still about 1.5 times of that in conventional PZT ceramics under the same field. Frequency responses above 5 Hz were not measured because of the small current limit (2 mA) of the high-voltage amplifier. Anyway, the results in Fig. 4 indicates that this actuator is more promising for low-frequency, large strain actuation applications.

The repeatability of the large actuation strain in the six-layer POP PZT based actuator was further examined under the applied field of 2 kV/mm at 0.1 Hz. Measurement was conducted up to 20 k cycles and the results were shown in Fig. 5 where each actuation curve was measured after the cycling and discharging the actuator. It can be seen that the large actuation strain of the actuator is very stable and almost does not change after 20 k cycles of operation, which is very promising for practical applications. This may also indicate that the domain structures as well as the interfacial stresses generated during the periodically orthogonal poling are very stable and does not change under normal operation, which is very similar to stable martensitic phase structures in the shape memory alloy actuators via the two-way shape memory effect [4].

We noticed that during successive uni-polar field loading/unloading, the charge accumulation problem is severe for the six-layer actuator. As shown in Fig. 6 (a), under the unipolar loading/unloading with the field amplitude of 2 kV/mm, the amount of the accumulated charge increased quickly with the loading cycles and saturated the reading of the electrometer in less than three cycles. The accumulated charge will slightly reduce the actuation strain, as seen in Fig. 6(b). To solve this problem, an asymmetric bipolar field of 0.1 Hz from −300 V/mm to 2 kV/mm was applied to drive the six-layer actuator. The small negative field used here is to avoid the possible depolarization under large negative field. It can be seen from Fig. 6(a) that during the asymmetric bipolar loading, the charge accumulation problem is not severe any more.

The actuation strain of the six-layer POP PZT actuator under the asymmetric bipolar field were also measured and the results were shown in Fig. 7. It can be seen from Fig. 7(a) that compared to the unipolar loading, the maximum actuation strain under bipolar loading is slightly decreased. Referring to Fig. 7(b), it can be seen that in bipolar loading, the strain in Region A is slightly reduced (from 0.53%–0.52%), while that in Region C is slightly increased (from 0.50%–0.51%). That is, the actuation strain is more uniform under the asymmetric bipolar loading. Under asymmetric bipolar loading, the slightly increase strain in Region C is easy to understand as this also appears in conventional piezoelectric actuators [24]. The decreased strain in Region A is due to the fact that negative field also induce positive switching strain in the in-plane poled region, i.e., the switching strain is quadratic effect, like the magnetostriction in magnetostrictive materials [2,3].

Based on the above results, we suggest driving the POP PZT based actuator using asymmetric loading from −300 V/mm to 2 kV/mm at 0.1 Hz. It is also safe to apply a field of 2.5 kV/mm to this actuator while in this case the domain switching turns to be instable thus the maximum strain oscillates [22]. Under even higher field, the actuator may break. A single layer POP PZT ceramic fractured along the interface between Region A and Region C when the unipolar field reaches 2.8 kV/mm. The large interfacial stresses caused by large misfit strains should be responsible for the observed fracture.

4. Conclusions

In summary, we proposed a special designed multilayer actuator based on the periodically orthogonal poled (POP) PZT ceramics and realized fairly uniform large actuation strain over 0.5% under a low field of 2 kV/mm at 0.1 Hz. The large strain is very stable after 20 k cycles of operation but drops quickly with increasing frequency. The severe charge accumulation problem during successive unipolar loading/unloading was solved by using bipolar loading from −300 V/mm to 2 kV/mm. Meanwhile, the strain becomes more uniform (0.51%– 0.52%) under the asymmetric bipolar loading.

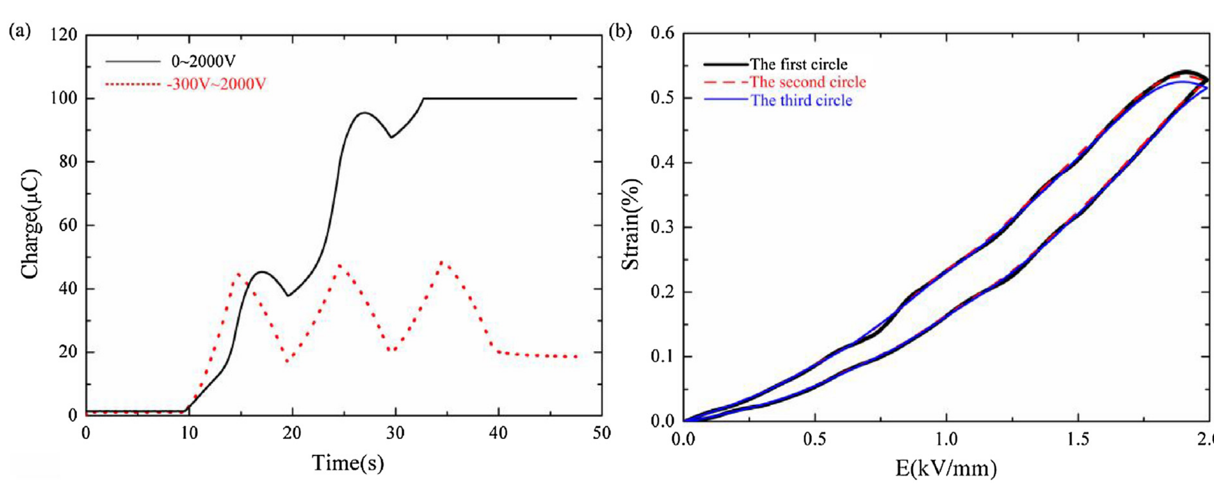

Fig. 6. Charge accumulation effect on the six-layer POP PZT actuator during three successive loading/unloading cycles at 0.1 Hz. (a) Charge accumulation curves under unipolar field of 2 kV/mm and asymmetric bipolar field from −300 V/mm to 2 kV/mm; (b) The actuation strain curves under three successive loading/unloading cycles of 0–2 kV/mm.

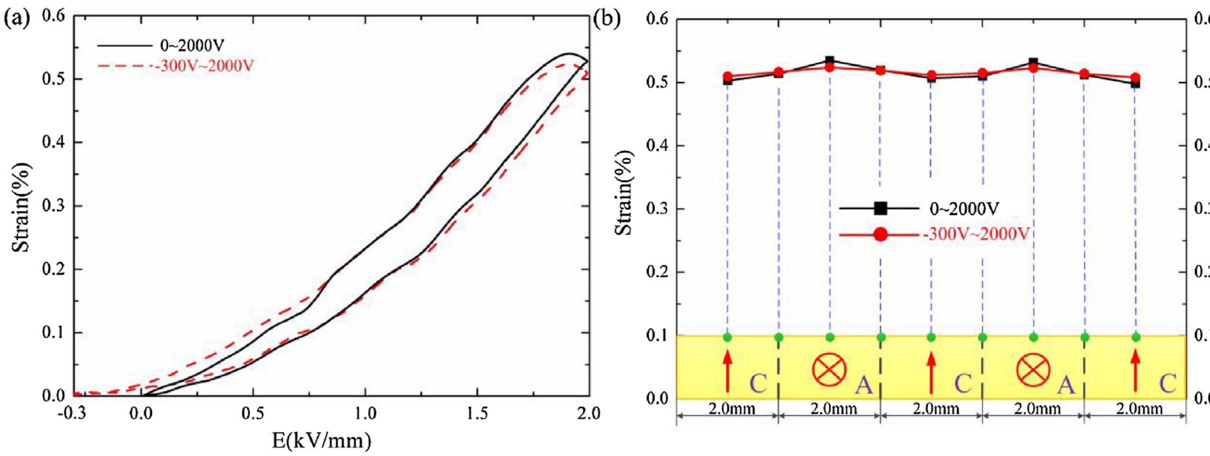

Fig. 7. Actuation strain of the six-layers POP PZT actuator under 0.1 Hz unipolar loading of 0–2 kV/mm and asymmetric bipolar loading of −300 V/mm to 2 kV/mm. (a) Strain curves; (b) Maximum actuation strain profile along the period direction (10 mm).

The proposed piezoelectric multilayer actuator could be very useful in a variety of industrial areas where large actuation is required. This work could change the traditional concept that the actuation strain of piezoelectric ceramics is very small. It is over 0.5% and not small from now. In our future works, further properties of the proposed actuator, such as the blocking forces, prestress dependent actuation, thermal stability, strain creep, etc., will be systematically studied.

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