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Research of the PZT polarization for deformable mirror

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Abstract. This paper demonstrates that the deformation of the piezoelectric deformable mirror (DM) is proportional to the transverse piezoelectric coefficient of the lead zirconate titanate (PZT) by the theoretical analysis. The optimal polarization conditions were obtained by experiments to optimize the performance of the DM. After the optimal polarization, the transverse piezoelectric coefficient of the PZT film d_{31} increases from 350 pm/V to 431 pm/V, which will improve the deformation of the DM.

Introduction

Piezoelectric effect has received widespread attention since it was found by Jacques Curie and Pierre Curie in 1880 [1]. With the rapid development of micro-electro-mechanical system (MEMS) technology, lead zirconate titanate (PZT) has been widely applied in micro sensors [2,3,4] and micro drives [5,6,7] due to its excellent piezoelectric properties and high electromechanical coupling coefficients.

The adaptive optics technology, which can correct dynamic aberrations, has been extensively used in astronomical imaging [8], vision science [9], microscopy [10], and high-power lasers [11]. Deformable mirror (DM) is the main component of adaptive optics as its execution unit. Piezoelectric DMs are attractive because of their low cost and large stroke. Deformation is the most important performance parameter of DM which directly affects DM's wavefront correction ability. Meanwhile the deformation of the piezoelectric DM is decided by its piezoelectric properties directly. Therefore, PZT piezoelectric properties affect the performance of the piezoelectric DM seriously.

In this paper, the relationship between the deformation of the DM and the transverse piezoelectric coefficient of the PZT is demonstrated by theoretical analysis to improve the performance of the DM. A polarization device was designed and fabricated. By measuring the transverse piezoelectric coefficient of the PZT film polarized under different conditions we can obtain the optimal polarization parameters, which can improve the performance of the DM.

The influence of the polarization to DM performance

An analytical model based on the theory of plates and shells was studied in our preceding work [12]. We can use the same analytical model to analysis the relationship between the deformation of DM and its piezoelectric properties. As shown in Fig. 1, the deflection of a disk unimorph DM can be represented as follows

$$w(r)=\frac{-d_{31}U(b^2-a^2)(a^2-r^2)}{\left(4b^2t_{pzt}\right)\left[\frac{t}{2}+\frac{2}{t}\left(\frac{1}{E_{pzt}t_{pzt}}+\frac{1}{E_{si}t_{si}}\right)\left(D_{pzt}+D_{si}\right)\right]} \quad \left(0\le r\le a\right) \qquad (1)$$

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$$w(r)=\frac{-d_{31}U\left[a^2(r^2-b^2)-2b^2\ln(\frac{r}{b})\right]}{\left(4b^2t_{pzt}\right)\left[\frac{t}{2}+\frac{2}{t}\left(\frac{1}{E_{pzt}t_{pzt}}+\frac{1}{E_{si}t_{si}}\right)\left(D_{pzt}+D_{si}\right)\right]}\qquad\left(a<r\le b\right) \tag{2}$$

a and b are the radii of the electrode and the DM, respectively. U is the voltage applied on the PZT film and t is the total thickness of the actuator. D_{pzt}, E_{pzt}, t_{pzt} and d_{31} are the flexural stiffness, Yang's modulus, thickness, and the transverse piezoelectric coefficient of the PZT film, respectively. D_{si}, E_{si}, t_{si} are the flexural stiffness, Yang's modulus, thickness of the silicon elastic layer, respectively.

The deformation shape of DM can be calculated from Eq. 1 and Eq. 2, and it's obviously that the deformation of DM is proportional to the transverse piezoelectric coefficient of the PZT film. In consequence, it's of great significance to obtain the optimal transverse piezoelectric coefficient of the PZT film by polarization.

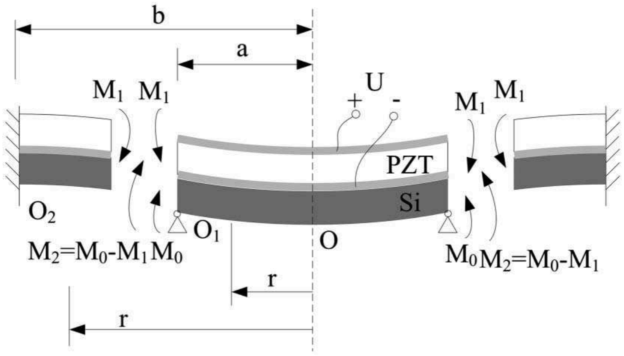


Fig. 1. Deflection of PZT disk unimorph actuator. The actuator radius is b and the top electrode radius is a. M0, M1 and M2 are moment caused by actuation of PZT, moment between two parts and equivalent moment applied on the central part, respectively.

Experiments

An experiment setup was established for polarization, whose schematic diagram is illustrated in Fig. 2. PTFE was chosen to make the polarization device because of its excellent chemical stability, high corrosion resistance, electric insulation and excellent heat resistance. In the polarization process, a DC electrical source is used to supply a high voltage to the PZT through the polarization device and a heating plate is used to heating the PZT which is immersed in the silicone oil. Using this experiment setup, the PZT can be polarized in different conditions such as different electric field intensities, different temperatures and different used time. It should be note that the PZT films should be depolarized by maintaining a high temperature of 170 degrees Celsius for 50 minutes before polarization.

The PZT film was glued to the copper film with epoxy to be a composite beam, which is a standard heterogeneous bimorph by considering as a device with only two layers: elastic and piezoelectric. Then the composite beam was clamped to be a cantilever, shown by Fig. 3, whose deflection was measured to calculate the piezoelectric coefficient d_{31}. According to the theoretical formula of the deformation of cantilever [13], the transverse piezoelectric coefficient can be represented by the following equation:

$$d_{31}=\frac{\delta\left[E_{pzt}^2t_{pzt}^4+E_{pzt}E_{cu}(4t_{pzt}^3t_{cu}+6t_{pzt}^2t_{cu}^2+4t_{pzt}t_{cu}^3)+E_{cu}^2t_{cu}^4\right]}{3t_{cu}(t_{pzt}+t_{cu})E_{pzt}E_{cu}L^2U}. \tag{3}$$

The subscripts pzt and cu in this equation refer to the elastic layer and piezoelectric layer, respectively. L is the length of the composite beam. U is the voltage applied on the PZT film. δ is the maximum deflection of the composite cantilever beam.

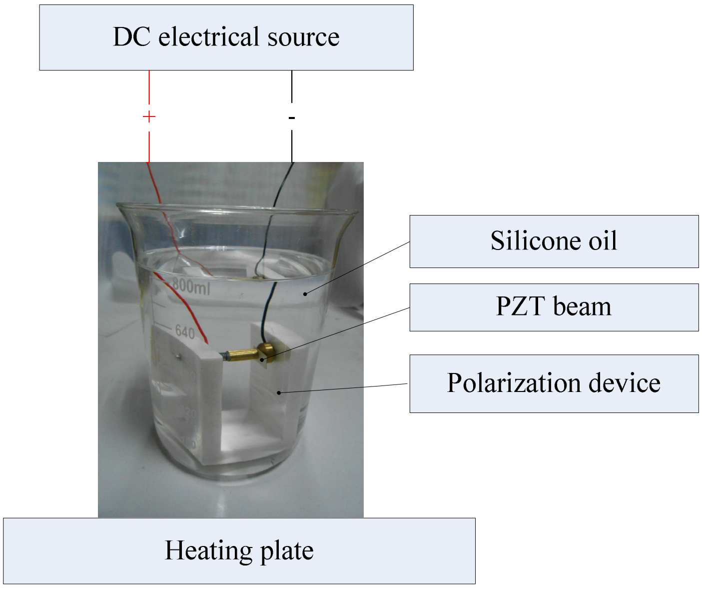


Fig. 2 The schematic diagram of the polarization setup.

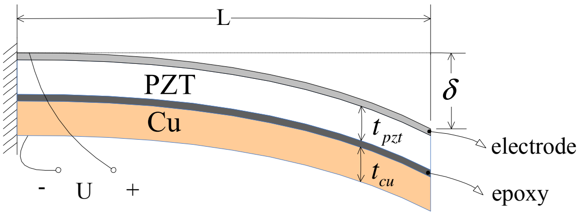


Fig. 3 The schematic diagram and deflection of the cantilever.

To facilitate the measurement of the transverse piezoelectric coefficient, the Yang's modulus of the PZT film can be calculated using theoretical formula Eq. 4 by measuring the resonant frequency of the beam.

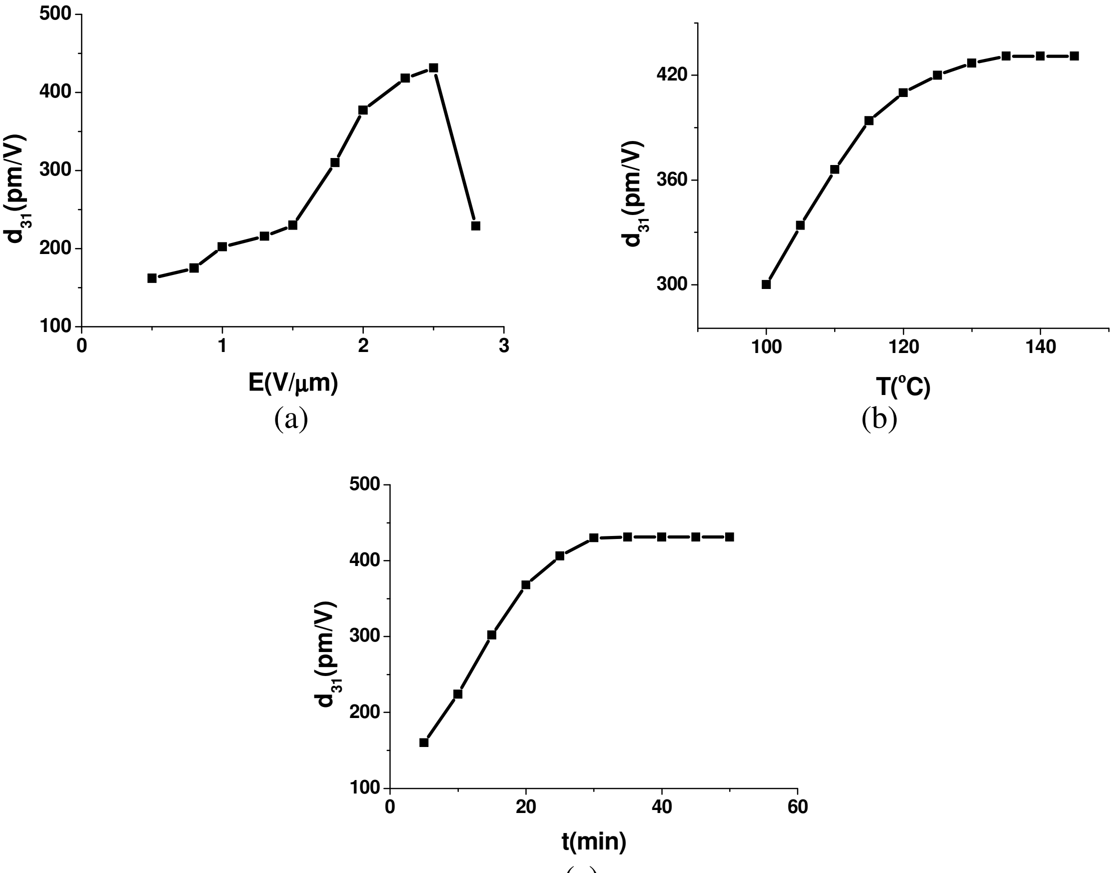
$$f_0 = 0.162 \times \frac{t_{pzt} + t_{cu}}{L^2} \sqrt{\frac{\left(E_{pzt} t_{pzt} + E_{cu} t_{cu}\right)\left(t_{pzt} + t_{cu}\right)}{\rho_{pzt} t_{pzt} + \rho_{cu} t_{cu}}} . \tag{4}$$

ρ_{pzt} and ρ_{cu} are the density of the piezoelectric layer and the copper elastic layer, respectively.

An optical heterodyne micro vibration meter was used to measure the resonant frequency of the composite beam and the deflection of the cantilever. The transverse piezoelectric coefficient d_{31} of cantilever polarized in different conditions can be calculated using Eq. 3 and Eq. 4.

Results and Discussion

The resonant frequency of the composite beam was confirmed to be 410 Hz by the free oscillation experiment. Hence the Yang's modulus of the PZT film can be calculated using Eq. 3 to be 60 GPa approximately. The PZT films were polarized under different electric field intensities, temperatures and used time to find the optimal polarization parameters. The transverse piezoelectric coefficients after polarization are shown in Fig. 4.



(a) (b)

(c)

Fig. 4 The transverse piezoelectric coefficients after polarization under different (a) electric field intensities, (b) temperatures and (c) used time.

It’s shown in Fig. 4(a) that d_{31} increases with the electric field intensity, but when the electric field is greater than 2.5 V/μm the electronic energy accumulation will rise the temperature of the PZT sharply which decrease d_{31} and lead to thermal breakdown eventually. It’s shown in Fig. 4(b) and (c) that d_{31} increases with the polarization temperature and used time, and it tends to be saturated when reaches a certain value. The optimal polarization parameters can be obtained from Fig. 4: the electric field intensity equals to 2.5 V/μm, the polarization temperature equals to 135 degrees Celsius and the used time of polarization process equals to 30 minutes. The maximum transverse piezoelectric coefficient d_{31} is 431 pm/V approximately.

It's important to note that the influence of the epoxy adhesive between PZT and copper is ignored which leads to the measurement result of d_{31} smaller than the actual value. The PZT films used in this paper are commercial products, whose transverse piezoelectric coefficient is about 350 pm/V before depolarization and repolarization. The optimal polarization make the d_{31} having an increase of 23% approximately.

Conclusions

This paper demonstrates the importance of improving the PZT coefficient for DM theoretically and obtains the optimal polarization condition experimentally. A polarization setup was established, and the PZT was polarized in different conditions. By comparing the transverse piezoelectric coefficients of these PZT films, the optimal polarization parameters and a maximum d_{31} of 431 pm/V were obtained. In our further work, the PZT films after optimal polarization will be used to fabricated DMs and further verify the importance of improving the PZT coefficient for the DM experimentally.

Some tips for DM using can also be known from this paper. DMs can sometimes be used for a long time at high temperature especially when used in high power laser systems. In consideration of the temperature of the depolarization, the temperature of DM should be controlled under the Curie temperature.

Acknowledgment

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