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Fabrication of PMN-PT piezoelectric actuators with ultrashort pulses

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Abstract

Lead-magnesium niobate lead-titanate (PMN-PT) crystals have outstanding piezoelectric properties, which make novel applications in acoustics or as transducers possible.
In the literature several methods for PMN-PT devices fabrication have been proposed, such as chemical etching, excimer laser ablation and ion milling.
We demonstrate the use of green femtosecond laser pulses for the fabrication of PMN-PT actuators, and show several key features of the fabrication method; absence of cracks, vertical and smooth device walls are essential requirements for device functionality. We show optimized fabrication parameters that allow the fabrication of actuators in a short time; finally, we present working devices which make clear the role of each fabrication requirement.

Keywords: piezoelectric crystals; ultrashort pulses; ultrafast; laser; cutting; microfabrication; actuators;

1. Introduction

Lead-magnesium niobate lead-titanate (PMN-PT) crystals, with their outstanding piezoelectric properties (Park and Shrout, 1997) extend the range of possible applications of electromechanical actuators (Baek et al., 2012).

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A method for the fabrication of an actuator must not compromise the piezoelectric properties of the crystal and needs to satisfy appropriate requirements for accuracy, flexibility and speed. Several fabrication methods have been presented in the scientific literature for PMN-PT-crystals based actuators, for example wet etching (Peng et al., 2008), dry etching (Ivan et al., 2012), excimer laser ablation (Ivan et al., 2012) and a ion milling (Baek et al., 2011).

In this paper, we present our tests of a PMN-PT microfabrication procedure using ultrashort laser pulses. We test ablation, cutting and microfabrication, forming the base for the microactuators presented in Martín-Sánchez et al, 2016.

2. Ablation, cutting and fabrication tests

For our ablation and cutting tests we use crystals purchased from CTG Advanced Materials, LLC (Bolingbrook, IL, USA) and TRS technologies (State College, PA, USA). Our laser is a Spectra-Physics Spirit, which we operate at its second-harmonic wavelength of 520 nm; it delivers pulses of 380 fs duration with a repetition rate variable from a few hundred Hz to 200 kHz. The pulses are focused with a telecentric f-theta lens of 100 mm focal length leading to a beam waist of 6 µm radius; the maximum pulse energy at the focus is of 7 µJ. The movement of the beam is controlled with a mirror scanner.

For the measurement of the ablation rate we machine circular regions of 500 µm diameter and the depth of a few tens of µm varying the pulse energy between 1.5 and 7 µJ, the pulse repetition rate between 12.5 and 200 kHz and the pulse spacing between 2 and 10 µm; we then measure the depth of the ablated region at the center using a profilometer.

We find that the ablation rate per pulse increases both with decreasing pulse spacing (pointing to both incubation and heating effects) and with increasing repetition rate (possibly an effect of heating). The edges of the ablated region are mostly free of cracks, except at the highest energy and lowest pulse spacing, while the topography of the ablated surfaces is consistent with the superposition of the individual pulse craters except at the lowest pulse spacing (2 µm) where irregular grooves appear (again possibly due to heating). The values of the ablated volume per pulse are between 10 and 50 μm^3/pulse; the ablated volume per unit energy is between approximately 4 to 7 $\mu m^3/\mu J$.

The cutting tests are arranged so to replicate the conditions of microfabrication. We place several cuts next to each other (the separation between cuts is of 5 µm), we fix the repetition rate to 25 kHz and the pulse spacing to 5 µm and we vary the energy between 2 and 7 µJ; we perform experiments both with laser polarization perpendicular and parallel to the direction of the cut (and therefore respectively p and s with respect to the cut walls). We perform enough passes till the cutting reaches saturation (that is, the projected pulse fluence on the walls of the cut is equal to the ablation threshold so no more ablation is possible).

In this case, unlike in the case of the ablation of large regions, cracks are formed at the edge of the cuts in the case of p-polarized laser light starting from about the energy of 5 µJ, while s-polarized light does not cause cracks up to our maximum energy of 7 µJ. The different crack formation between s- and p-polarized light can be due to a higher absorption of p-polarized light at the inclined walls.

Given these observations, for the fabrication tests we select the following set of parameters: 5.5 µJ energy, 25 kHz repetition rate, 5 µm pulse spacing. The polarization cannot be chosen as the devices have complex contours that lead to a position-dependent polarization. At this energy the wall angle is approximately of 85°; since we perform our fabrication on 300 µm-thick crystals, we need to place 30 to 40 parallel laser cuts in order to cut through the crystal consistently – for simplicity we prefer adding a few cuts rather than refocusing the laser as a function of the cut depth, which would require an additional calibration.

Under these conditions, the minimum distance between features on the front face of the crystals is about 60 to 70 µm; these are at the back face then separated by a distance variable between 15 µm to just a few µm.

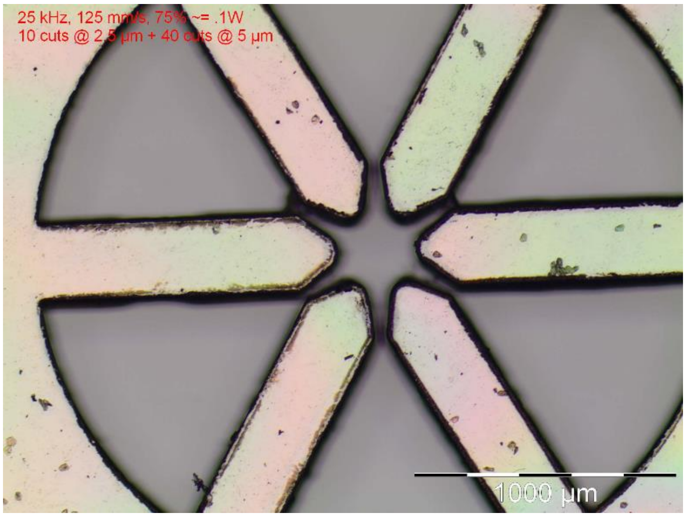

Fig. 1. Crystal cut with 5.5 µJ pulses, 25 kHz repetition rate and 5 µm pulses spacing, ready for the fabrication of a microactuator.

With these parameters, the structures which form the basis for the actuators demonstrated in Martín-Sánchez et al, 2016, which are a few mm wide, and possess relatively complex contours and smallest features of the order of a few tens of µm, can be fabricated in about 20 minutes, enabling in this way device optimization. The final devices allow full in-plane control of the stress tensor and transfer of this stress to nano-systems.

An example cut crystal, ready for the fabrication of a microactuator, is shown in Fig. 1. The piezoelectric properties of the PMN-PT crystal result preserved by the fabrication procedure.

3. Conclusions

Ultrashort-pulse laser microfabrication is a flexible procedure which preserves the piezoelectric properties of PMN-PT crystals and allows the fabrication of microactuators with features of a few tens of µm in relatively thick crystals. The fabrication is quick enough to enable the optimization of the devices.

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