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# Edge geometry effects on resonance response of electroplated cylindrical Ni/PZT/Ni magnetoelectric composites

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Trilayer Ni/PZT/Ni cylindrical magnetoelectric (ME) composites were prepared by electrodeposition, a process, which creates sub-millimeter raised edges due to current concentration near sharp points. The ME response in both axial and vertical modes was measured with the edges, with only outer edges removed, and with both outer and inner edges removed. The ME voltage coefficient improved at resonance by 40% and 147% without the edges in the vertical and axial modes, respectively. The observed improvements in three different samples were only present at the ME resonance and no changes were detected outside of the ME resonance. Mechanical quality factor at resonance also improved with no effect on the resonant frequency. Experimentally demonstrated minor geometry changes resulted in substantial ME improvement at resonant frequency. This study demonstrates device performance optimization. The observed effects have been attributed to improved vibrations in terms of decreased damping coefficient and enhanced vibration amplitude at resonance.  [http://dx.doi.org/10.1063/1.4998947]

## I. INTRODUCTION

The magnetolectric (ME) effect is the interaction between the magnetization and electric polarization in multiferroic materials.[1] The ME effect can arise directly between the ferromagnetic and ferroelectric orders, such as in single phase multiferroics, or can be indirectly created via stress/strain in the ME composite.[2] However, single phase multiferroics typically provide weak ME coupling due to electronic configurations favoring magnetization being antagonistic to those favoring polarization.[3] On the other hand, ME composites consisting of magnetostrictive and piezoelectric phases achieve strong ME effect,[4] especially when Metglas and Terfenol-D are used as the magnetostrictive layers.[5] It is important to note that because the ME composite effect depends on the magnetostrictive material's geometry, different physical characteristics of the magnetostrictive layer will result in different ME output[6] due to elastic losses and resonance quality.[7] Many research studies have been conducted to improve ME performance at resonance. Lopez et al. studied the dependence of the converse magnetoelectric coupling (CME) on the bonding interface in composite annular ME structures.[8] Chavez et al. compared the CME coefficient between shrink fitted and epoxy bonded multiferroic cylinder composite structures.[9] Pan et al. analyzed the performance of various electroplated Ni layered geometries, including trilayered plate, bilayered and trilayered cylinder structures.[10]

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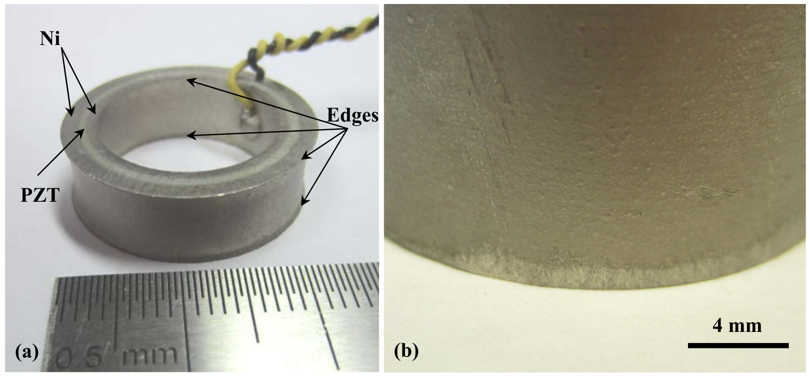



FIG. 1. (a) Trilayered Ni/PZT/Ni cylindrical composite prepared by electroplating before inner and outer edges removal; (b) outer edges filed off.

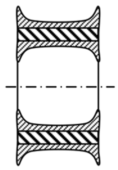
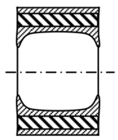
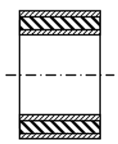
However, little information can be found about the effect of edges created when the ME composite is fabricated using electrodeposition. Electroplating creates raised edges that run around the contour of an object's surface due to electrical current concentrating near corners and points.[11] An example of these raised sub-millimeter edges is shown in Fig. 1(a). In this paper it is found that these raised edges decreased the ME voltage coefficient of the composite. ME measurements were conducted with an electroplated Ni/PZT/Ni trilayer cylinder to study how these protrusions affect ME performance. Data presented in this paper is from experiments performed using the same cylinder to eliminate material variations, which could cause measurement variability. However, similar ME performance improvement effects were measured in three different samples, proving that the observed effect is real. An unaltered cylinder was tested first, followed by the cylinder with outer edges removed (Fig. 1(b)), and finally with both inner and outer edges removed.

## II. EXPERIMENTAL DETAILS

Trilayer Ni/PZT/Ni cylindrical composite, shown in Fig 1(a), was prepared by electroplating. The $\Phi 20\times\Phi 18\times 8$ mm$^3$ PZT-5H ceramic cylinder was supplied by the Institute of Acoustics, Chinese Academy of Sciences, with a thin Ni layer present on both interior and exterior cylinder surfaces, produced by electroless deposition. The sample was radially polarized and cleaned, as described in reference 12. Next, the PZT ring was submerged in a bath of nickel aminosulfonate solution to electroplate thick Ni layer onto the ring surfaces. After electroplating, upper and lower cylinder surfaces were grinded to remove excess Ni. However, sub-millimeter edges were left on the inner and outer cylinder surfaces, as seen in Fig. 1(a). All cylindrical samples previously reported by this research group contained these small edges.[13,14]

ME effect characterization was carried out using the measurement system described earlier.[15] ME voltage coefficients, $\alpha_{E,V}$ or $\alpha_{E,A}$ were obtained by superimposing DC bias magnetic field ($H_{DC}$) with an alternating magnetic field ($\delta H$) applied perpendicular to the axis of the cylinder (vertical mode) or parallel to the axis of the cylinder (axial mode). The ME voltage coefficient was calculated using the formula $\alpha_E = \delta V/(t_{PZT} \cdot \delta H)$, where $t_{PZT}$ is the thickness of the PZT and $\delta H$ is the applied magnetic field. All experimental data reported here were obtained from the same sample to prevent variations in electrical and mechanical properties that may occur due to slight differences in material composition or preparation process. However, three different samples were tested and exhibited the same effect of ME performance improvement with removed edges at resonance. The first experiment was conducted using the original sample with both outer and inner edges present, as shown in Fig. 1(a). The second experiment was conducted with the outer surface edges removed, as shown in Fig. 1(b). The third experiment was conducted with both outer and inner edges removed. A file and a dremel tool were used to remove the edges. Grinding groves are clearly seen in Fig. 1(b). The Ni layers' maximum thickness and sample mass are listed in Table I for the sample with edges, no outer edges, and both outer and inner edges removed. The removal of sub-millimeter Ni edges changed the sample mass by only 1-2%.

TABLE I. Ni/PZT/Ni sample cross-section, maximum thickness and mass.

| Cylinder cross-section | Condition | Outer Ni layer thickness, mm | Inner Ni layer thickness, mm | Sample mass, g |
|---|---|---|---|---|
|  | With edges | 1.41 | 1.14 | 11.074 |
|  | No outer edges | 1.106 | 1.14 | 10.923 |
|  | No edges | 1.106 | 0.619 | 10.816 |

## III. RESULTS AND DISCUSSION

Fig. 2 shows the ME voltage coefficient dependence on magnetic field bias $H_{DC}$ at magnetic field frequency $f$ = 1 kHz in both vertical and axial modes. The $\alpha_{E,V}$ and $\alpha_{E,A}$ graphs differ from each other; however, the trend is the same as reported previously.[14] The $\alpha_{E,V}$ peaks at 0.75 V/cm·Oe, 0.77 V/cm·Oe and 0.74 V/cm·Oe for the sample with edges, with no outer edges and with no outer and inner edges, respectively, while the $\alpha_{E,A}$ peaks at 0.53 V/cm·Oe, 0.52 V/cm·Oe and 0.51 V/cm·Oe. The curves in both vertical and axial modes almost overlap with each other. Thus, the ME performance is practically unchanged for the sample with edges, no outer edges, and no inner and outer edges at non-resonant frequencies for both axial and vertical modes. These experiments provided optimal $H_{DC}$ for each mode.

By setting the optimal magnetic field bias of $H_{DC}$ = 190 Oe for the vertical mode and $H_{DC}$ = 750 Oe for the axial mode, the ME voltage coefficients as functions of magnetic field frequency $f$ were obtained, as seen in Fig. 3. Peak details are shown in the corresponding insets. The ME voltage coefficients have maxima close to $f$ = 65 kHz in all cases. Fig. 3(a) shows that $\alpha_{E,V}$ increases from 26.17 V/cm·Oe to 36.64 V/cm·Oe, a 40% improvement after the outer cylinder edges were removed. As seen in Fig. 3(b), $\alpha_{E,A}$ increased from 3.93 V/cm·Oe to 9.72 V/cm·Oe in the axial mode, an

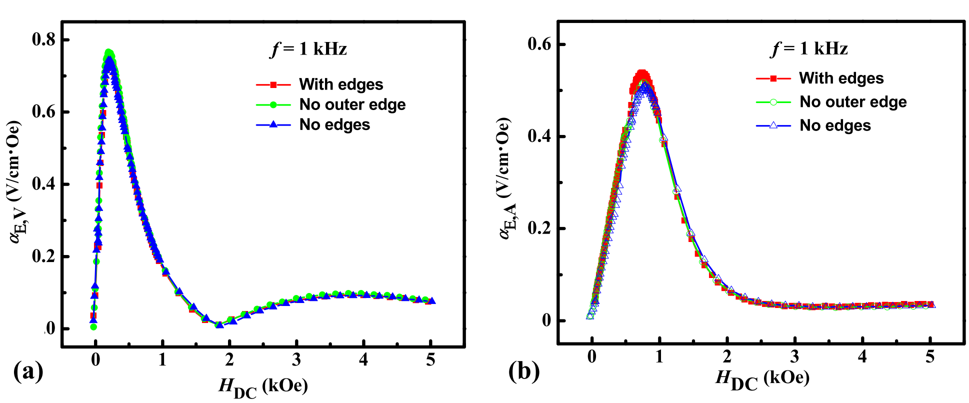



FIG. 2. (a) Vertical ME voltage coefficient $\alpha_{E,V}$ and (b) axial ME voltage coefficient $\alpha_{E,A}$ dependence on magnetic field bias $H_{DC}$.

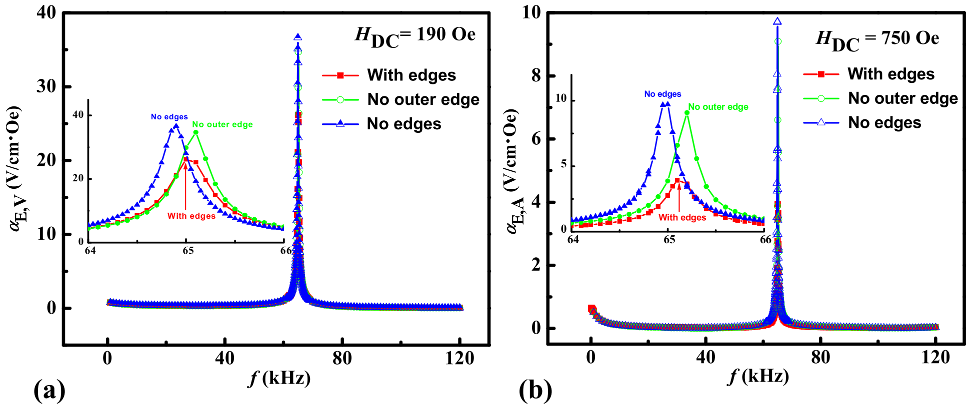



FIG. 3. (a) Vertical ME voltage coefficient $\alpha_{\mathrm{E,V}}$ and (b) axial ME voltage coefficient $\alpha_{\mathrm{E,A}}$ dependence on magnetic field frequency $f$ at optimal magnetic field bias $H_{\mathrm{DC}}$.

enhancement of 147% for the sample with no outer and inner edges. However, as seen from the inset in Fig. 3, the resonant frequency changes very slightly after the edges were removed. For example in the vertical mode, the resonant frequency is 65 kHz, 65.1 kHz and 64.9 kHz for the sample with edges, with no outer edges and with no outer and inner edges, respectively. These minimal resonant frequency differences are not due to the minor sample mass change in Table I, but are mainly caused by the improved maximum vibration amplitude without the sub-millimeter edges. Outside of resonance, the ME output is the same before and after edge removal in both modes, as shown in Fig. 2.

Fig. 4 shows $\alpha_{\mathrm{E,V}}$ and $\alpha_{\mathrm{E,A}}$ dependence on magnetic field bias $H_{\mathrm{DC}}$ at resonant frequency. Apparently, the ME voltage output improved significantly around the optimal magnetic field bias, while no significant changes were observed outside of the optimal magnetic field range. These results indicate that the ME voltage is significantly enhanced only at the ME resonance with optimal applied magnetic field when the edges were removed. The ME effect enhancement can be attributed to improved resonant vibration amplitude, which is related to the effective mechanical quality factor $Q_{\mathrm{m}}$, as described by Borovsky et al.[16] The $Q_{\mathrm{m}}$ can be calculated according to the 3 dB method as: $Q_{\mathrm{m}} = f_{\mathrm{r}}/(f_2 - f_1)$, where $f_r$ is the ME resonant frequency and $f_2$ and $f_1$ are the frequencies where $\alpha_E = \alpha_{E\,\max}/\sqrt{2}$.[17] It was calculated that $Q_{\mathrm{m}}$ = 173 for the sample with edges, $Q_{\mathrm{m}}$ = 232.7 for the sample with no outer edges and $Q_{\mathrm{m}}$ = 247.4 for the sample with no outer and inner edges in the vertical mode.

Three cylinders with similar geometry were tested to ensure results validity and repeatability. All cylinders demonstrated similar ME improvements at resonance with edges removal.

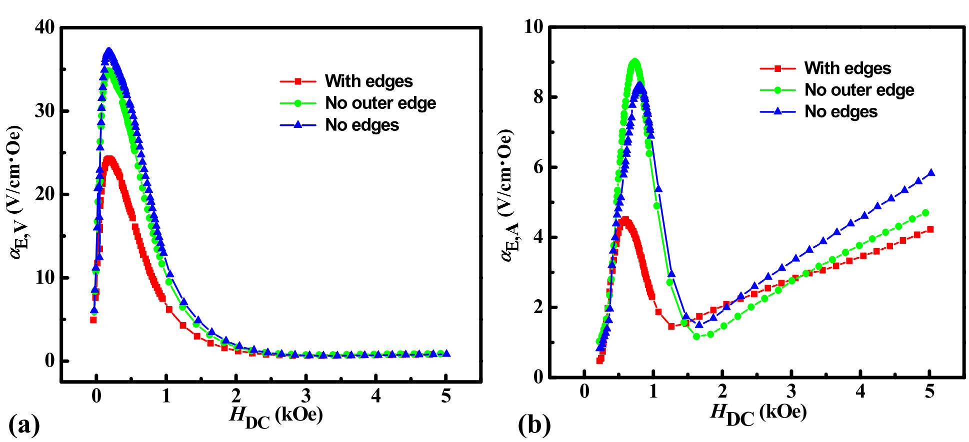



FIG. 4. (a) Vertical ME voltage coefficient $\alpha_{\mathrm{E,V}}$ and (b) axial ME voltage coefficient $\alpha_{\mathrm{E,A}}$ dependence on magnetic field bias $H_{\mathrm{DC}}$ at resonant frequency.

Demonstrated results indicate that as the edges of the cylinder were removed, the quality of the resonance improved. This may be caused by several effects, including increased resonant vibration amplitude and resonance tuning.[18] It should be noted that the electrical properties of the composite remained the same. Instead, only the geometry of the magnetostrictive layer has been changed by mechanical removal of edges.

## IV. CONCLUSIONS

In summary, the effects of edges removal on an electroplated cylindrical Ni/PZT/Ni layered composite were studied. The magnetoelectric voltage coefficient of the smoothed sample was greater than the original sample with edges in both axial and radial modes. The ME resonant frequency remained almost unchanged in all cases, even though the quality factor improved once the edges were removed. This effect is caused by the mechanically altered magnetostrictive layer geometry improving ME composite performance at resonance.

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