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Note: Autonomous pulsed power generator based on transverse shock wave depolarization of ferroelectric ceramics

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Autonomous pulsed generators utilizing transverse shock wave depolarization (shock front propagates across the polarization vector $\boldsymbol{P}_0$) of $Pb(Zr_{0.52}Ti_{0.48})O_3$ poled piezoelectric ceramics were designed, constructed, and experimentally tested. It was demonstrated that generators having total volume of 50 cm^3 were capable of producing the output voltage pulses with amplitude up to 43 kV with pulse duration 4 μs. A comparison of high-voltage operation of transverse and longitudinal shock wave ferroelectric generators is given. © *2010 American Institute of Physics*. [doi:10.1063/1.3505489]

The generation of pulsed voltage and pulsed currents by shock-compressed lead zirconate titanate and barium titanate ferroelectric ceramics was reported for the first time in 1957.[1] Studies of Huguenot's adiabatic curves and of the physical and electrical properties of ferroelectrics shock-compressed with light gas guns and explosively accelerated pellets, which initiated planar shock waves in the investigated samples, have been performed since then and continued until present time.[2–9]

Miniature explosively driven prime power sources utilizing the shock wave depolarization of ferroelectrics have been under development since the late 1990s.[10] Earlier, we developed an autonomous explosively driven generator based on longitudinal (shock wave propagates along the polarization vector $\boldsymbol{P}_0$) shock wave depolarization of lead zirconate titanate $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) ferroelectrics.[10–15] There are two factors that affect the pulsed power generation by longitudinal ferroelectric generators (LFEGs). The first factor is shock front splitting and dispersion in longitudinally shock-compressed PZT 52/48 ferroelectrics.[2,3] Another factor is the requirement to use a significant amount of high explosives (HEs) to increase the output energy of LFEGs.

In this note we report on our development of the design of an autonomous miniature ferroelectric generator (FEG) that is based on transverse (shock wave propagates across the polarization vector $\boldsymbol{P}_0$) shock wave depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectrics. It follows from our experimental results that shock front splitting and dispersion do not have significant effects on generation of pulsed power with transverse ferroelectric generators (TFEGs).

The design of transverse FEG developed in this work is shown in Fig. 1(a). It contains an explosive chamber, a metallic impactor (flyer plate), a plastic cylindrical body, and a ferroelectric element. Two output terminals were attached to the contact plates of the ferroelectric element.

The ferroelectric element of the TFEG was placed inside the plastic cylindrical body in such a way that the polarization vector $\boldsymbol{P}_0$ [shown by the circle with a dot in the center in Fig. 1(a)] was normal to the direction of propagation of the shock wave front.

The diameter of the generator was 35 mm. The PZT element holder was filled with an epoxy (Pacer Technology SY-SS) as electrical insulating material. The thickness of the epoxy layer between the top of the epoxy cartridge and the ferroelectric element of TFEG was 12 mm. The flyer plate was made of 6061 aluminum alloy, and the air gap between the flyer plate and the top of the epoxy filling (acceleration path) was 5 mm. In all FEG experiments described in this paper, we used an HE charge of 18 g of C-4 (detonation velocity 8.04 km/s and theoretical dynamic pressure at the shock front 36.7 GPa) along with RP-501 explosive bridge-wire detonator supplied by Teledyne RISI Inc.[16] Explosive experiments were conducted in the facilities of the Energetic Materials Research Laboratory of the Missouri University of Science and Technology, Rolla, MO.

PZT 52/48 ferroelectric disks (trade name EC-64) used in the generators were supplied by ITT Corp.[17] We studied the performance of FEGs with PZT disks of six sizes (Table I). Silver contact plates were deposited on both faces of each PZT disk by the manufacturer. All ferroelectric disk elements were poled across the thickness to their remnant polarization by the manufacturer.

To compare the operation of transverse FEGs developed in this work with that of longitudinal FEGs,[10] we conducted a series of experiments with LFEGs [Fig. 1(b)] having the same dimensions and containing identical PZT 52/48 elements as those in the TFEGs (Table I). The polarization vector $\boldsymbol{P}_0$ of the ferroelectric element [shown by the arrow in Fig. 1(b)] was parallel to the direction of propagation of the shock wave.

The operation of the transverse FEGs was as following. After detonation of the HE charge, the flyer plate was accelerated to high velocity under the action of the shock wave and high-pressure gases. The flyer plate impacted the epoxy

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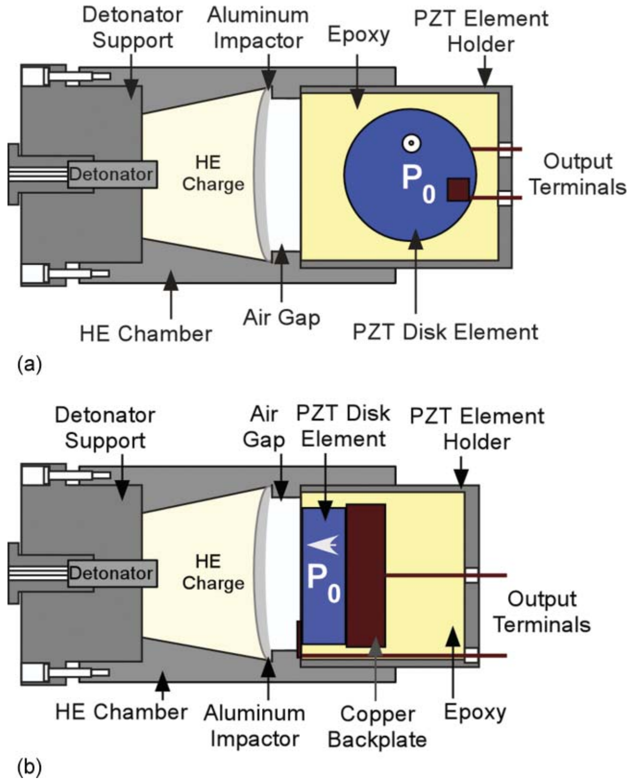

FIG. 1. (Color online) Schematic diagram of (a) transverse FEG and (b) longitudinal FEG.

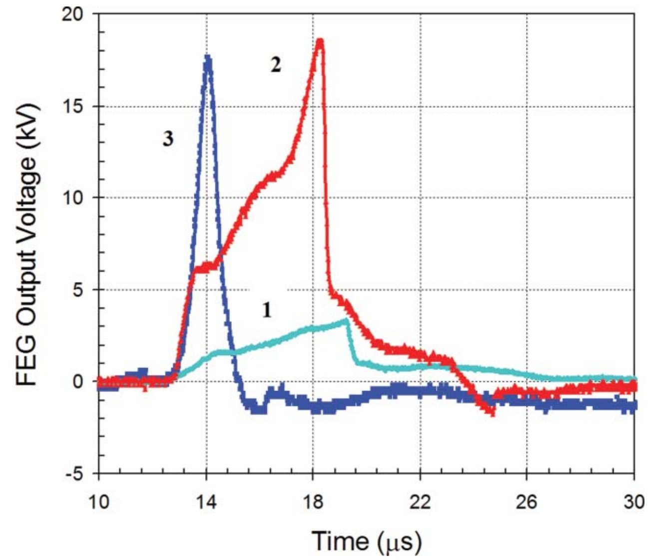

FIG. 2. (Color online) Typical waveforms of output voltage produced by a TFEG for case 1 (plot 1), a TFEG for case 3 (plot 2), and a LFEG for case 3 (plot 3).

cartridge and initiated a shock wave in the epoxy; the shock then traveled to the ferroelectric element that was placed within the epoxy. Prior to the initiation of the shock wave, the electric field in the element was equal to zero because the surface charge density (the bonded charge) compensated for the polarization obtained during the poling procedure of the element. The transverse shock wave propagated in the ferroelectric element and depolarized it. As a result of the shock wave depolarization, the bonded charge was released at the contact plates of the element and an electromotive force appeared at the output terminals of the FEG. Detailed descriptions of the operation of the longitudinal FEG are given in Refs. 10–15.

We performed systematic studies of longitudinal FEGs and transverse FEGs with a high resistance load. High resistance mode of electrical operation of the FEG is important for engineering applications. In all these experiments, we used a North Star PVM-5 high-voltage probe (resistance 400 MΩ, capacitance 12 pF, transition time 4 ns) as the load for the FEGs. The FEGs were placed in an explosive containment chamber for the test, and the output terminals of the FEGs were connected to the voltage probe outside the chamber. The pulsed signals were recorded with a Hewlett-Packard Infinium oscilloscope (2 GS/s, bandwidth 500 MHz). Details of the experimental setup can be found in Refs. 10–15.

TABLE I. Sizes of PZT 52/48 disk elements of the FEGs studied in this paper.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Diameter of PZT disk (mm)	26.2	27.0	25.0	25.0	24.2	22.2
Thickness of PZT disk (mm)	0.65	2.1	5.1	6.5	10.4	15.9

Typical waveforms of the output voltage produced by transverse FEGs for case 1 (see Table I for the cases) and case 3 are shown in Fig. 2. The amplitude of the voltage pulse produced by the TFEG for case 1 (plot 1 in Fig. 2) was $U(t)_{max}$ = 3.52 kV. An increase of PZT disk element thickness from 0.65 to 5.1 mm resulted in an increase of the output voltage produced by the TFEG for case 3 (plot 2 in Fig. 2) to $U(t)_{max}$ = 18.6 kV. The full-width at half-maximum (FWHM) of the high-voltage pulses produced by TFEGs for case 1 and case 3 was 4.9 and 3.8 μs, respectively (Fig. 2).

Figure 2 also presents a typical waveform of the output voltage produced by a longitudinal FEG for case 3 (see plot 3). The output voltage amplitude was $U(t)_{max} = 17.8$ kV, which was nearly that obtained by the TFEG for case 3. At the same time, the FWHM of the voltage pulse produced by the LFEG for case 3 was significantly less in comparison with that for TFEGs, 0.9 μs. The shorter pulse length was likely due to the shorter shock wave front propagation path in the LFEG, where the shock front was not propagating along the diameter of the PZT disk as in the TFEG, but across the disk thickness (Fig. 1).

Amplitudes of high-voltage pulses produced by TFEGs and LFEGs versus thickness of their PZT 52/48 disk elements are shown in Fig. 3. The amplitude of the high voltage produced by TFEGs was reproducible. The voltage amplitude was directly proportional to the thickness of PZT disk element in all disk thickness ranges from 0.65 to 15.9 mm. The slope of the voltage–thickness curve was about 2.7 kV/mm.

The amplitude of the output voltage pulse produced by LFEGs with PZT disk elements from 0.65 to 6.5 mm in thickness (case 1 through case 4) was close to that produced by

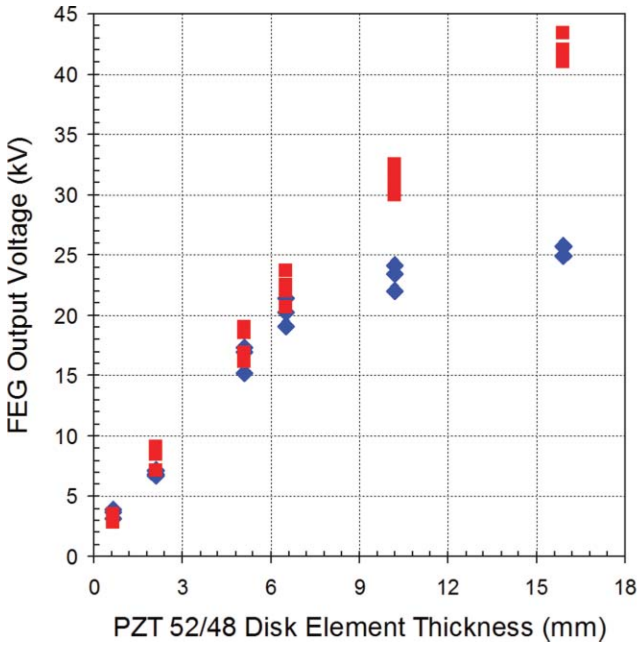

FIG. 3. (Color online) Amplitude of output voltage pulse produced by TFEGs (squares) and LFEGs (diamonds) versus thickness of PZT 52/48 disk element.

TFEGs (Fig. 3). Increasing the PZT disk thickness to 10.4 and 15.9 mm (case 5 and case 6) resulted in significant output voltage decreases in LFEGs in comparison with that in TFEGs. The deterioration of output voltage with increased PZT element thickness was probably caused by shock front splitting and shock front dispersion in the PZT 52/48 elements of LFEG.[2,3]

In conclusion, miniature sources of primary power utilizing transverse shock depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectric ceramic elements were designed, constructed, and experimentally tested. The generators demonstrated reliable and reproducible operation. It follows from experimental results that shock front splitting and shock front dispersion do not have significant effects on the operation of transverse FEGs. The output voltage produced by the generators exceeded 40 kV.

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