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The depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectrics by cylindrical radially expanding shock waves and its utilization for miniature pulsed power

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The effects of depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) poled ferroelectrics by cylindrical radially expanding shock waves propagated along and across the polarization vector $\boldsymbol{P}_0$ were experimentally detected. Miniature (total volume 100 cm^3) autonomous generators based on these effects were capable of producing output voltage pulses with amplitudes up to 25 kV and output energies exceeding 1 J. © *2011 American Institute of Physics*. [doi:10.1063/1.3585145]

I. INTRODUCTION

The development of autonomous sources of prime electric power is a key part of some modern research and development projects.[1–3] One of the possible ways to produce prime voltage and current is to utilize the effects of shock-induced depolarization of poled ferroelectrics.[4] Systematic studies of depolarization effects, the physical and electrical properties of ferroelectrics compressed by planar shock waves initiated in the ferroelectric materials by light gas guns began a few decades ago and continue to the present time.[5–23] The advantages of a planar shock wave are its stable geometry, constant pressure along the front, and constant shock wave front velocity. Each of these advantages makes it possible to simplify theoretical models used for the analysis of shock wave experiments.[1,12–15] At the same time, the sizes of experimental systems used for the investigation of physical properties of materials compressed by planar shock waves are very large.[24] It is obvious that these complex systems can only be used for academic studies, not for engineering applications.

Earlier we developed compact autonomous explosively driven ferroelectric generators (FEGs) based on the depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectric disks by quasi-planar longitudinal shock waves (the shock wave front propagates along the polarization vector $\boldsymbol{P}_0$).[25–30] One of the main limitations of this design[25–30] is that an n-fold increase of the diameter of the ferroelectric disk (and correspondingly the FEG output energy) leads to an n^3-fold increase of the mass and volume of the high explosive (HE) charge and, correspondingly, size and weight of the FEG.

In this paper, we used a new approach to the FEG design. We explored cylindrical radially expanding shock waves, which, in a fashion opposite to planar shock waves, do not create stable geometries and constant pressures in shock-compressed ferroelectric elements. We present the results of our successful experiments on the depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectric ceramic materials using cylindrical radially expanding shock waves, and of the utilization of this effect for the development of miniature sources of prime power.

II. LONGITUDINAL DESIGN

A schematic diagram of a miniature generator utilizing depolarization of PZT 52/48 ferroelectrics by a cylindrical radially expanding shock wave that propagates along the ferroelectric element's polarization vector $\boldsymbol{P}_0$ (i.e., a longitudinal shock) is shown in Fig. 1(a). The device contains a ferroelectric hollow cylinder, a HE charge, and two output terminals. The polarization vector, $\boldsymbol{P}_0$, and the propagation direction of the shock wave front, $\boldsymbol{U}_S$, are shown in Fig. 1(a) by arrows. We initiated a radially expanding shock wave within the ferroelectric element by detonating the cylindrical HE charge.

We used PZT 52/48 (trade name EC-64) hollow ferroelectric cylinders supplied by ITT Corporation[31] with an inside diameter $a = 9.0$ mm, an outside diameter $b = 19.0$ mm, a wall thickness $d = 5.0$ mm, and a length $l = 19.0$ mm. These PZT 52/48 cylinders were poled across their thickness to the remnant polarization by the manufacturer. The manufacturer deposited silver contact plates (electrodes) on the inner and outer surfaces of the hollow cylinders. The deposition of the electrodes was not to the very edge of the PZT cylinders, but to within 1.5 mm of their edges (Fig. 1) to reduce the probability of electric discharge across the end surfaces of the elements. In addition, we encapsulated the edges of the PZT cylinders with epoxy to improve the electrical insulation of the devices (Fig. 1). The total volume of the system was 9.5 cm^3. The physical properties of PZT 52/48 are available online.[31]

The 1.5 g HE charge was loaded in the central hole of the PZT cylinder (Fig. 1). In each experiment, we used desensitized RDX HE (Chapman–Jouguet state pressure of 22.36 GPa, theoretical dynamic pressure at the shock front of 36.7 GPa, and detonation velocity of 8.1 km/s) as the main charge and detonated the HE charge with an RP-501 exploding bridge-wire detonator supplied by Teledyne RISI Inc..[32] The experimental devices were placed in an explosive containment chamber for the test, and the output terminals were

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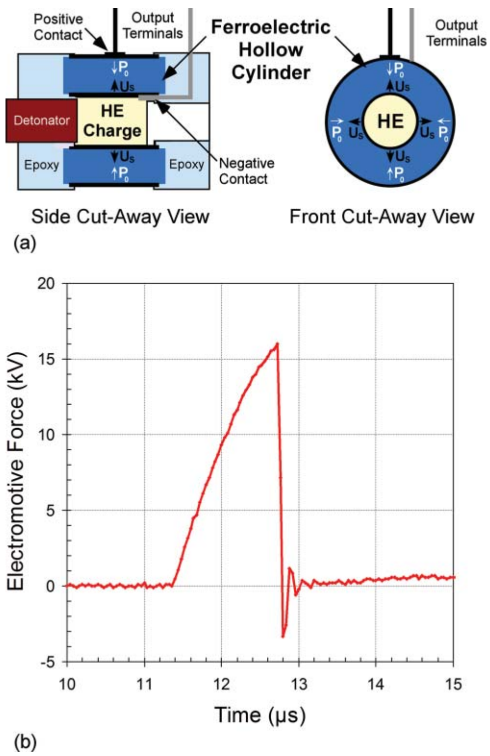

FIG. 1. (Color Online) (a) Schematic diagram of the FEG utilizing the depolarization of PZT 52/48 ferroelectrics by a cylindrical radially expanding shock wave that propagated along the polarization vector $\boldsymbol{P}_0$ (a longitudinal shock). $\boldsymbol{U}_S$ is the shock vector. (b) A typical waveform of the electromotive force generated at the electrodes of the shock-compressed ferroelectric element.

connected to a North Star PVM-5 high voltage probe (resistance 400 MΩ, capacitance 12 pF, transition time 4 ns) outside the chamber. We conducted the explosive experiments in the facilities of the Energetic Materials Research Laboratory of the Missouri University of Science and Technology, Rolla, MO.

The operation of the FEG (Fig. 1) was as follows. After initiation of the HE charge, the detonation wave travelled longitudinally and radially in the HE, which initiated a substantially radial expanding shock wave at the inner wall of the PZT cylinder. The shock wave front propagated in the body of the ferroelectric element, principally along the polarization vector $\boldsymbol{P}_0$. During this propagation, the length of the shock wave front line was increasing in direct proportion to the radius of the shock wave front, and the shock pressure was decreasing due to geometrical factors. In addition, the pressure decreased due to the propagation of the shock wave in the (non-explosive) ferroelectric media. In designing these devices, we used the following reasoning: if depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ occurs due to longitudinal shock compression by cylindrical radially expanding shock waves, the bonded charge should be released at the electrodes of the element and an electromotive force (EMF) should be generated at the output terminals of the system (Fig. 1).

We performed five explosive experiments with FEGs of the type shown in Fig. 1. A typical waveform of the output voltage produced by one of these devices is shown in Fig. 1(b). The amplitude of the voltage pulse was $U_{max} = 16.3 \pm 1.7$ kV.

Earlier we experimentally demonstrated that the thickness of the ferroelectric elements, d, is the main parameter responsible for the high voltage amplitude produced by quasi-planar shock-wave FEGs operating in the open circuit mode.[25] If we use this criteria to evaluate the depolarization effect we can find that there is no significant difference between the amplitude of a high voltage pulse produced by the FEGs utilizing depolarization of PZT by a cylindrical radially expanding shock wave ($U_{max} = 16.3 \pm 1.7$ kV, $d = 5.0$ mm) and that produced by FEGs designed to utilize quasi-planar shock wave geometry ($U_{max} = 17.0 \pm 0.5$ kV, $d = 5.1$ mm).[25] This is a direct evidence that the effect of depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ by a cylindrical radially expanding shock wave propagated along the polarization vector $\boldsymbol{P}_0$ was experimentally detected.

The FEG is a capacitive-type prime power source. The output energy, W, produced by a FEG is directly proportional to the square of the amplitude of the FEG output voltage, U_{out}, and to the capacitance of the ferroelectric element, C_G:

$$W = \left(C_G U_{out}^2\right)/2. \qquad (1)$$

The C_G can be determined from geometrical dimensions and dielectric properties of the ferroelectric element:

$$C_G = \frac{2\pi\varepsilon\varepsilon_0}{\ln\left[\dfrac{b}{a}\right]} l, \qquad (2)$$

where ε_0 is the vacuum dielectric constant, ε is the relative dielectric constant of the ferroelectric material, a and b are inside and outside diameters of the PZT 52/48 cylinder, respectively, and l is the cylinder length. Accurate measurement of the relative dielectric constant, ε, of shocked ferroelectrics is a very difficult task. To estimate the energy generated by a shocked ferroelectric element we used the value of ε for unpoled PZT 52/48 ferroelectrics provided by the manufacturer, 1140% ± 7%.[31] Substitution of these parameters into Eq. (1) gives us an estimation of the output energy of the FEG (Fig. 1), $W = 0.22 \pm 0.04$ J.

III. TRANSVERSE DESIGN

We used the design approach based on shock compression of ferroelectrics by a cylindrical radially expanding shock wave for the development of the FEG, where the shock wave front propagated across the polarization vector $\boldsymbol{P}_0$ of a PZT 52/48 element (i.e., a transverse shock). A schematic diagram of this FEG is presented in Fig. 2(a). The device contained a rectangular ferroelectric element encapsulated in an epoxy cartridge, two output terminals, a cylindrical HE charge placed on the axis of the generator, and a detonator. The C_G of this FEG can be determined using the following expression:

$$C_G = (\varepsilon\varepsilon_0/d)A, \qquad (3)$$

where d is the ferroelectric element thickness and A is the electrode area. Generator output energy can be increased

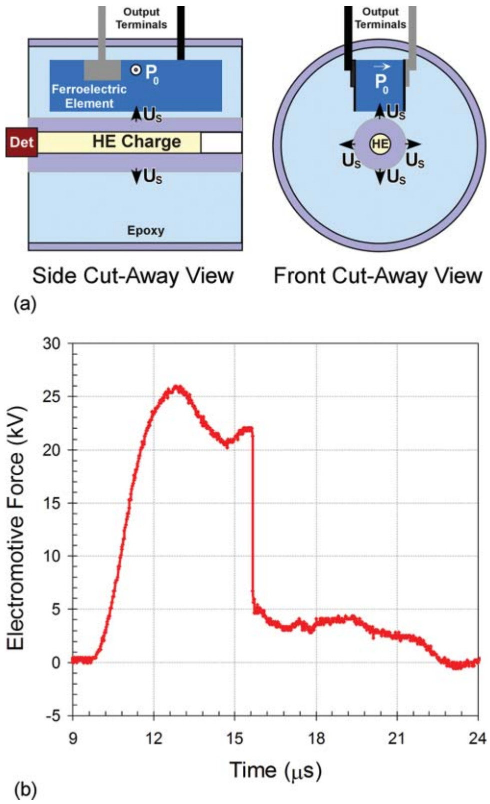

FIG. 2. (Color Online) (a) Schematic diagram of the FEG utilizing the depolarization of PZT 52/48 ferroelectrics by a cylindrical radially expanding shock wave that propagated across the polarization vector $\boldsymbol{P}_0$ (a transverse shock). $\boldsymbol{U}_S$ is the shock vector. (b) A typical waveform of the electromotive force generated at the electrodes of the shock-compressed ferroelectric element.

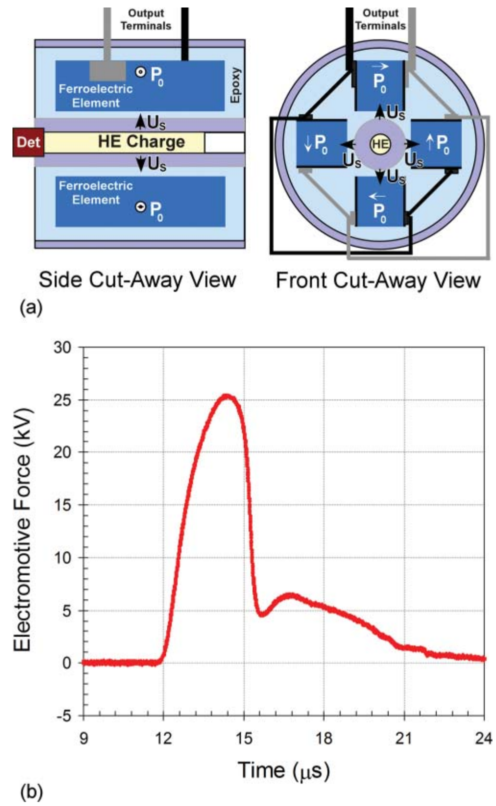

FIG. 3. (Color Online) (a) Schematic diagram of the four-element FEG utilizing the transverse depolarization of PZT 52/48 ferroelectrics by a transverse radially expanding shock wave initiated from a cylindrical HE charge placed on the axis of the generator. $\boldsymbol{U}_S$ is the shock vector. (b) A typical waveform of the electromotive force generated at the electrodes of the shock-compressed ferroelectric element.

without increasing the FEG diameter by lengthening the rectangular ferroelectric element and/or placing additional ferroelectric elements in the system (Figs. 2 and 3).

ITT Corp.[31] supplied the PZT 52/48 rectangular ceramic elements of (12.7(thick) × 19.0(width) × 50.8(length)) mm^3. PZT 52/48 elements were poled across their thickness to the remnant polarization by the manufacturer. The polarization vector of the element and the direction of propagation of the shock wave front are illustrated in Fig. 2(a) by arrows. For these experiments, we inserted a 2.1 g cylindrical HE charge into a plastic tube of 6.0 mm inner diameter and 12.0 mm outer diameter. A single RP-501 detonator at one end of the HE charge provided the detonation impulse.

The FEG (Fig. 2) was operated in this fashion. After initiation of the HE charge, the detonating explosives created a radially expanding shock wave in the system. The shock wave front propagated through the epoxy filling entered the body of the ferroelectric element, and then spread through the element across the polarization vector $\boldsymbol{P}_0$. We hypothesized that if the transverse shock compression of PZT 52/48 by cylindrical radially expanding shock waves caused the depolarization of the element, the bonded charge should be released at the electrodes of the element, and an EMF pulse should be produced at the output terminals of the FEG.

We performed five experiments with FEGs of the design shown in Fig. 2(a). A typical waveform of the EMF pulse produced by a FEG of this type is presented in Fig. 2(b). The amplitude of the output voltage was $U_{max} = 25.7 \pm 1.9$ kV, and the output energy of the FEG (Eqs. (1) and (3)) was $W = 0.25 \pm 0.04$ J. The ability of FEGs of this design to generate high voltage pulses such as the one illustrated (Fig. 2) is a direct evidence of the effect of depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ by a cylindrical radially expanding shock wave propagated across the polarization vector $\boldsymbol{P}_0$.

The cylindrical symmetry of the system (Fig. 2) makes it possible to place several ferroelectric elements around the axial explosive charge. We performed experiments with FEGs utilizing the simultaneous transverse depolarization of two and four rectangular PZT 52/48 elements by radially expanding shock waves. A schematic diagram of one of our generators is shown in Fig. 3(a). The FEG contained four PZT 52/48 elements, an axial HE charge, and two output terminals. We placed the PZT 52/48 elements symmetrically around the cylindrical HE charge, and the elements were electrically connected in parallel (Fig. 3).

We performed four experiments with FEGs like the one shown in Fig. 3(a). Figure 3(b) illustrates a typical waveform of the output voltage produced by a FEG of this type. The U_{max} was 25.4 kV, with a rise time $\tau = 2.5$ μs. The average voltage amplitude produced by the FEG with four elements, $U_{aver} = 25.8 \pm 2.4$ kV, was practically equal to that produced by a FEG with a single PZT 52/48 element (Fig. 2).

This allows us to conclude that each of the four elements was depolarized by cylindrical radially expanding shock waves. The output energy of a four-element FEG (Fig. 3) was $W = 1.01 \pm 0.18$ J.

IV. CONCLUSION

The effect of depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ by cylindrical radially expanding shock waves was experimentally detected. We utilized this effect for the development of miniature autonomous explosively driven prime power sources.

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