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Compact High-Voltage Generator of Primary Power Based on Shock Wave Depolarization of Lead Zirconate Titanate Piezoelectric Ceramics

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The design and performance of a compact explosive-driven high-voltage primary power generator is presented. The generator utilizes a fundamental physical effect—depolarization of ferroelectric materials under longitudinal shock wave impact, when the shock wave is initiated along the polarization vector **P**. These primary power sources, containing energy-carrying elements made of lead zirconate titanate poled piezoelectric ceramics, with the volume from 0.35 to 3.3 cm^3, are capable of producing pulses of high voltage with amplitudes up to 21.4 kV. The amplitude and full width at half-maximum of the high-voltage pulses are directly proportional to the thickness of the energy-carrying element, with coefficients of proportionality of 3.42 ± 0.12 kV/mm (amplitude) and 0.125 ± 0.01 μs/mm (width). The specific energy density of these ferroelectric energy-carrying elements reaches 76 mJ/cm^3. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1771490]

Generation of primary electrical power by compact autonomous sources is critical to the success of many modern scientific and engineering projects.[1,2] Explosive-driven electrical generators are considered the most efficient compact pulsed power devices.[1,3,4] Two new types of autonomous explosive driven pulsed power generators have been developed recently.[5–14] These ultracompact generators of primary power, 9–25 cm^3 in volume, based on the physical effect of shock wave demagnetization of high-energy hard ferrimagnets and ferromagnets,[6–8] are capable of producing high voltage pulses with amplitudes of tens of kilovolts[7,8] and high currents of several kiloamperes.[7,9,13,14]

Another type of primary power source utilizes the electromagnetic energy stored in piezoelectric and ferroelectric materials that generate voltages under an external mechanical stress.[15,16] We have developed a series of pulsed power generators based on shock wave compression of ferroelectric materials. In order to make these generators very compact, explosive materials were used to initiate the shock waves in the ferroelectric energy-carrying elements. In this article, we describe one specific design of a compact explosive driven high-voltage primary power source. This particular design provides the most reliable and controllable electrical operation of the device, largest amplitude of high-voltage pulses, and maximum output energy for all types of ferroelectric energy-carrying elements used in our experiments. The generator utilizes depolarization of poled piezoelectric ceramics, referred to as ferroelectric materials or ferroelectrics, due to longitudinal shock wave impact. The shock wave propagates parallel to the polarization vector **P**.

Figure 1 shows a schematic diagram of the explosive-driven shock wave ferroelectric generator (FEG). The FEG
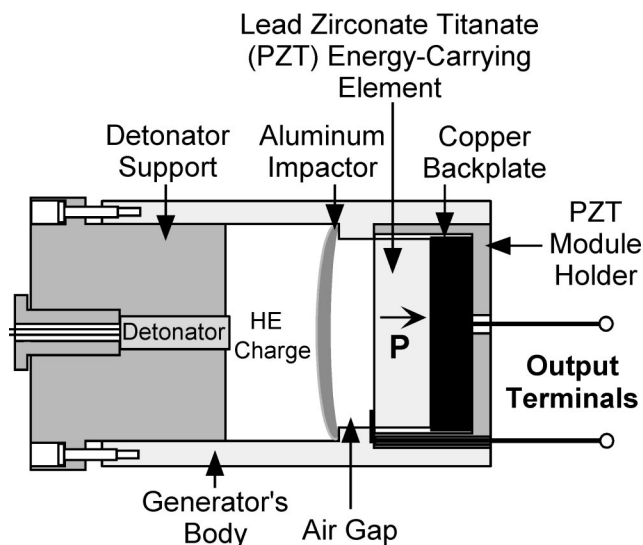

FIG. 1. Schematic diagram of a shock wave ferroelectric generator.

consists of a cylindrical body, an explosive chamber, a holder containing the ferroelectric module (the energy-carrying element), and a load circuit. In order to avoid electric breakdown during the operation of the generator the cylindrical body of the FEG is made of electrically insulating material. We use three types of plastics with good results: high-density polyethylene, polyvinylchloride (PVC), and polycarbonate.

A series of experiments were performed to determine the effect of the body wall thickness on the operation of the FEG. There was no significant difference in the generation of high-voltage pulses by FEGs having body wall thicknesses in the range of 2 to 30 mm. The generator's body can be thus a thin, lightweight plastic shell, just a few millimeters larger than the diameter of the ferroelectric module, that holds the parts of the FEG together until they are destroyed by the detonation of the explosive charge.

The explosive part of the FEG contains a high explosive (HE) charge, a hemispherical metallic impactor (flyer plate), and a cylindrical plastic detonator support containing an exploding bridgewire detonator (RP-501 supplied by Reynolds Industries Systems Incorporated[17]). The C-4 high explosive was used in all the experiments described in this paper (90.2% RDX, 5.78% dioctyl adiapate, 1.57% motor oil, 2.45% polyisobutylene, with Chapman-Jouguet state pressure of 22.36 GPa, and detonation velocity of 8.1 km/s). The mass of C-4 charge was varied from 12 to 17 g.

The flyer plate is responsible for initiation of the shock wave in the ferroelectric energy-carrying element. The shape of the aluminum flyer plate was determined in computer simulations so that a planar shock wave was generated in the ferroelectric body.[18] The air gap (acceleration path) between the flyer plate and the ferroelectric module's front plate was 5 mm.

The cylindrical ferroelectric energy-carrying element was bonded to a copper backplate that was 1 mm larger in diameter than the ferroelectric module. The backplate thickness was 5 mm. To bond the ferroelectric disk to the backplate a silver-loaded epoxy was used. The copper backplate provided shock impedance matching, to minimize reflection of the stress wave when it reached the back face of the ferroelectric module. The silver-loaded epoxy provided an electrical contact and reduced the capacitive reactance of the bond to a negligible value. The ferroelectric module, along with the copper backplate, was centered in a cylindrical plastic holder (Fig. 1).

Two output electric terminals of the FEG were connected to metallic contact plates deposited on the surface of the ferroelectric disk. One output terminal was bonded to the ferroelectric disk front plate (which was subjected to high-pressure impact) by silver-loaded epoxy. The other one was bonded to the copper backplate.

In order to determine the effects of the generator design and of the geometry and size of the ferroelectric energy-carrying elements on the parameters of the high-voltage output pulses, the same ferroelectric material, EC-64 lead zirconate titanate (PZT) poled piezoelectric ceramic (supplied by EDO Corp.[19]), was used in all experiments.

Parameters of EC-64 PZT were as follows: density 7.5 $\times 10^3$ kg/m^3, dielectric constant $\varepsilon = 1300$, Curie temperature

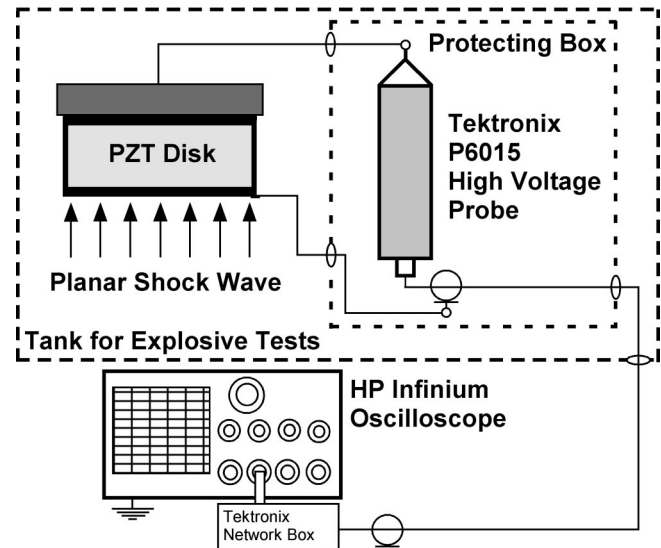FIG. 2. The experimental setup and circuit diagram for generation and measuring high-voltage pulses produced by a shock wave FEG.

320°C, Young's modulus 7.8×10^{10} N/m^2, piezoelectric constant $d_{33} = 295 \times 10^{-12}$ C/N, piezoelectric constant $g_{33} = 25 \times 10^{-3}$ m^2/C.

The experimental setup and circuit diagram of the system for generation and measuring high-voltage pulses are shown in Fig. 2. Experiments were performed in a steel explosives test chamber. High-voltage pulses were monitored with a Tektronix high voltage probe (Model P6015), which was enclosed in a protective steel container placed in the explosive chamber. The distance between the probe and the generator was less than 220 mm. Pulsed signals were recorded by Hewlett-Packard Infinium oscilloscopes (bandwidth 500 MHz, 2 GS/s). Electric parameters of the ferroelectric energy carriers were measured with a Hewlett-Packard 4275A LCR-meter.

PZT disks, having diameters of 25 mm and different thickness (2.5 mm, 5 mm, and 6.5 mm), were used in the experiments. All PZT disks were poled to their full remnant polarization values.

Within the FEG, after ignition of the detonator and detonation of the C-4 charge, the aluminum flyer plate (Fig. 1) is accelerated under the action of a shock wave and high-pressure gases. The collision of the flyer plate with the ferroelectric disk's front plate initiates a shock wave in the ferroelectric body. The shock wave propagates through the PZT disk and depolarizes it. All generators described in this paper were designed in such a way that the direction of shock wave travel was parallel to the polarization vector **P** (Fig. 1). This type of generator is referred to as a longitudinal FEG. The depolarization process releases the induced charge on the metallic end plates of the ferroelectric disk and a voltage pulse appears on the high-voltage output terminals of the generator.

In the first series of experiments, waveforms of high-voltage pulses produced by FEGs had an irregular shape; the high-voltage pulse amplitude and pulse width varied significantly for different experiments performed with PZT disks of the same dimensions. After a series of investigations, includ-
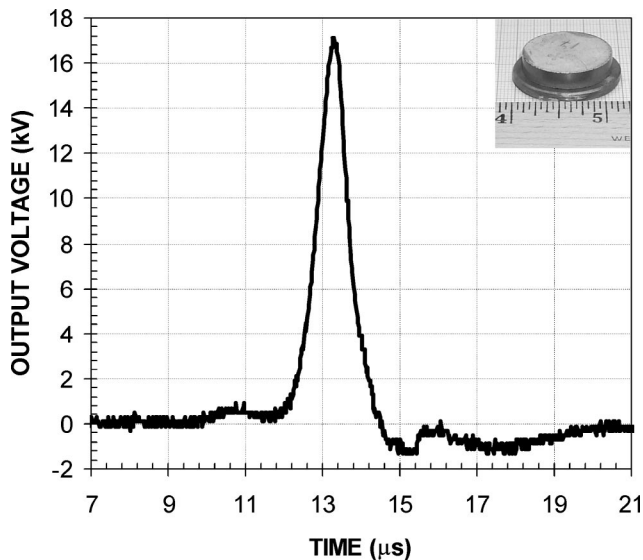
FIG. 3. A typical waveform of the high-voltage pulse produced by FEG containing PZT disk of $D=25$ mm and $h=5$ mm. The photograph of the PZT disks is shown in the inset.

FIG. 4. The amplitude, U (black), and FWHM (gray) of high-voltage pulses produced by FEGs versus PZT disk thickness (disk diameter $D=25$ mm).

ing high-speed photography, we determined that the electric breakdown took place not on the high-voltage terminals, but on the sidewalls of the ferroelectric disks. This was not due to surface flashover, since the PZT sidewall was cleaned carefully before assembling the device. Instead, it was due to the creation of detonation-generated plasma by the explosive charge. This plasma, which was expanding into the annulus surrounding the PZT disk, caused the breakdown.

The ferroelectric module holder was redesigned to eliminate the plasma induced breakdown. The gap between ferroelectric disk sidewall and the inside wall of the plastic holder was increased to 2.5 mm and filled with hard insulating material (epoxy). Figure 3 shows typical waveforms of high-voltage pulses generated by an FEG with the redesigned ferroelectric module holder (PZT disk thickness $h=5$ mm). The waveform has a regular shape and shows no signs of the electric breakdown seen in earlier tests. The high-voltage pulse amplitude is 17.2 kV, with full width at half-maximum (FWHM) of 0.91 μs. There was no significant difference in amplitude, waveform and FWHM of high-voltage pulses obtained in different experiments with PZT disks of the same dimensions.

Figure 4 presents the amplitude and FWHM of high-voltage pulses versus PZT disk thickness obtained from 17 tests. The high-voltage pulse amplitude and FWHM are highly reproducible. The amplitude and FWHM are directly proportional to the PZT disk thickness, with coefficients of proportionality 3.42±0.12 kV/mm (amplitude) and 0.125±0.01 μs/mm (FWHM).

High-voltage pulses generated due to quick depolarization of ferroelectric energy-carrying elements under shock wave impact can be used to charge a capacitor bank or they can be applied to an active load.

In this series of experiments, all PZT disks were placed in holders in such a way that their polarization vector was oriented along the direction that the shock wave propagates (Fig. 1). The "negative" metallic contact plates of the disks
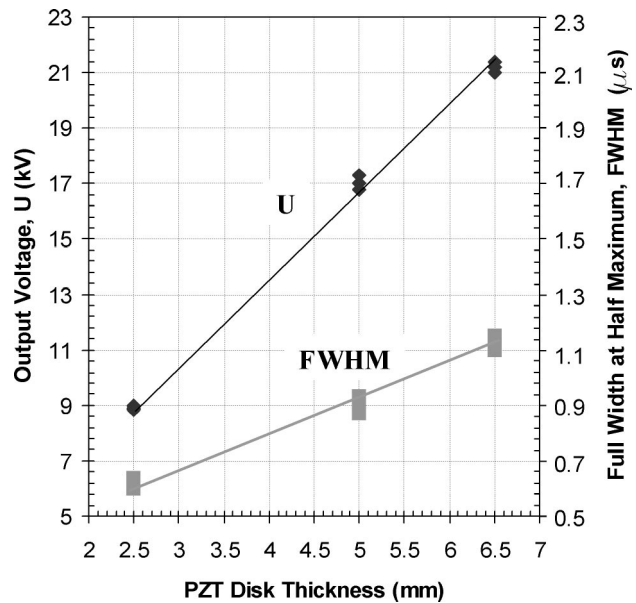
were grounded and the "positive" contact plates were connected to a high-voltage probe (Figs. 1 and 2). The polarity of all high-voltage pulses generated in this series of experiments was positive.

We performed a series of experiments to generate high-voltage pulses when the polarization vector of PZT disks was oriented against the direction of shock wave propagation. In this series of experiments, the "positive" metallic contact plates of the disks were grounded and the "negative" contact plates were connected to a high-voltage probe. The polarity of all pulses produced by the FEGs was negative. Comparison of amplitudes, shapes and FWHMs of high-voltage pulses generated in this series of experiments and in the series of experiments with reverse polarity of the PZT disks (described above), allows one to conclude that there is no significant difference in pulse parameters and that the only difference is the polarity of the signal. Therefore, making the energy-carrying element of the shock wave ferroelectric generator in the form of a stack of PZT disks having reverse polarity would be a straightforward way to generate a high-voltage sinusoidal wave.

The equivalent circuit of the FEG operating in the high-voltage mode consists of the pulsed voltage, U_g, induced on the output terminals of the generator due to the shock wave depolarization of the PZT energy-carrying element, the ca-
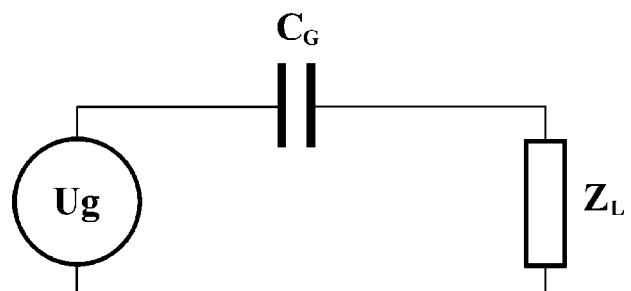

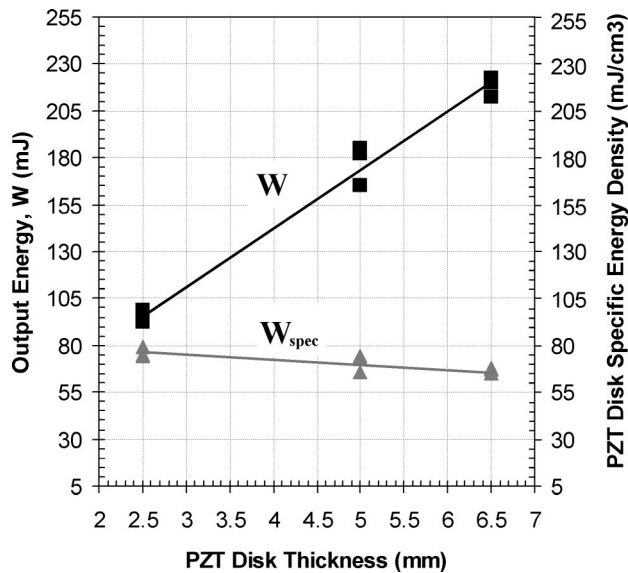FIG. 5. Equivalent circuit of the FEG operating in the high-voltage mode.

FIG. 6. Output energy, W (black), of the FEG operating in high-voltage mode and corresponding specific energy density, W_{spec}, of PZT energy carriers (gray) versus PZT disk thickness (disk diameter $D=25$ mm).

pacitance of the ferroelectric energy-carrying element, C_G, and the impedance of the load, Z_l, connected in the series (Fig. 5). The impedance of the high-voltage probe [which served as a load in the high-voltage experiments (Fig. 2)] was 100 MΩ, so the current in the electrical circuit of the generator was less than 0.3 mA. This is practically an open circuit operation of the FEG.

To estimate FEG energy production in the high-voltage mode, one can use the relationship for the operation of PZT electromechanical transducers in the open circuit mode:[15] $W=C_0 U_{OC}^2/2$, where W is the energy produced by the generator, C_0 is the capacitance of the PZT energy-carrying element, and U_{OC} is the open circuit voltage amplitude produced by the generator.

Figure 6 shows energy produced by the FEG operating in the high-voltage mode and the corresponding specific energy density of the PZT energy-carrying element for all three types of PZT disks. The increase of the PZT disk thickness leads to the increase in energy produced by the FEGs from $W=95\pm3$ mJ ($h=2.5$ mm) to $W=218\pm4$ mJ ($h=6.5$ mm). At the same time, it reduces the specific energy density

from $W_{spec}=76.4\pm0.8$ mJ/cm^3 ($h=2.5$ mm) to $W_{spec}=67.1\pm0.8$ mJ/cm^3 ($h=6.5$ mm). These experimentally obtained values of specific energy density of the PZT energy-carrying elements are in good agreement with results of theoretical calculations based on the phenomenological model of the operation of an explosive driven shock wave ferroelectric generator.[20]

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