High Voltage Generator With Adjustable Delay Between Two Nanosecond Pulses

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Abstract—In this letter, we present the experimental setup of a newly designed, high voltage (up to 10 kV), nanosecond duration pulse generator. Based on the frozen wave concept, the generator includes two optoelectronic photoconductive switches placed in a compact three ports coaxial structure. The generator is able to produce unipolar, bipolar and paired pulses with adjustable interpulse delay between 5 ns and 200 ns. An electromagnetic frequency characterization of the generator evidenced its suitability for the implementation of kilovolt ultra-short pulse with delay tunability.

Index Terms—High voltage nanosecond pulse generator, pulse shaping, bipolar and paired pulsed, optoelectronic photoconductive semi-conductor switches, high energy laser, electromagnetic frequency characterization.

I. INTRODUCTION

HIGH intensity pulsed electric fields (tens of kV/cm) with the duration in the range of nanoseconds (nsPEF) have been widely investigated in the last few decades [1]. They have been proved highly efficient for different domains such as military applications, food processing, environmental science and biomedical applications [2]. In the biomedical field, the application of these pulses has resulted in various cellular effects such as cytoskeletal disruption, plasma membrane permeabilization, loss of mitochondrial activity, leading to cellular death by apoptosis or necrosis [3], [4]. Moreover, numerous studies showed that applying nsPEF to biological cells can affect intracellular membranes and cell structures [3]. However, studies evidence that, for example, cells or 3D spheroids responses to 10 ns duration nsPEF highly depend on the pulse parameters such as temporal shape, duration, intensity and polarity [3], [5]. Applying bipolar pulses i.e., alternating positive and negative pulses, may induce cancellation of some previously mentioned effects caused by unipolar-shaped pulses [6]. However, if a delay is introduced between the pulses, cancellation can be inoperative [3], [5]. Effects can also be enhanced by applying two, time-delayed, positive pulses [3], [5]. The intensity of the second pulse can play an important role as well in the cancellation or the strengthening outcomes [7].

Thus, the developments proposed in this paper concern delayed, asymmetric ultra-short pulse generation that allows further exploration of biological effects, in particular the possibility of modulating cellular and tissue responses for adaptive therapies. Indeed, generators that can produce repetitive nanosecond and sub-nanosecond pulses with controllable energy and time delays are required to accomplish further biomedical studies and to ensure a better understanding of the interaction mechanism between nsPEF and biological samples. The nsPEF generator proposed in this study is based on the frozen wave concept that consists in storing high electrical energy in a pulse-forming circuit and then releasing it using high-power ultrafast switching elements [8]. In the literature, three main methods of the pulse-forming circuits were studied and classified as a function of energy storing and/or releasing type. For instance, Marx generators are based on the direct capacitor discharge [9], [10]. Inductive energy discharge is implemented in [11], [12]. Recently, the combination of a Blumlein pulse forming line with the boost method was proposed to improve pulse voltage amplitude and energy conversion efficiency [13]. Ultra-short pulsed electric field generators require one or several switches to control the instant and the releasing speed of the energy initially stored. For breakdown voltages up to several kilovolts and rise times of a few nanoseconds, typical switches are metal-oxide-semiconductor field effect transistors (MOSFET) [12], diode opening switches, and thyristors [14], [15]. For their abilities to sustain high voltages and switch with sub-nanosecond rise times, spark gap switches [16] and optoelectronic switches such as photoconductive semiconductor switches (PCSS) are used [5], [17]–[19]. To introduce a delay between the two paired or bipolar pulses, a cable extension of variable length, can be introduced between the switching elements and the termination of the line constituting the internal geometry of the generator [5]. However, some pulse generators based on all-solid-state components produce 2 ns bipolar and unipolar pulses, with interphase delays up to 120 ns [20].

In this paper, we present a 0.9 ns high-voltage (up to 10 kV) pulse generator able to create unipolar, bipolar, and paired pulses with variable amplitude and adjustable delay between the pulses constituting the output waveform (5 ns to 200 ns).

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The maximum delay value is relatively long, i.e., greater than 200 times with respect to the pulse duration, allowing further investigations of bioeffects never reported before. In this generator, the energy stored in a transmission line is released by the ultrafast activation, with a laser optical beam, of two PCSSs placed in a three ports coaxial structure (see figure 1). A 3-ports coaxial structure is newly designed with a compact structure that integrates the transmission line and allows the generation of pulses with a duration shorter than 1 ns with amplitudes up to 20 kV bias voltage. Moreover, we have for the first time to our knowledge generated sub-nanosecond duration, delayed, paired pulses. The frequency bandwidth of the generator coaxial structure obtained through an electromagnetic characterization is first determined. Typical generated pulses with unipolar, bipolar, or paired shapes and variable delays between pulses constituting the output waveform are also presented.

II. MATERIALS AND METHODS

The proposed generator, presented in Fig. 1, is composed of a three-port coaxial structure containing two PCSSs. The PCSSs are connected through a 16-cm transmission line (metallic rod) that determines the pulses duration. The PCSSs are high voltage diodes supporting up to 20 kV bias voltage in DC configuration (X200FG, VMI, USA) with a recovery time of 200 ns. The PCSSs are axial-leaded, glass body diodes made from diffused stacked silicon wafers. The PCSS diodes are passivated with a hermetic glass and the silicon stacks are terminated with tungsten pins and silver leads. To avoid temporal jitter and PCSS’s progressive destruction in time, they are used in their linear running regime. However, for reliability reasons the PCSSs are replaced every year. The PCSSs are triggered by a high-energy Nd:YAG laser (PL2241A, Ekspla, Lithuania) operating at 1064 nm, generating Fourier transform optical pulses of 35 ps with a repetition rate of 20 Hz. Regarding the optical energy needed to turn the PCSSs into their conducting state, a high optical energy is required which also depends on the bias voltage [2]. The laser delivers up to 12 mJ allowing to simultaneously switch the two PCSSs by decreasing their internal resistance down to few ohms [2]. The coaxial structure is connected, on port #1 through 83-dB attenuation chain (Barth Electronics Technology, USA), to a 12 GHz sampling oscilloscope (DSO, TDS6124C, Tektronix, USA) for pulses acquisition and measurements. HN (R176404, R176021, Radiall, France) and THT (THT20, Radiall, France) are used as connectors on ports #1-2 and #3, respectively. To avoid electric discharge, the coaxial structure was filled with commercial vegetable colza oil containing traces of carbohydrates, sugars, proteins and salt. A high voltage DC power source (SR20kV-300W, Technix, France) connected via port #3 through a 1 MΩ resistor is used to supply the transmission line. By switching the PCSSs with an optical infrared pulse from the isolating into conducting state, the electrical energy is released from the transmission line through port #1 forming a squared shaped electrical pulse. Bipolar, paired, or unipolar pulses are generated by connecting port #2 to a short circuit, open circuit, or a 50 Ohm load, respectively. Moreover, bipolar or paired pulses with a delayed second pulse are created by inserting coaxial cables with variable lengths between port #2 and the circuit termination connector (short or open circuit). For instance, by introducing a meter-long cable, the two pulses created by the release of the progressive and regressive waves, initially locked up on the central coaxial line, are delayed by 10 nanoseconds.

To determine the frequency behavior and limitations of the circuit, an electromagnetic frequency characterization of the 3-ports coaxial structure was carried out. The scattering $S$ parameters of the structure were measured for frequencies up to...
3 GHz. For the measurements, the two PCSSs were replaced by conducting rod wires. Ports #1 and #2 were connected to a vector network analyzer (VNA 8753, HP, USA) via HN-to-N adaptors and port #3 was disconnected from the circuit.

III. RESULTS

A. Coaxial Structure Electromagnetic Characterization

To evaluate the influence of the insulation on the electromagnetic scattering $S$ parameters (Fig. 2), two configurations were measured i.e., the coaxial structure without or with oil between the metallic rod line and the coaxial structure. As the coaxial structure is symmetrical and reciprocal between ports #1 and #2, only $S_{11}$ (reflection parameter) and $S_{21}$ (transmission parameter) are presented. Oscillations on the measurements are caused by the not-strictly 50 ohms impedance matching of the structure when the frequency increases. The impedance mismatch induces reflections created at discontinuities i.e., between the connectors and the metallic rod line. The reflection coefficient $S_{11}$ is lower than -10 dB, i.e., less than 10 % of the incident power is reflected back, up to 100 MHz and 2 GHz, for the coaxial structure without and oil filled, respectively. By adding the insulation oil, a 50 ohms impedance matching is obtained thus limiting mismatches and reflections and contributes to significantly extend the matching bandwidth up to 2 GHz. Moreover, the transmission coefficient $S_{21}$ of the system loaded with oil is higher than -1 dB up to 450 MHz and is equal to -5 dB at 2 GHz, a frequency corresponding to the highest part of the pulse duration spectrum. With larger adaptation and transmission frequency bandwidths of the coaxial structure and its connectors, shorter pulses duration and rise times down to 125 ps can be generated without significant losses.

B. Electric Pulses

The generator allowed producing three pulse shapes for bias voltages up to 10 kV and inter-pulse delays ranging from 5 ns to 200 ns. Fig. 3(a) presents typical generated pulse shapes i.e., unipolar, bipolar, and paired, obtained for a 4 kV bias voltage. The generated pulses present slight oscillations related to the non-perfect impedance matching of the coaxial structure for high frequencies and the residual PCSSs conducting state resistance. The unipolar pulse duration at full width at half maximum (FWHM) is 0.9 ns. The total duration of the bipolar and paired pulses is 2 ns. The first pulse maximum amplitude and rise time slightly vary with pulses shapes. Pulses rise times, considered between 10% and 90% of the pulse maximum amplitude, are in average around 150 ps ± 25 ps. The first pulse maximum amplitudes are 1.47 kV, 1.58 kV, and 1.7 kV for bipolar, unipolar, and paired pulses, respectively. The delay of approximately 0.5 ns between bipolar and paired pulses is due to the forward-reverse propagation delay within the line (9 cm) between PCSS2 and the termination on port #2 connector.

Paired and bipolar pulses with different inter-pulse delays were generated. By introducing coaxial cables with lengths ranging between 0.5 m and 20 m, the corresponding electrical delays were varied between 5 ns and 200 ns. Fig. 3(b) illustrates waveforms with delays of 5 ns, 50 ns, 100 ns, 150 ns, and 200 ns, obtained for a bias voltage of 4 kV. It can be observed that the amplitude of the second pulse decreases as the delay increases. For delays of 5 ns, 50 ns, 100 ns, 150 ns and 200 ns, the voltage attenuation of the second positive (paired) pulse with respect to the first pulse are 32%, 37%, 48%, 63% and 67% respectively. For the bipolar pulses, the attenuation values of the second pulse were of 7%, 20%, 35%, 39% and 53% for the previously mentioned delays, respectively. This attenuation is due to losses during the propagation of the pulses through the coaxial cables, connectors and the PCSSs as well as to the electronic pair recombination phenomenon. As its name indicates, this phenomenon manifests in the recombination of the whole-electrons pairs and it leads the PCSSs progressively
back to their OFF-state. The observed final pulses for more important delays are less intense than the one with shorter delays as the transmission coefficient through the PCSS varies over time. This drawback can be overcome in part by lightening the PCSS1 with a second delayed optical pulse which again decreases the resistivity of the component thus allowing the transmission without loss of the second delayed pulse. In Table I the attenuation rate between the two pulses for both bipolar and paired pulses were calculated as a function of the bias voltage and the inter-pulse delay. We observe that the attenuation level highly depends on the value of the delays, while it appears to be insensitive to the variation of the bias voltage value. We can also notice that paired pulses are more attenuated (12%) compared to bipolar pulses. These additional losses can be attributed to the reflection of the second pulse at the line end terminated by an open circuit. We evaluated the rise time and the maximum amplitude of the first part of bipolar pulses as a function of the bias voltage varying from 2 kV up to 10 kV. The rise time is relatively steady with the bias voltage in the range of 150 ps ± 25 ps. The maximum amplitude of the first pulse varied between 0.86 kV and 3.7 kV. As the bias voltage increases, the first pulse amplitude decreases compared to the theoretical maximum values, i.e., half of the bias voltage. For instance, for 2 kV and 10 kV, the measured amplitudes are 86% and 74% of the maximum theoretical values using 12 mJ optical energy. This evolution can be attributed to the Franck–Keldysh effect corresponding to the semiconductor absorption coefficient variation versus the bias voltage [22].

IV. CONCLUSION

We have designed, built, and characterized a new generator allowing to produce pulses of ultra-short duration of 0.9 ns and rise time of 150 ps in average. Three different forms of pulses are generated, including bipolar, paired, and unipolar pulses, with various amplitudes (up to 10 kV) and controllable inter-pulse delays ranging between 5 ns and 200 ns. A frequency characterization of the generator's 3-port compact coaxial structure showed its wide frequency matching and its ability to provide ultra-fast switching for nanosecond electrical pulse generation. Bipolar and paired pulses with 5 different delays, i.e. 5 ns, 50 ns, 100 ns, 150 ns, and 200 ns were presented. The influence of the inter-pulse delays and the bias voltage on the pulses amplitude and rise times were studied. Further investigations will allow evidencing the generator capabilities and extending the exploration possibilities of biomedical effects. This compact technology farther opens the way of hundreds of picoseconds pulses with high amplitude up to 20 kV bias voltage.

REFERENCES


