NANOSECOND PULSE GENERATOR USING DIODE OPENING SWITCH FOR CELL ELECTROPERTURBATION STUDIES *

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Abstract

Studies of short pulse cell electroperturbation require high-voltage nanosecond pulses delivered to low-impedance electroporation cuvette loads. We present the design and operation of such a pulse generator based on series and parallel connected ordinary rectifying diodes as an opening switch. The generator is designed to produces 5 ns wide, 10 kV amplitude pulses into a 10 Ω cuvette load. The design incorporates a primary IGBT switch. Pulses produced by the IGBT are compressed by one low-loss, nanocrystalline, saturable core compression stages. The compressed pulses are fed to the diode opening switch through a fast, ferrite saturable core transformer. The all-solid-state design results in reproducible pulses and reliable, long-life operation. The prototype system currently generates pulses of 18.4 ns wide and 4.56 kV amplitude under repetition rate of 20 Hz.

I. INTRODUCTION

High voltage nanosecond electric pulse is essential to the electroperturbation study of biological cells. The response of the cells upon electric pulse exposure depends on the pulse width and amplitude. Pulse longer than 1μs normally results in electroporation, which stands for opening of pores on outer cell membrane temporarily or permanently [1]. When the duration of the pulse reduced to nanosecond range, the cell nuclei can be affected without adversely affecting the outer cell membrane. Further experimental investigations of electroperturbation require compact pulse generators with readily variable output parameters [2].

The desired pulse amplitude and duration is determined by the required electric field and electrode geometry. In order to generate 5-10 MV/m electric field in a standard cuvette load with 1mm electrode gap, pulses with 5-10 kV in amplitude are required. A repetition rate of around 10 Hz is also preferred for the observation of the effects with good statistics.

Previous diode pulse generator designed for electroperturbation research can only generated pulses with 600 V in amplitude into 50 Ω load [3], which is good for microscopic study of the cells suspended in micro-chamber. In order to expose massive cells to electric pulses for further experiment, a larger chamber like the standard cuvette is necessary. Shifting to cuvette camber results in reduction of load impedance from 50 Ω to 10 Ω. As a consequence of adopting standard cuvette in experiment, the peak current for the diode to interrupt increases dramatically from 30 A to 1000A. Switching such a large current to the load in only a few nanoseconds raises great challenge. In this situation, the parasitic inductance significantly worsens the performance of the pulse generator. In current version of pulser, the output pulse is only 4.56 kV in amplitude and 18.4 ns in width. Further improvement is in progress to tackle this problem.

II. DESIGN

As an improved version to its predecessor, the system can be seen as a magnetic compression stage cascading into a diode pulse generator similar to previous design. The circuit diagram is shown in Fig. 1 (a). In the magnetic compression stage, the initial pulses (3 kV, 1μs) are generated by switching the IGBT. Then these pulses are compressed from 1us to 100ns by saturable inductor L_1. The recovery diode switch stage takes these pulses as its input. The working principle of this stage is very similar to previous diode pulser [3]. Briefly speaking, in this stage, the pulse will first be compressed by a factor of 2 through the saturable transformer T_2. This way, 1 kA peak current is generated in the energy storage inductor, which is the leakage inductor of transformer T_2. Once reaching 1 kA, the reversed current through this inductor will be commuted into the cuvette load by the diode opening switch and a 10 kV pulse will be generated.

The stage-by-stage design starts from calculating required pulse parameters at the load and works backwards to IGBT switch. The picture of constructed pulse generator is shown in Fig. 1 (b).

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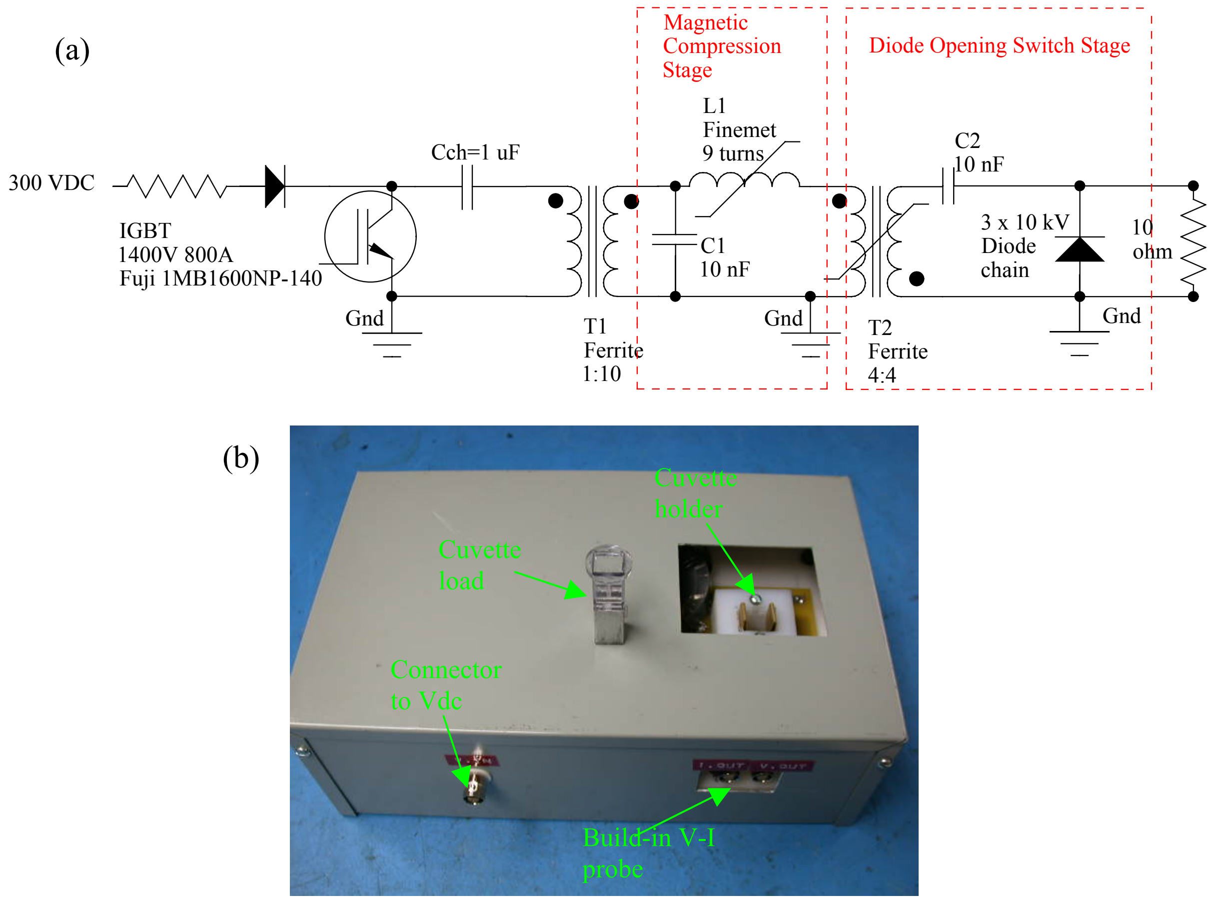

Figure 1. (a) Circuit diagram of the pulse generator. (b) Constructed pulse generator with a cuvette load.

A. Electrical Characteristics of Cuvette Load

The load to the pulse generator is a standard electroporation cuvette as shown in Fig 1 (b). The electrodes of the cuvette are two pieces of Aluminum plate with the size of 1cmx2.5cm. The two electrodes are separated by a gap of 1mm. During the experiment, the camber defined by the electrodes and plastic wall is filled with a nutrient solution in which the cells are suspended. At the operation frequency of the pulse generator, the load impedance Z_L is about 10 Ω. In order to generate a 10 MV/m electric field in the camber, pulses with 10 kV in amplitude are required. Accordingly, the output current will be 1kA. Considering a pulse width of 5 ns, the energy delivered per pulse is approximately 50 mJ.

B. Diode Opening Switch Stage

The output energy comes from storage inductor, which is the inductor formed by the secondary winding of saturated transformer T_2. According to the current and energy values from pervious calculation, we can determine the inductance value of the storage inductor, which is L_{sat2}=100 nH.

When the diode turns off, the current in L_{sat2} will be switched to the load. Therefore, the diode turn-off time will determine the rising time of the output pulse. In order to turn off the diode fast, quarter period of the L_{sat2} ,C_2 series circuit must be shorter than the diode recovery time. And when a diode is fully saturated by forward current, it will suffer a reverse recovery time, which is the interval from diode current reverse flowing to turning off of the diode. The reverse recovery time is normally in hundreds of nanoseconds range, which will make the output pulse width significantly longer. In our design, MURS2510 diodes are used. The maximum forward pumping time without fully saturating the diode is tested to be about 200 ns for a single diode. The diode is rated 1 kV, 25 A. In order to withstand an output voltage of 10 kV, a chain of ten diodes in series is applied. Three diode chains are parallel connected to reduce the pre-pulse pedestal caused by the resistive phase of the diodes. The diodes block shows a different performance comparing with single diode. The maximum forward pumping time reduces to about 100 ns.

Due to the compression ratio of 2 in the saturable transformer, the diode reverse condition time is 50 ns, which is also quarter period of the L_{sat2}, C_2 circuit, $\frac{\pi}{2}\sqrt{L_{sat2}\cdot C_2}$. Here we can calculate the value of C_2 = 10 nF and the peak charging voltage across C_2 is 3 kV.

The actual current through diode is shown in Fig. 2. The amplitude of the current is half of the designed value. The reason may be because that the parasitic inductance in the circuit increases the LC period and reduces the current accordingly.

C. Saturable Core Transformer

The transformer is wound on a CMD5005 ferrite core from Ceramic Magnetics. The dimensions of the core are OD = 50.8 mm, ID=25.4 mm, H=12.7 mm. So we can calculate the effective core area A_{core}= 161.3 mm^2, and average magnetic path length l_c = 119.7 mm. The core saturates at B_{sat} = 0.33 T. According to the datasheet, the core will work fine in a wide frequency range up to 100 MHz.

From the analysis of the diode stage, the secondary winding should have an inductance of 100nH when the core saturates. So, we need 5 turns for the secondary winding. The transformer has a turn ratio of 1:1, so the primary wind will be 5 turns too.

In actual circuit construction, the leakage inductance of the transformer contributes to the total inductance as well as the parasitic inductance of the diode chain and the PCB trace. So the primary and secondary windings were wound close to each other in order to reduce leakage inductance. The actual turn number is also reduced to 4 turns for both primary and secondary for best performance.

In Fig. 2, the forward pumping time is 182 ns and the reverse pumping time is 58 ns. These values are larger then the designed values because the parasitic problem mentioned above. And the peak forward and reverse current are 256A and 560 A respectively.

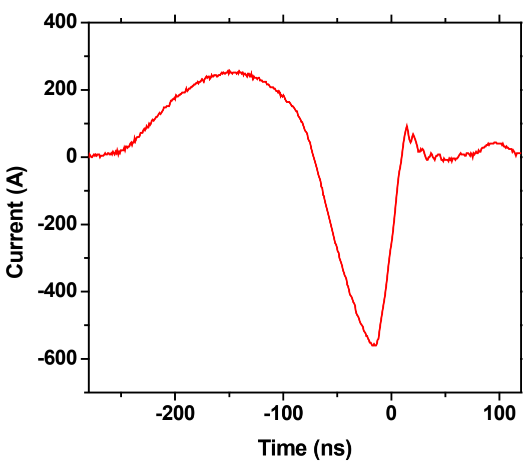

Figure 2. Current through diode D. Forward current: 256 A, 182 ns; Reverse current: 560 A, 58 ns.

D. Magnetic Compression Stage

The output of the magnetic compression stage will feed into the primary of the saturable transformer T_2. So the output pulse of this stage should be a pulse of 100ns duration and 3 kV in amplitude.

The saturable transformer has a ratio of 1:1, so the capacitor C_1 in magnetic compression stage will have the same values as C_2 in order to match the impedance. The capacitor will discharge through the saturable inductor L_1 to C_2. The discharge time is half period of the LC series circuit, $\pi\sqrt{L_1 \cdot C_1 // C_2}$, which is also the forward pumping time (100 ns) of the diode stage. This way, the saturated inductance of L_1 is determined.

To achieve high compression ration, a core with large saturation magnetic flux density (B_{sat}) is preferred. Finemet core from Hitachi is chosen for its large B_{sat} (1.23 T). The external dimension of the core is OD=50.8 mm, ID=25.4 mm, H=12.7 mm. The effective core area is estimated to be A_c=121 mm^2. Calculation suggests that 7 turns on the core is needed to get correct forward pumping time. In this configuration, it is capable to compress a 1.3 µs pulse to 100 ns.

During construction of the pulse generator, we found that the inductor L_1 saturated a little early with 7 turns. To solve the incorrect timing, 2 more turns was added to the core, which makes a total number of 9 turns. In the constructed compression stage, 1 µs input pulse can be compressed to 180 ns. The real compression ratio for this stage is about 5.

E. IGBT Switch

The primary switch of the pulse generator is an IGBT. The switch connects the primary stage of T_1 with the charging capacitor C_{ch} With a turn ratio of 1:10 in T_1, peak voltage of 300V on C_{ch} raises to 3 kV on C_1. In a lossless system, the C_{ch} should match the effective capacitor of secondary to gain high energy transfer efficiency. From formula $C_{ch}=(10:1)^2C_1$, we get C_{ch} = 1 µF. Considering the peak current of 500A, an IGBT from Fuji with voltage rating of 1400V and current rating of 800A is selected.

III. OPERATION

The present system used a resistive charging supply. The pulse generator has been tested at repetition rates of 20 Hz. Typical output into a cuvette load with 85 µl RPMI is shown in Fig. 3. The pulse amplitude is 4.56 kV, and the FWHM is 18.4 ns.

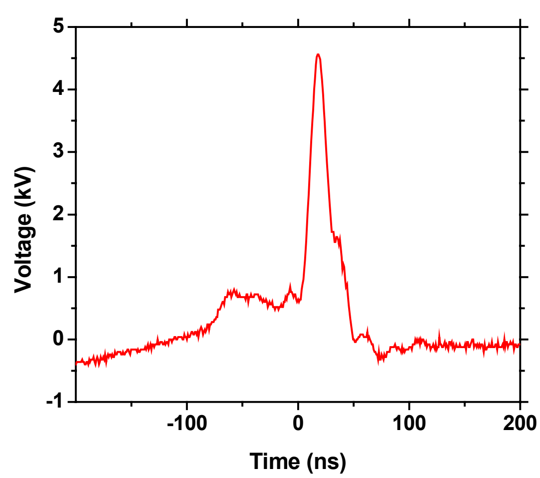

Figure 3. Output pulse to the cuvette load: 4.56 kV, 18.4 ns FWHM

By varying the charging voltage in certain range, different output amplitudes can be achieved without effect the output pulse width too much. In Fig. 4, the effect of charging voltage on the output pulse is shown. When the charging voltage less than 250 V, the pulse width increased dramatically. The reason may be because the incorrect saturation time of L_1 under low voltage.

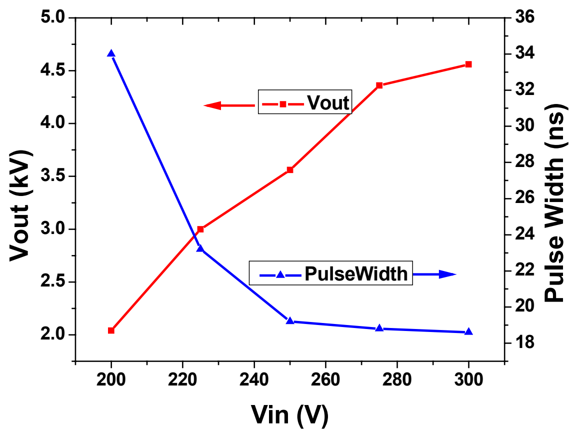

Figure 5. Output pulse amplitude and width vs different charging voltage

IV. SUMMARY

A nanosecond diode pulse generator is designed and constructed. The design goal of 5 ns and 10 kV into a 10 Ω cuvette load is not fully achieved yet. The existing prototype generator gives pulses of 18.4 ns and 4.56 kV for a 10 Ω cuvette load. Improvement of the pulse generator is in progress.

V. REFERENCES

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