Simple MOSFET-Based High-Voltage Nanosecond Pulse Circuit

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***Abstract*—Using simple but powerful electronics concepts, such as a mass produced Schmitt trigger and integrated MOSFET driver in novel circuit applications, a simple 400-V 75-ns pulse generator (pulser) has been designed, developed, and tested. For a 50-Ω matched load, the pulser produces extremely well-defined, repetitive high-voltage pulses that are free from overshoot and ringing. The width of the pulses is adjustable from 75 ns to 10 ms with the fall times of a few tens of nanoseconds for a negative wave and a repetition period of 1.5 μs with the existing setup. By upgrading to a more complex driver circuit, much lower pulsewidths are possible. Using a 1–4 mm standard commercial cuvette, it is possible to generate electric fields of 4–1 kV/cm with this pulser. The purpose is to try to do electroporation mediated gene therapy on mammalian cells at higher electrical field strengths and submicrosecond or microsecond pulsewidths compared to conventional 200 V/cm and tens of millisecond-duration pulsewidths.**

***Index Terms*—High voltage, nanosecond pulse, power MOSFET, pulse generator, pulsed-power technology, rise time, transmission line.**

I. Introduction

NANOSECOND, microsecond, and millisecond scale high-voltage pulse generators are required for cell electroporation therapy (EPT), genetic therapy, and research, in addition to ultrasonic cleaning, chemical-free bacterial decontamination, and medical imaging [1]–[11]. In the past, these low-impedance loads demanded expensive components or circuits designed with complex or hybrid topologies [1], [12]–[14]. Recent advancements in semiconductor doping and deposition techniques have led to high-volume production of power metal–oxide–semiconductor field-effect transistors (MOSFETs) capable of nanosecond-scale slew rate, of tens of amps current ratings and Rds-on (drain-source on resistance) in the low ohms while still being capable of switching hundreds of volts [15]–[18]. Such devices allow for decreased circuit complexity due to their simple drive requirements, fast slew rate, and high power capacity. The design focus can be directed toward circuit simplicity, layout, proper reactive compensation, and optimal construction. Attention must be paid to proper circuit construction to minimize pulse distortion. Rise and fall time, ringing, overshoot, and ramping contribute to the degradation of energy passed to the load in an individual pulse and to the power delivered by a pulse train or periodic signal. At nanosecond-scale pulsewidths, the frequency content exceeds gigahertz frequencies. Loads that are not matched will reflect and distort the signals and any comparison of findings by researchers can only be compared incidentally, not analytically. A pulse delivered by an instrument-grade generator into uncompensated amplifiers will be distorted.

The purpose of this work is to build a low-cost nanosecond to microsecond pulse generator that can be used for electroporation-mediated gene therapy and enhancement of drug delivery applications. This is to take advantage of the electroporation or electropermeabilization technique which is simple, physical, easily controllable, and efficacious [4], [19]. Typically, electric field strengths of 1300 V/cm and 100-μs pulses are used for EPT [9], [10] and for gene therapy low voltage, but longer pulses, such as 200 V/cm, and 20–50 ms were used [6], [8]. The viability or cell survival after electroporation is still to be optimized. The efficacy of the technique depends on the pulse duration among other parameters [1], [4], [5], [8]. It is envisioned that the survival of various mammalian cells can be substantially improved by using short pulses of higher intensity. To that end, this pulse generator was designed and developed due to the unavailability of commercial economical and variable submicrosecond pulse generators.

II. Nanosecond Pulse Generator Design

A circuit was designed to drive a 50-Ω resistive load with a 1–400 V 75-ns pulse. The circuit includes three stages comprising an integrated variable frequency and variable-duration pulsewidth signal source, an inverter/driver stage, and a power buffer consisting of an passively loaded single-power MOSFET. The circuit construction is physically optimized to reduce distortion and retain signal integrity while minimizing reflected power from the circuit and load. The driver selected was an On Semiconductor MC33151 integrated 15-ns tr, dual, inverting Schmitt trigger input with totem pole outputs. The buffer is an IXYS DE275-501N16A radio-frequency (RF) MOSFET with 500-V Vdss, 16-A Id, and 6-ns rise time. The MOSFET is biased into cutoff and the circuit is designed to maximize rise time and operated common source for optimal efficiency. The MOSFET works against a passive load composed of three parallel 150-Ω high-power resistors. The voltage sources are linear designs with the signal source and driver supplies actively regulated.

The circuit was designed to explore the possibility of using products that are mass manufactured for standard consumer applications in a very simple, low-cost circuit that will function well as a research quality high-voltage nanosecond-scale pulse generator for EPT and gene therapy applications. The circuit was implemented using exclusively off-the-shelf devices and was constructed of commercially available RF groundplane

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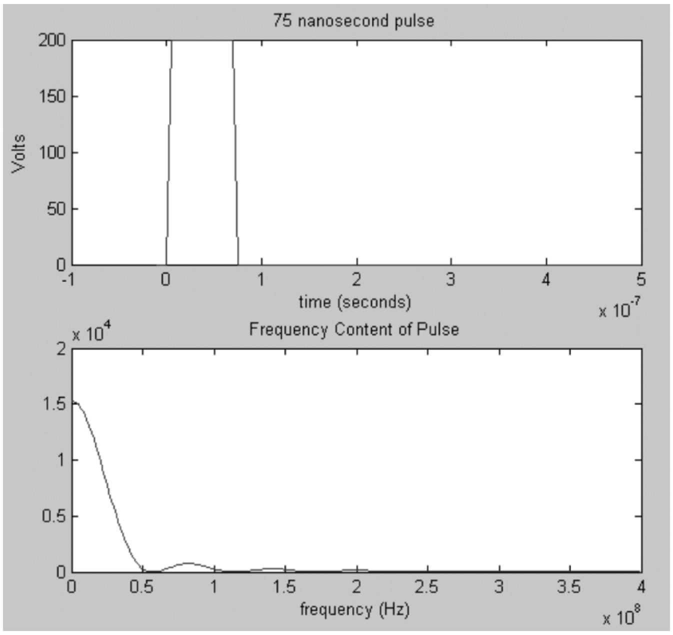

Fig. 1. FFT analysis of a 200-ns pulse using MATLAB.

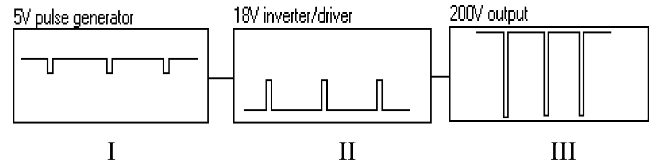

Fig. 2. Simple three-stage design that minimized complexity. I. Nanosecond scale pulse. II. Output stage driver. III. Output stage.

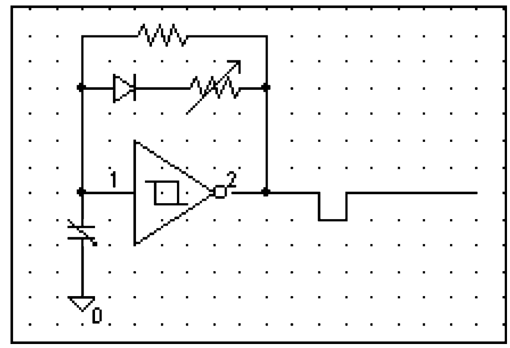

Fig. 3. Signal source circuit: the variable resistance is 300 Ω, the other resistance is 15 k, the capacitance is 150 pF, and the diode used is IN4148.

microstrip prototype components manufactured by RDI Wainwright and Surfboard. Total circuit cost was only several hundred dollars including power supplies, coaxial cabling, and dummy load. Effort was made to construct a circuit that can be duplicated by any researcher without access to a machine shop, high-cost signal generators, microwave linear amplifiers, or custom printed circuit board facilities. Initially, a 200-V power supply for the output stage was decided upon since 250-V bridge rectifiers and high-quality 250-V capacitors are inexpensive and commonly available. However, the voltage output can be increased to 400 V by changing the tap connection to 120 : 240 V AC setting of the isolation power transformer utilized, driven by a 0–140 V AC Variac and doubling the voltage rating of the capacitors by connecting them in series pairs. This configuration allowed circuit testing and troubleshooting at a continuously variable 0–400 V voltage range. Linear power supplies were used exclusively to minimize noise in the circuit. The 18-V driver supply is regulated down from a linear 34-V supply. The 5-V logic level supply is on the circuit board and is regulated from the 18-V source to double the supply ripple rejection.

A fast Fourier transform (FFT) analysis via MATLAB of a 200-V ns pulse indicated that the circuit required megahertz frequency bandwidth construction considerations (Fig. 1). High-frequency circuits demand microstrip groundplane construction to minimize parasitic circuit impedances and induced oscillations or reactive reflections. A survey of available prototyping systems indicated that commercially available radio frequency (RDI Wainwright's Solder Mount) and surface mount (Capitol Advanced Technologies' Surfboard) modular development circuit boards specifications fall within the design parameters.

To minimize design complexity, a simple, three-stage topology was conceptualized and implemented. A two-stage circuit was designed and built but proved unstable and unreliable. The circuit would pulse for several minutes until the MC33151 failed and shorted input to output. The present circuit consists of a variable-width pulse signal generator, an integrated driver/inverter, and a power output stage (Fig. 2). The three-stage design proved to be reliable and simple.

III. Signal Source, Driver, and Output Circuit

The first stage consists of a logic-level 75-ns pulse generation circuit. This circuit is a modified version of a square wave generator circuit [20]. This is based on a time-domain reflectometry circuit principle. The circuit uses a Schmitt trigger-based relaxation oscillator functioning as an astable multivibrator. This particular version proved useful in that the low and high pulsewidths could be made variable and the selection of the On Semiconductor MC74AC14 integrated circuit was optimal from a performance standpoint. Variable passive devices were used to allow empirical optimization of the built circuit. The variable resistance is 500 Ω and the fixed resistance is 15 k. The variable capacitor is 150 pF and the diode is IN4148. Fig. 3 illustrates the schematic. The signal source circuit was built in various physical forms and tested at pulsewidths as long as 3 ms with no change in performance noted.

Analysis of the signal source pulser (Fig. 3) shows the short-duration time (ts) of the negative pulses and comparatively longer time (tl) periods between negative pulses are determined by RC time constants of the passive components. C is the capacitor, R long (Rl) determines the longer time duration between pulses, and R short (Rs) is a smaller value that, in parallel with Rl, determines the short pulse duration. The MC74AC14 Schmitt trigger is designed with hysteresis between the positive threshold ($Vt+$) and negative threshold ($Vt-$) switching voltages. Typical, published values are $Vt+ = 3.5$ V and $Vt- = 1.0$ V. Values for these two parameters must be measured in the circuit to accurately predict pulse times. ts is the time taken to discharge the capacitor through both resistors. The capacitor voltage (Vc) discharges to $Vt-$. R is both resistors in parallel ($Rl \parallel Rs$). $V(\infty)$ is 0 V, the

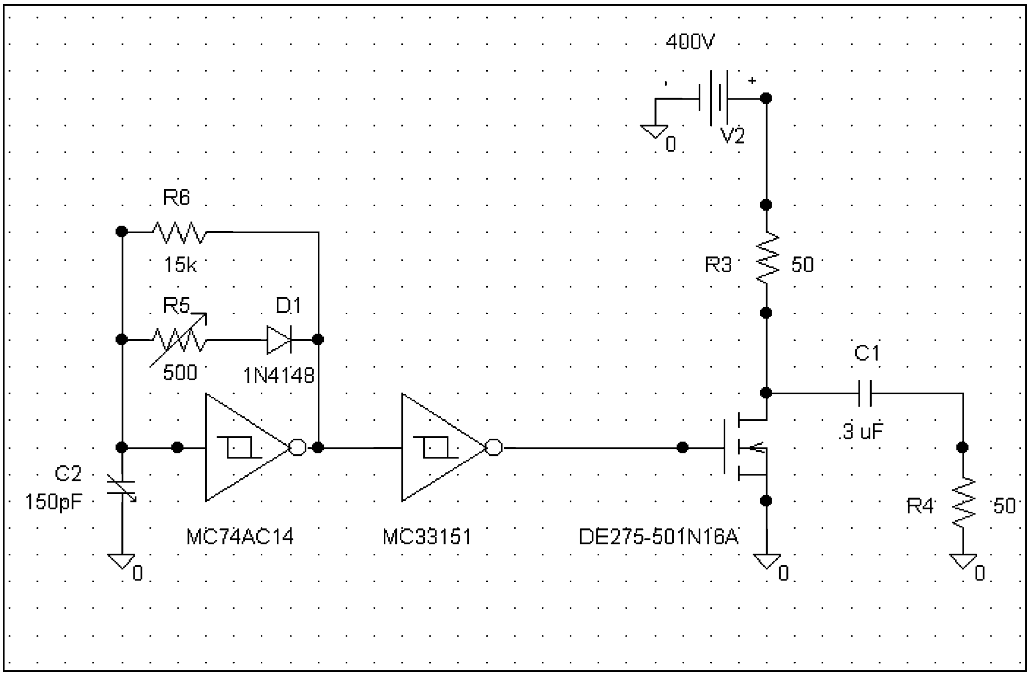

Fig. 4. Circuit schematic of the design—Schmitt trigger produces fast rise time, integrated driver meets specifications needed, and Totem pole BJT can sink/source 1.5 A to drive MOSFET.

potential the capacitor would discharge to if the Schmitt trigger did not switch

$$Vc(t) = V(\infty) + [\mathrm{V}(0) - V(\infty)] \exp\left(-\frac{\mathrm{t}}{RC}\right)$$

$$Vt- = 0 + [Vt+ - 0] \exp\left(-\frac{t}{RC}\right)$$

$$Vt- = [Vt+] \exp\left(-\frac{t}{RC}\right)$$

$$\frac{Vt-}{Vt+} = \exp\left(-\frac{t}{RC}\right)$$

$$\ln\left(\frac{Vt-}{Vt+}\right) = -\frac{t}{RC}$$

$$ts = -RC\left[Ln\left(\frac{Vt-}{Vt+}\right)\right]$$

$$ts = -Rl \parallel Rs^{*}C\left[Ln\left(\frac{Vt-}{Vt+}\right)\right].$$

tl is the time for the capacitor to charge from $Vt-$ to $Vt+$ through Rl. $V(\infty) = Vs$ is the supply voltage

$$Vc(t) = V(\infty) + [V(0) - V(\infty)] \exp\left(-\frac{t}{RC}\right)$$

$$Vt+ = Vs + [Vt- - Vs] \exp\left(-\frac{t}{RC}\right)$$

$$\left[\frac{(Vt+ - Vs)}{(Vt- - Vs)}\right] = \exp\left(-\frac{t}{RC}\right)$$

$$\ln\left[\frac{(Vt+ - Vs)}{(Vt- - Vs)}\right] = -\frac{t}{RC}$$

$$tl = -Rl^{*}C\left\{\ln\left[\frac{(Vt+ - Vs)}{(Vt- - Vs)}\right]\right\}.$$

The repetition frequency is $1/(ts + tl)$.

The 5-V signal source pulse is amplified to 18 V by an integrated inverter/driver [21]. The MC34151 is designed to drive MOSFET gates and is capable of sinking or sourcing 1.5 A into a 1000-pF gate capacitance. An inverting device was selected to eliminate the overshoot and ringing evident in the signal source pulse. When inverted, the noise is below the threshold voltage of the driver gate and is eliminated. After being inverted, the long duration 1.5-μm pulse becomes the delay between 75-ns pulses driving the output stage. The manufacturers' data sheet specified 15-ns rise and fall time into 1000 pF. This parameter degraded to 30 ns with the 1800-pF load of the output power devices gate capacitance. The driver proved to be the circuit's limiting factor in that aspect and also failed to trigger with pulses shorter than 75 ns in width. Discrete inverter/driver designs are being developed and will decrease the circuit's minimum pulsewidth and decrease rise and fall time performance.

The output stage consists of a single n-channel enhancement mode power MOSFET in common source configuration. The IXYSRF DE275-501N16A is capable of 500-V Vds, 16-A Id, and tr of 6 ns. None of these parameters were tested at their limits, but the device performed as specified within the capabilities of our circuit.

The output stage was passively loaded by three parallel 150-Ω resistors to yield a source impedance close to 50-Ω. The MOSFET drain was connected to a 50-Ω microstrip transmission line and ac coupled through coaxial connections and RG-58 cable to a 50-Ω dummy load.

IV. Results and Discussion

The circuit schematic of the design, the MOSFET pulser, and the pulse generator as they were built are shown in Figs. 4, 5, and 6, respectively. Capacitances from circuit elements to ground created by low-impedance solder pads and striplines

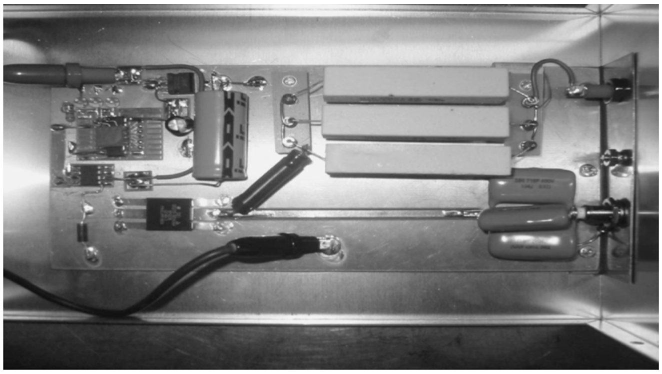

Fig. 5. Prototype with ground plane and solder mount or surfboard PCBs—transmission line construction.

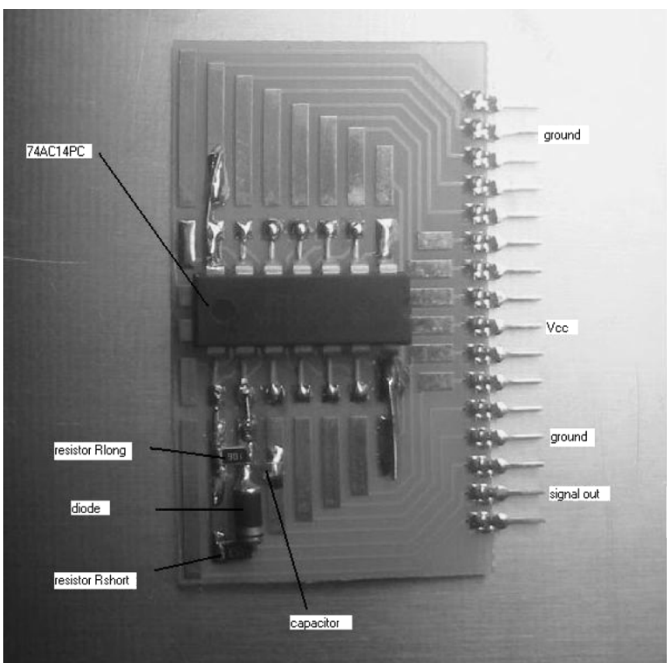

Fig. 6. Detail of pulse generator circuit with surface mount passive devices to illustrate the physical level design.

as well as wiring and lead inductances are not shown. The MC74AC14 operates from a 5-V supply and the MC33151 from an 18-V supply. The variable devices in the pulse generation circuit were optimized for switching stability, minimum pulsewidth, and speed suitable for a 50-Ω matching load. Figs. 7–9 show typical output voltage pulses at 200, 350, and 400 V, respectively. The peak gate voltage applied is 18 V. It can be seen that the pulses produced by the 50-Ω matched circuit have a well-defined rectangular shape and are free from ringing and overshoot. During testing, the time scale was increased from 5 ns/div to 10, 25, and 50 ns/div. to verify if there are pulse reflections. It was found, in all cases, that the pulses were free from pulse reflection, as displayed when the scope was set to each of the above extended time scales, since the load, the input impedance, etc., are all matched at 50 Ω. Figs. 10 and 11 show the fall and rise times obtained at 350 V output at 5-ns time scale in the scope. The 10%–90% fall time was 9 ns and the rise time was 22 ns.

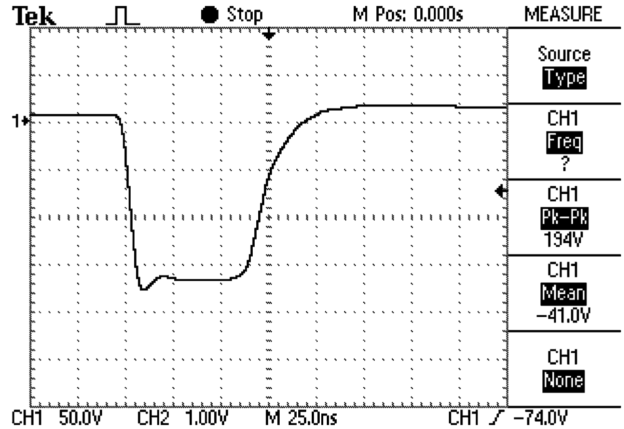

Fig. 7. Output voltage pulse waveform with 50 Ω load in response to the applied input voltage of 202. The output voltage is 194. The horizontal scale is 25 ns per division. The vertical scale is 50 V per division. The pulsewidth is about 75 ns. The fall time is about 10 ns. The waveform was recoded on a Tektronix TDS 210, 60-MHz 1-GS/s Digital Storage Scope.

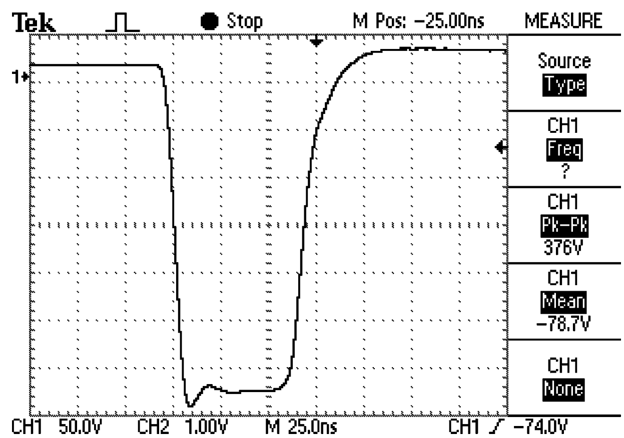

Fig. 8. Output voltage pulse waveform with 50 Ω in response to the applied input voltage of 385 V. The output voltage is 376 V. The horizontal scale is 25 ns per division. The vertical scale is 50 V per division. The pulsewidth is about 70 ns. The fall time is about 10 ns. The waveform was recoded on a Tektronix TDS 210, 60-MHz 1-GS/s Digital Storage Scope.

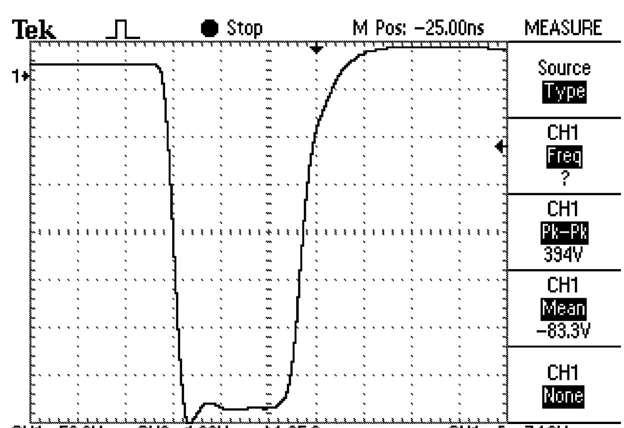

Fig. 9. Output voltage pulse waveform with 50-Ω load in response to the applied input voltage of 408 V. The output voltage is 394. The horizontal scale is 25 ns per division. The vertical scale is 50 V per division. The pulsewidth is about 70 ns. The fall time is about 10 ns. The waveform was recoded on a Tektronix TDS 210, 60-MHz 1-GS/s Digital Storage Scope.

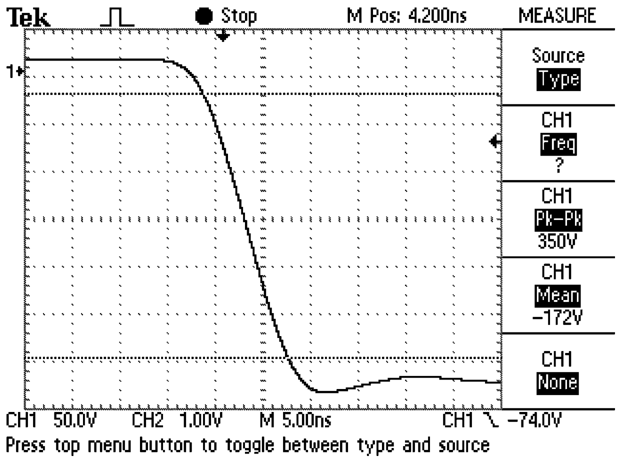

Fig. 10. Close-up view of the output voltage pulse showing the fall time details for the 350 V wave with 50-Ω load. The horizontal scale is 5 ns per division. The vertical scale is 50 V per division. The rise time is about 9 ns. The waveform was recoded on a Tektronix TDS 210, 60-MHz 1-GS/s Digital Storage Scope.

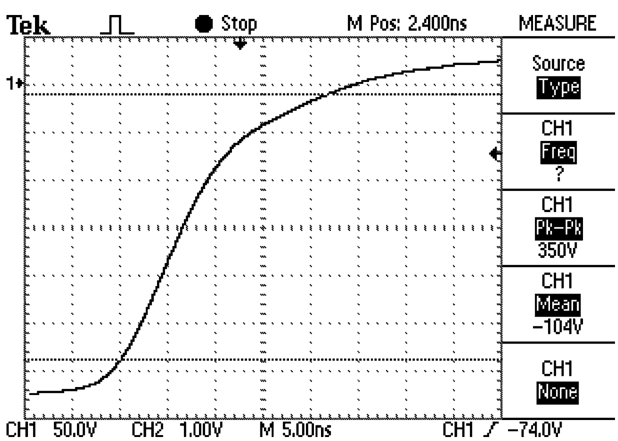

Fig. 11. Close-up view of the output voltage pulse showing the rise time details for the 350 V wave with 50-Ω load. The horizontal scale is 5 ns per division. The vertical scale is 50 V per division. The rise time is about 22 ns. The waveform was recoded on a Tektronix TDS 210, 60-MHz 1-GS/s Digital Storage Scope.

All efforts were made to ensure compatibility with established radio transmission and industrial standardization. Any reactive load can be easily compensated for and matched to a 50-Ω source impedance presented by a circuit. Commonly available matching networks, coaxial transmission lines, and connectors maintain the 50-Ω impedance. The results of the testing of this circuit indicate that it performs as designed. The circuit was built using broadband circuit prototyping techniques. 50-Ω microstrip transmission lines were utilized to minimize circuit inductance and reduce signal distortion due to impedance mismatches. While the topology of the circuit remained unchanged, the values of the passive components were varied to establish the limiting values that would yield satisfactory waveforms into a 50-Ω load. Further work is ongoing to make it suitable for loads other than 50 Ω also so that it can be effectively used to test various biological cell suspensions for either gene therapy or cancer drug enhancement.

V. Summary

A novel but simple and economical nanosecond pulse generator based on Schmitt trigger and Integrated circuit driver and a single MOSFET buffer was designed, built, and tested successfully. Schmitt trigger produces fast rise time. Totem pole BJT driver output can sink or source 1.5 A (continuous) to drive the MOSFET. The voltage sources are linear designs with the signal source and driver supplies actively regulated. Linear power supplies were used exclusively to minimize noise in the circuit. There is no ringing or overshoot typical of these kinds of circuits. Transmission line construction was implemented due to nanosecond scale timings involved. Local 5 V power supply was used for driving the pulser. The pulser is capable of producing variable voltage, pulsewidth, and off-duration pulses. There is no reason why this design configuration cannot be extended to the 1000-V n-channel power MOSFETs that are available now. Active load compensation for using this pulser for various biological applications is ongoing.

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References

[1] K. J. Muller, V. L. Sukhorukov, and U. Zimmermann, "Reversible electropermeabilization of mammalian cells by high-intensity, ultra-short pulses of submicrosecond duration," *J. Membrane Biol.*, vol. 184, pp. 161–170, 2001.

[2] S. J. Beebee, P. M. Fox, L. J. Rec, L. K. Willis, and K. H. Schoenbach, "Nanosecond, high intensity pulsed electric fields induce apoptosis in human cells," *FASEB J.*, vol. 17, Aug. 2003.

[3] K. H. Schoenbach, S. Katsuki, R. Stark, E. S. Buescher, and S. J. Beebe, "Bioelectrics—new applications for pulsed power technology," *IEEE Trans. Plasma Sci.*, vol. 30, pp. 293–300, Feb. 2002.

[4] H. Potter, "Review-electroporation in biology: methods, applications and instrumentation," *Anal. Biochem.*, vol. 174, pp. 361–373, 1988.

[5] E. Neumann, A. E. Sowers, and C. A. Jordan, Eds., *Electroporation and Electrofusion in Cell Biology*. New York: Plenum, 1989.

[6] R. Heller *et al.*, "Intradermal delivery of interleukin-12 plamid DNA by in vivo electroporation," *DNA Cell Biol.*, vol. 20, no. 1, pp. 21–26, 2001.

[7] L. M. Mir *et al.*, "High efficiency gene transfer into skeletal muscle mediated by electric pulses," in *Proc. Nat. Acad. Sci.*, vol. 96, 1999, pp. 4262–4267.

[8] J. Gehl, "Electroporation: Theory and methods, perspectives for drug delivery, gene therapy and research," *Acta Phys. Scand.*, vol. 177, pp. 437–447, 2000.

[9] S. B. Dev, D. P. Rabussay, G. Widera, and G. A. Hoffmann, "Medical applications of electroporation," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 206–223, Feb 2000.

[10] D. P. Rabussay, G. S. Nanda, and P. M. Goldfarb, "Enhancing the effeciveness of drug-based cancer therapy by electroporation," *Tech. Cancer Res. Treatment*, vol. 1, pp. 71–82, 2002.

[11] K. Schoenbach, R. P. Joshi, R. H. Stark, F. C. Dobbs, and S. J. Beebee, "Bacterial decontamination of liquids with pulsed electric fields," *IEEE Trans. Dielect. Elect. Insulation*, vol. 7, Oct. 2000.

[12] U. Hahn, M. Hermann, F. Leipold, and K. H. Schoenbach, *Nanosecond, Kilovolt Pulse Generators*. Piscataway, NJ: IEEE, 2002.

[13] S. Kono, J. Kolb, and K. H. Schoenbach, "Ultra-short pulsed electric field generators for the study of subcellular effects," in *Proc. Electromed 2003*.

[14] C. P. Hancock, A. R. Owens, and K. O'Grady, "Simple voltage generator for producing well-defined nanosecond pulses in excess of 1 kV," *Proc. Inst. Elect. Eng.—Sci., Meas. Technol.*, vol. 144, pp. 229–233, Sept. 1997.

[15] M. Behrend, A. Kuthi, P. T. Vernier, L. Marcu, C. Craft, and M. Gundersen, "Micropulser for real time microscopy of cell electroperturbation," in *Proc. Int. Power Modulator Conf.*, Hollywood, CA, 2002.

[16] B. Hickman and E. Cook, "Evaluation of MOSFET's and IGBT's for pulsed power applications," in *Proc. IEEE Pulsed Power Plasma Science Conf.*, 2002.

[17] W. M. Arnold and R. Patherick, "A four-channel high-voltage, pulse-train amplifier," in *Proc. 8th Electronics New Zealand Conf.*, 2002.

[18] A. Ahmed, *Power Electronics for Technology*. Englewood Cliffs, New Jersey: Prentice-Hall, 1999.

[19] M. Winterhalter, K. Klotz, R. Benz, and W. M. Arnold, "On the dynamics of the electric field induced breakdown in lipid membranes," *IEEE Trans. Ind. Applicat.*, vol. 32, Jan./Feb. 1996.

[20] *Master Handbook of 1001 Practical Electronic Circuits, Solid State Edition*, K. Webster, Ed., 1988, p. 185.

[21] G. Englund, "Build your own cable radar," *Electronic Design*, pp. 97–98, Oct. 1, 1998.

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Raji Sundararajan, photograph and biography not available at the time of publication.