Experimental Demonstration of a Compact, High Average Power, Pulsed Power Driver for Printed-Circuit Board Nonlinear Transmission Lines

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Abstract — **Nonlinear transmission lines (NLTLs) are a promising technology for high power microwave (HPM) generation. However, NLTLs are also typically characterized by relatively short RF pulse widths, on the order of tens to hundreds of nanoseconds. One approach to increasing the overall average microwave power is the application of short excitations in very high pulse repetition frequency, thus yielding a high effective RF duty cycle. This research details the development of a compact pulsed power driver capable of delivering up to 3 kV high voltage excitation, with pulsed widths between 100 – 500 ns, and multi-MHz pulse repetition frequency to a PCB-based NLTL HPM source.**

Keywords* — *High voltage pulse generator, nonlinear transmission line, high power microwave

I. Introduction

Nonlinear transmission lines (NLTLs) are a unique type of high power microwave (HPM) source that are able to produce short, high power radiofrequency (RF)-to-microwave frequency bursts from a unipolar excitation. Unlike vacuum-based HPM sources, microwave production in NLTLs does not rely on an electron beam freely propagating in vacuum [1]. Instead microwave production is achieved via some combination of nonlinearity, dispersion, and material dipole motion [1]. Various sub-types of NLTLs exist, which employ nonlinearities in dielectric and magnetic materials, as well as semiconductors [2]. Notably, NLTLs utilizing nonlinear magnetic materials generally feature superior characteristics at higher GHz to multi-GHz frequencies (e.g. [3]), which motivates their interest here.

Magnetic material-based NLTLs typically fall into the category of either gyro-type lines, which rely on rapid realignment and precession of magnetic domains that couple in and out of the operational mode, thus generating microwaves (e.g. refs. [4-7]) or dispersive-type lines, which rely on pulse sharpening and dispersion to break up a unipolar excitation into a sequence of solitons, electrically observed as an RF packet [8-10]. Notably, a dispersive-type NLTL was previously demonstrated by E. Schrock *et al.* [11] on a printed circuit board (PCB), and only required 1-3 kV to generate a high power RF output at 100s of MHz. However, one drawback to this PCB-based NLTL, which is characteristic to virtually all NLTLs that have been experimentally realized to-date, is that the RF output typically features short duration. Here we report the development of a simple high voltage (HV) pulsed power driver, capable of delivering pulses at multi-MHz pulse repetition frequency, with the intention of significantly increasing the RF output duty cycle from a NLTL HPM source.

II. Experimental Results

In this section, we describe two solid-state pulse generators and their performance characteristics. The first pulse generator uses a single 3.3 kV MOSFET in a hard-switched configuration, while the second pulse generator is an all-solid-state 4-stage Marx generator. Experimentally measured voltage waveforms for both pulse generators tested into a 50 Ohm dummy load are reported. Finally, the single-switch pulse generator is used to excite a PCB-based NLTL and RF generation at an HV pulse repetition frequency of 100 kHz is reported.

A. Solid-State Single Switch Pulse Generator

The solid-state single switch pulse generator developed here used a single GeneSiC Semiconductor G2R120MT33J SiC MOSFET (3.3 kV blocking voltage, 100 A (pulsed) current rating), in a high-side, hard-switched configuration (see Fig. 1). The gating of the MOSFET is controlled by a TTL pulse that is isolated through an optocoupler which brings the low-voltage referenced TTL pulse to drain-referenced floating potential, where the signal then controls a floating gate driver. Drain-referenced floating power is provided by a single 1 Watt, 12 V to 15 V isolated DC-DC converter (3 kV isolation). A parallel

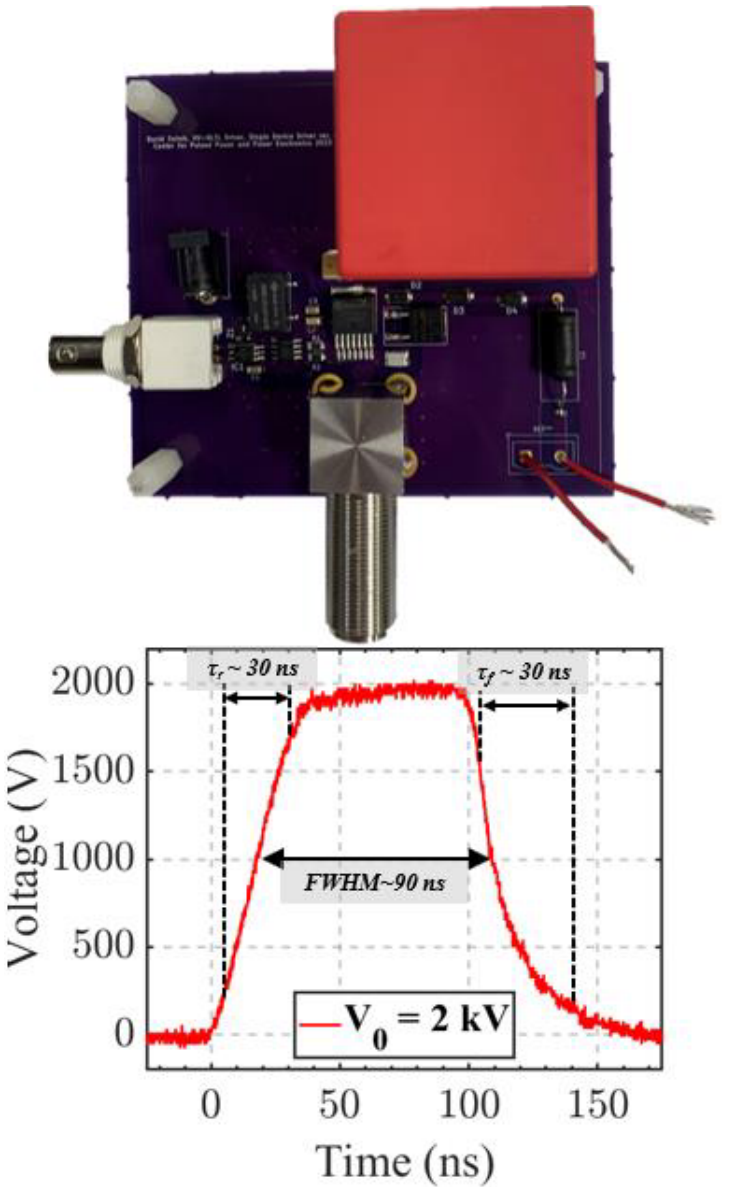

Fig. 1. (top) Fabricated single-switch HV pulsed power driver. (bottom) Example 100 ns, ~2 kV HV pulse produced by the single-switch driver tested into a 50 Ohm dummy load.

combination of HV ceramic and HV film capacitors are charged from an external power through a charging inductor and stack of series diodes, which were employed to protect the HV power supply. Note that the HV supply available for these tests had a 2 kV upper limit, which restricted the voltage range for the testing that is reported here.

The single switch driver was experimentally observed to provide a ~30 ns risetime for pulses up to 2 kV (power supply limited) and displayed consistent, stable performance for varying pulse width when tested into a 50 Ohm dummy load. Overall, this device demonstrated high stability under varying conditions in a low-complexity package. However, this topology requires high prime voltage and is fundamentally limited by the availability of devices rated for the necessary voltage, current, rise times, and power dissipation of interest to this effort. In addition, this topology also features very limited waveform flexibility capability when compared to more sophisticated pulse generator topologies [12, 13].

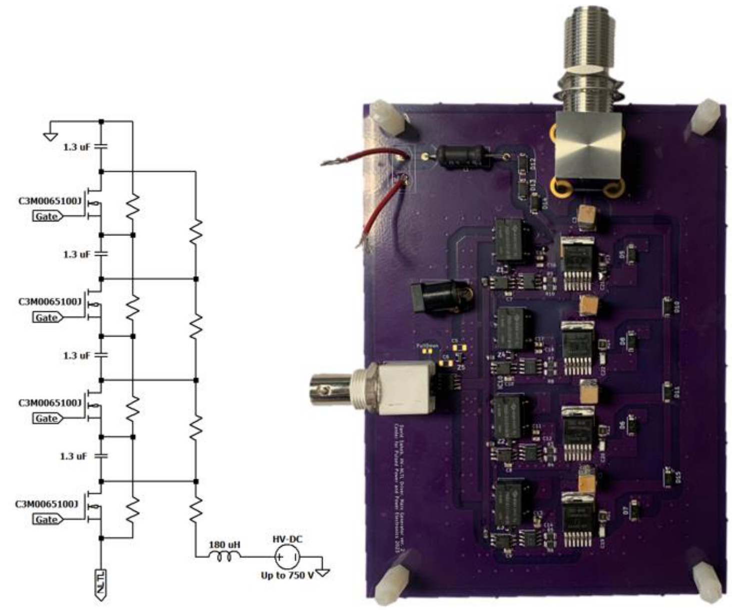

Fig. 2. (Left) Schematic of solid-state Marx generator. (Right) Fabricated solid-state Marx generator.

B. *Solid-State Marx Generator*

As second candidate NLTL driver, a solid-state Marx generator (see review of Zhong *et al*. [14]) was also developed. This pulse generator was a 4-stage device employing a single, C3M0065100J Wolfspeeed SiC MOSFET (1 kV blocking voltage, 90 A (pulsed) current rating) at each stage (i.e. four MOSFETs total). For operation, the Marx capacitors are charged to a maximum of 750 V in parallel, then discharged through the MOSFETs to the load. 1 MΩ charging resistors are used to provide stage-to-stage isolation during operation. Similar to the single-switch HV pulse driver, floating power and opto-isolators are used to gate each MOSFET at the local, floating drain-referenced potential.

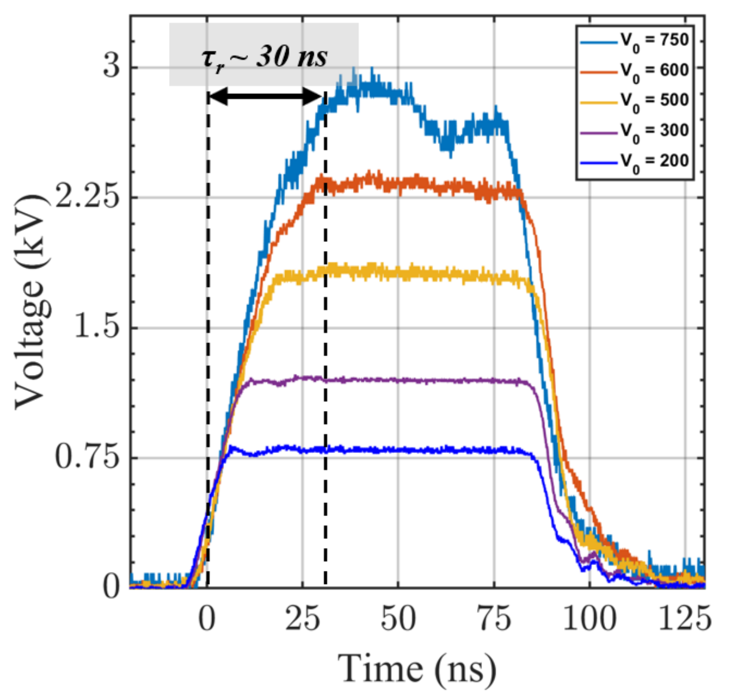

Fig. 3. Experimentally measured output of the 4-stage solid-state marx generator for varying charge voltage (V_0), tested into a 50 Ohm dummy load.

Experimentally measured Marx generator output voltages at varying charge voltages are shown in Fig. 3. For charging voltages up to 600 V (~2.3 kV output pulsed voltage), reasonable pulse characteristics were observed. At a higher charge voltage of 750 V (~2.8 kV output pulsed voltage), the output waveform features a non-negligible dip and generally less desirable pulse characteristics, which is the focus of ongoing investigation.

Compared to the single-switch pulse generator, the solid-state Marx generator is a considerably more complex device, requiring more components and overall, more complex design. In exchange for this additional complexity, the Marx generator requires lower charging voltage, which enables the use of lower voltage switching devices. Further, with additional design, the marx generator topology would also allow for flexible waveform capability (e.g. [12, 13]), which may be especially valuable for driving an NLTL HPM source.

C. Operation with an NLTL Load

A discrete-element NLTL was developed to be tested with the previously discussed HV pulse generators, see Fig. 4. This NLTL is identical to the earlier design of E. Schrock *et al.* [11], with the exception that slightly larger ferrite cores were used, which resulted in higher series inductance. The NLTL is only briefly reported here, and the reader is referred to [11] for a more complete description of the NLTL.

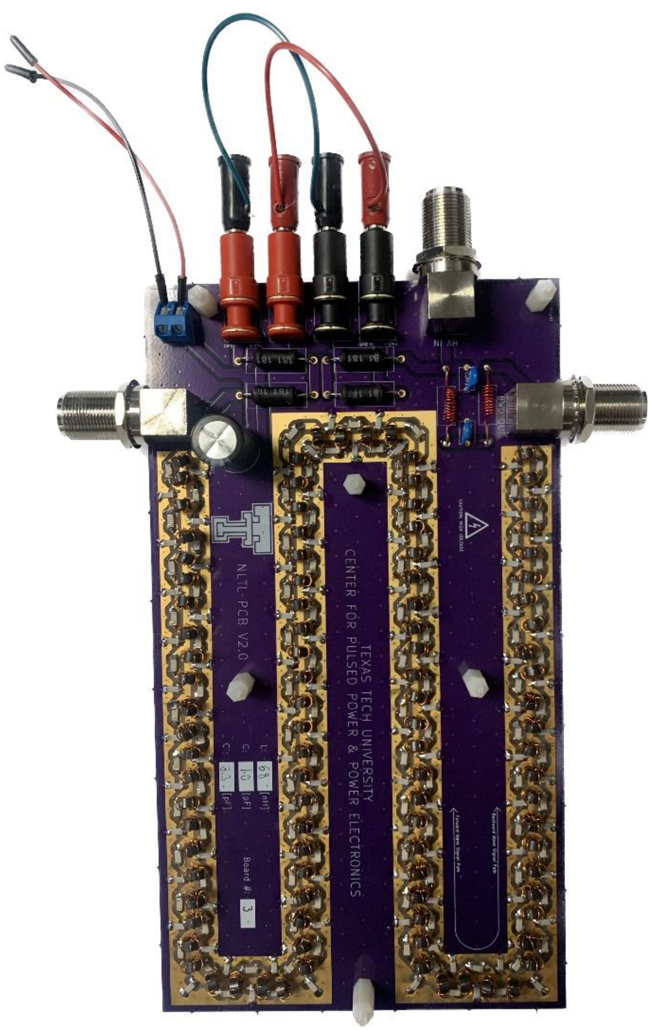

Fig. 4. Fabricated NLTL used to test the HV pulse generators and demonstrate RF output.

The NLTL design utilizes a 100-stage sequence of parallel capacitors (18 pF parallel to ground) and series saturable inductors (~170 nH, unsaturated), which were wound on Fair Rite material 43 toroid cores (NiZn). A second set of capacitors (3.3 pF) are used to link the capacitor-inductor node between every other stage. The NLTL is initially biased by a DC current that flows through the entire NLTL, thus giving an initial bias to the inductors. The bias current source is protected from the HV excitation by an RF choke. The input HV excitation is also passed through a low pass filter, which allows the HV excitation to pass to the NLTL, but blocks any RF from feeding back into the pulsed power driver. The output of the NLTL was taken at the forward port, measured using an HV Barth Electronics attenuator, which also served as a 50 Ohm termination.

Owing to its superior stability and pulse characteristics, the single-switch pulse generator was selected to drive the NLTL. Figure 5 gives an example waveform, measured for a 2 kV excitation, and 600 mA bias current. At the output of the forward-wave port, and RF pulse is observed with a maximum peak-to-peak voltage of ~800 V (~10 kW). Figure 5 also shows the FFT of the output waveform, showing a clear peak at 141.6 MHz, which corresponds to the temporal period of the oscillations in the output voltage. Notably, the duration of the RF output was only a few tens of nanoseconds, which is consistent with earlier works.

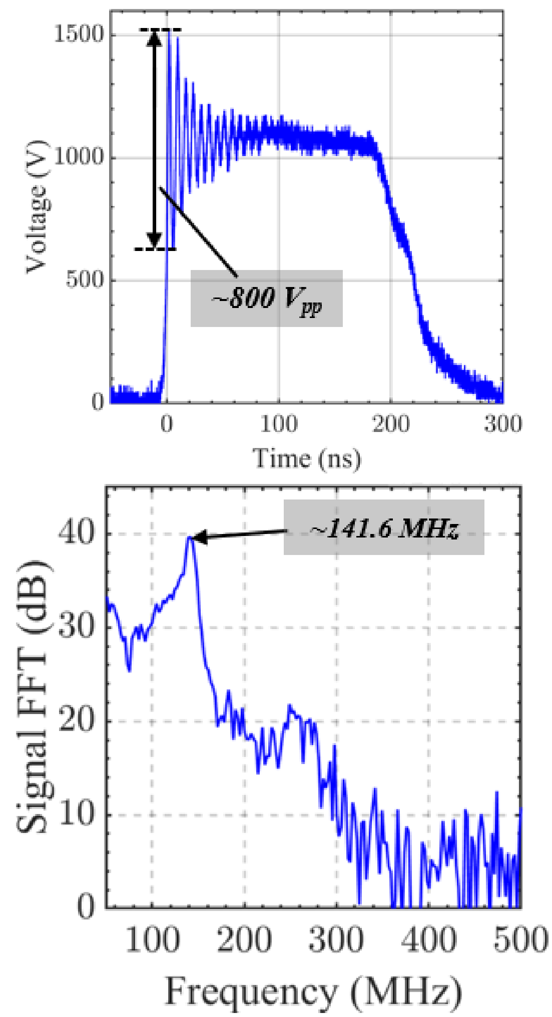

Fig. 5. (top) Measured output voltage from the NLTL for a 2 kV input and 600 mA bias current. (bottom) FFT of the output voltage showing a strong peak at ~141.6 MHz..

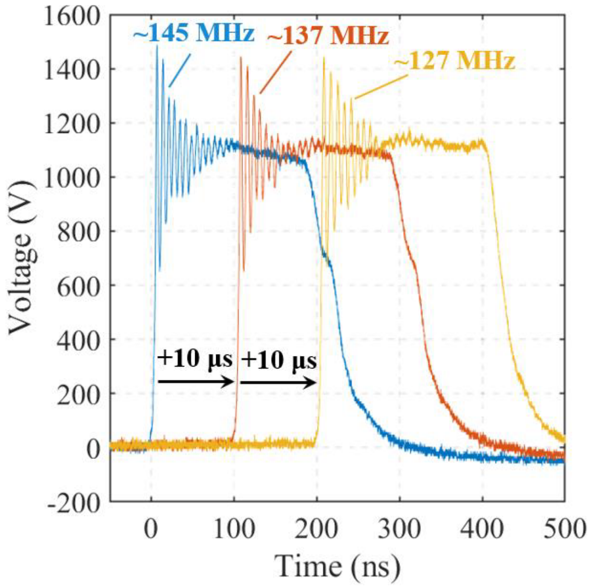

Fig. 5. Measured NLTL output resulting from consecutive HV pulses (100 kHz PRF, 1.8 kV applied HV pulse amplitude, 800 mA bias).

To test the ability of the driver and NLTL to operate at higher pulse repetition frequency (PRF) and higher RF output duty cycle, a short 100 kHz PRF burst of 1.8 kV pulses were used to drive the NLTL (800 mA bias), see Fig. 5. Though RF generation was observed for each pulse, it was observed that the output frequency shifted ~10 MHz per pulse for the first three pulses, which is believed to be the result of the external bias not fully resetting the saturable inductors prior to the next excitation. In addition, initial attempts to achieve RF output for higher PRFs at MHz frequencies failed to exhibit RF output for subsequent pulses, which is again believed to be a limitation of the bias circuit. It is noted that in earlier work a gyro-NLTL was demonstrated to maintain RF output even at PRFs up to 65 MHz [15].

III. Conclusion

Two high voltage pulse generators were developed and tested into a 50 Ohm dummy load. The first pulse generator was a single switch device, which used 3.3 kV MOSFET in a hard-switching configuration. Initial tests into a 50 Ohm dummy load with this device showed excellent, stable pulse characteristics up to 2 kV, which was limited by the available HV supply. A second, more complex 4-stage, all-solid-state Marx generator was also developed and tested into a 50 Ohm dummy load. This device featured reasonable pulse characteristics up to ~2 kV output voltage, but sporadic behavior was observed at higher output voltage. The simple, single switch pulse generator was tested into a PCB-based discrete element NLTL, which showed more than 10 kW RF output at ~140 MHz. Additional tests at a 100 kHz PRF demonstrated the ability to generate RF, at least in the early pulses.

Future work will iterate on the solid-state marx generator design to improve pulse characteristics and allow for high average power performance via the use of charging diodes for stage-to-stage isolation. In addition, flexible waveform capability similar to refs. [12, 13] will be explored, and finally, a more comprehensive characterization the PRF performance limits of the NLTL will be completed.

IV. Acknowledgments

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