GaN-HEMT in Gate-Boosted Operation as Closing Switch in a Blumlein Generator With Adjustable Pulselength

Martin Sack , Dennis Herzog, and Georg Müller

***Abstract*—Capacitively coupled gate-boosted operation allows for a fast turn-on of a GaN HEMT. However, as part of the gate drive circuit, a voltage source exhibiting a short rise time is crucial. A three-stage Marx circuit based on avalanche transistors acting as fast closing switches has been employed as a voltage source for the driver. It has been operated at a stage voltage of approximately 280 V. The Marx circuit is connected to the capacitor inserted for compensating the inductance in series to the gate. It forms a capacitive voltage divider in combination with the gate's voltage-dependent input capacitance, limiting the gate-source voltage. The circuit has been set up and tested successfully connected to an essentially resistive load up to a drain-source voltage of 600 V at the GaN-HEMT. With a load of 50 Ω, when operating the device at 600 V a fall time of 0.6 ns was measured for the drain-source voltage. A test with a load impedance of 16.6 Ω resulted in a respective fall time of 0.7 ns. For the generation of fast-rising voltage pulses, the closing switch has been implemented into a Blumlein generator connected to a matched load. The use of one switch at the end of each of the two transmission lines of the Blumlein configuration allows for a control of the polarity and the length of the voltage pulse applied to the matched resistive load connected to the generator. With a delay line in Blumlein configuration for the generation of pulses of 10 ns pulselength the generation of pulses having an adjustable pulselength of between 1 and 5 ns has been shown for positive and negative polarity of the output pulse.**

***Index Terms*—Avalanche transistor, Blumlein generator, GaN HEMT, gate-boosted operation, Marx generator.**

I. Introduction

RECENT work on driver circuits for power semiconductors operating as closing switches in pulsed-power circuits deal with the generation of a fast-rising voltage across the input capacitance of the power semiconductor. A commercially available thyristor can be turned on within significantly less than 1 ns using the impact ionization wave triggering mode [1], [2]. It requires a fast rise of the trigger voltage across the thyristor to more than twice of the thyristor's breaktown voltage at a gradient of more than 1 kV/ns. Thereby, the capacitance of the thyristor needs to be charged. As a driver for this application, different circuits are under investigation, comprising a spiral generator [3], a pulse generator based on semiconductor opening switch (SOS) diodes [4], and MOSFETs in gate-boosted operation [5].

Capacitively coupled gate-boosted operation enables a MOSFET or insulated-gate bipolar transistor (IGBT) to turn on with a much faster rise time than listed in the data sheet [6]. Thereby, the gate boosting circuit comprises a capacitor in series to the parasitic inductance in the gate circuit and, hence, compensates the inductance such that the resonance frequency of this circuit is raised significantly resulting in a faster turn-on of the MOSFET or IGBT switch. The gate driver needs to provide the gate charge required for turning on the semiconductor switch. An extra voltage is needed to charge the additional series capacitor, which must be supplied by the driver in addition to the gate-to-source voltage.

The described method of capacitively coupled gate-boosting has been successfully demonstrated at Karlsruhe Institute of Technology for IGBTs back in 2016 [7]. With an appropriate series capacitor and a driving voltage of 80 V a rise time of the collector current of 49 ns (10%–90%) has been measured for an IGBT, which exhibits under the operating conditions listed in its data sheet a current rise time of 400 ns, resulting in a decrease in rise time by a factor of approximately 8. The initial motivation for the research on capacitively coupled gate boosting was the need for a large number of fast but affordable semiconductor switches for the setup of a high-voltage arbitrary waveform generator able to deliver a peak voltage of up to 120 kV. The gate-boosted operation allowed the selection of slower and, hence cheaper IGBTs and speed them up by means of gate-boosted operation.

In the recent years, SiC-MOSFETs evolved as an alternative for IGBTs exhibiting fast rise times in the order of approximately 15 ns at drain-source voltages of significantly above 1 kV. Moreover, GaN-HEMTs became commercially available having rise times of less than 5 ns. However, the GaN-HEMTs are currently commercially available for a maximum drain-source voltage of 650 V only. In order to turn on a SiC-MOSFET almost as fast as a GaN-HEMT, a driver based on a half-bridge configuration equipped with GaN-HEMTs and featuring capacitively coupled gate-boosting at a driving voltage of 150 V has been set up and operated successfully [8]. At a drain-source voltage of 1000 V at the SiC-MOSFET a rise time of the voltage across the resistive load of 3.3 ns has been measured. However, an increase of the driving voltage in

The authors are with Karlsruhe Institute of Technology, Institute for Pulsed Power and Microwave Technology, 76131 Karlsruhe, Germany (e-mail: martin.sack@kit.edu).

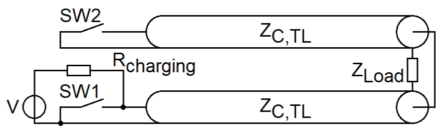


Fig. 1. Blumlein Generator with two closing switches and charging circuit.

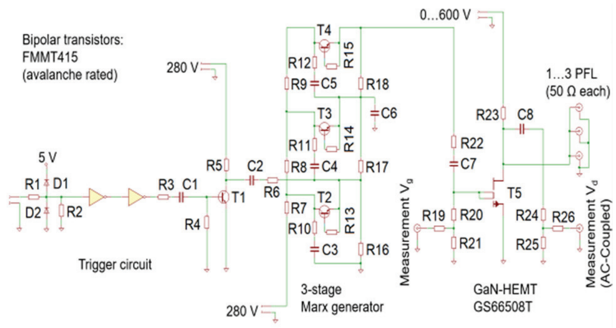


Fig. 2. Simplified schematic comprising the trigger circuit, the three-stage Marx generator, and the GaN HEMT.

combination with a smaller series capacitor in the gate circuit did not result in a faster rise time. So, if a driver is too slow or not capable of providing sufficient power for charging the gate fast enough, it may limit the fall time of the gate voltage in the course of the turn-on process.

In order to push such limitations toward a faster turn-on, a novel driver circuit based on a Marx configuration to operate a GaN-HEMT as a closing switch has been set up and tested. The Marx generator has been set up using bipolar transistors operated in avalanche mode as closing switches.

A bipolar transistor operating in avalanche mode is known to function as a fast-closing switch at a voltage level of up to a few hundred volts [9]. However, the lifetime of such a switch is highly dependent on conduction time and losses [10]. Both must be kept sufficiently low to avoid a significant reduction in lifetime. Recently, a two-stage Marx circuit using avalanche transistors as switches has been combined with a GaN HEMT, so that the Marx circuit acts as a driver for the GaN HEMT in a source-follower configuration [11]. As expected, a reduction in the circuit's output impedance was demonstrated. However, to operate a Blumlein configuration, a switch connected to ground potential is required. For this reason, the combination of a Marx circuit as a driver for a GaN-HEMT switch in gate-boosted mode has been investigated.

The switch has been implemented into a Blumlein generator to generate rectangular pulses [12]. A Blumlein generator comprises two transmission lines of equal length and characteristic impedance, and a closing switch, as shown in Fig. 1, initially neglecting the switch SW2. To avoid load reflections, the load impedance Z_{load} must be matched to twice the characteristic impedance of each transmission line $Z_{C,\text{TL}}$. The pulselength is twice the propagation delay of each transmission line. If a second closing switch (SW2 in Fig. 1) is added to the end of the second transmission line, the pulselength and the polarity of the output pulse can be controlled by varying the delay time between the closing of both switches and their order of closing. Thereby, the maximum pulselength is still limited by the length of the transmission lines.

II. Marx Circuit as Driver for a GaN HEMT in Gate-Boosted Operation

A. Circuit Description

Fig. 2 shows a simplified schematic of a Marx circuit connected to the gate of a GaN HEMT (type GS66508T [13]) as a driver. For the initial experiments presented later in this article, a three-stage arrangement was chosen for the Marx generator. It comprises the transistors $T2$, $T3$, and, $T4$ according to Fig. 2. Since the pulse voltage is only required during the gate charging process, a pulse circuit can advantageously replace a half-bridge configuration. Due to the inherent voltage multiplication of the Marx circuit, the charger can be designed for a lower voltage than for a half-bridge configuration with the same output voltage. Please note that the aim of this experimental circuit is to achieve a fast turn-on with a short conduction time of the GaN HEMT only. For a longer on-time of the GaN HEMT, an additional switchable dc supply path to the gate would be needed. A bipolar transistor specified for avalanche operation has been selected as the switch [10].

Capacitor $C7$ has been inserted to reduce the capacitance of the gate circuit in order to increase its resonant frequency. It forms together with the input capacitance of the GaN-HEMT a capacitive divider [8]. The increased driving voltage delivered by the Marx circuit compensates for this divider ratio such that after the gate charging process a usual gate-source voltage of approximately 6 V is reached. However, the GaN-HEMT's input capacitance depends both on the gate-source voltage V_{GS} and drain-source voltage V_{DS}. Therefore, the design is based on the gate charge required to render the GaN HEMT well conductive, which is given in the data sheet [13]. The value of the capacitor $C7$ has been matched to the peak voltage of the Marx circuit such that the charge stored in capacitor $C7$ is equal to the charge that must be injected into the gate to turn on the GaN HEMT according to its datasheet [13]. The charge to be applied to the gate depends on the drain-to-source voltage. For the design, a value for the gate charge valid for $V_{\text{DS}} = 400$ V has been assumed. Thereby, a discharge of the input capacitance via the current path through the resistors $R19$, $R20$, and $R21$ in parallel to the gate has been neglected due to the short charging time. The Marx circuit was designed to be electrically short. Damping resistors ($R10$, $R11$, $R12$, and $R22$) have been added to prevent the circuit from ringing.

$C7$ and $R22$ were constructed as a combined series and parallel arrangement of 3×3 surface-mounted devices of equal values, so that the combination has the same impedance as one element. The width of this arrangement is almost equal to the width of the GaN-HEMT's package resembling together with adjacent ground planes the configuration of a microstrip line.

B. Trigger Process

Initially, the capacitors of the Marx circuit are charged to approximately 280 V. An external TTL level trigger signal is applied to the trigger input. The avalanche transistor $T1$ is triggered by injecting a current pulse into its base terminal and acts as a booster for the trigger signal. The avalanche transistors of the Marx circuit are triggered by applying an overvoltage well above their breakdown voltage. A pulse of negative polarity is applied to the output of the first stage via capacitor $C2$, causing its switch to close due to this additional voltage applied to it in addition to the charging voltage of the stage capacitor $C3$. The switches of the other stages close because of the transient overvoltage applied to them, while charging the stray capacitance versus ground potential, according to the well-known ignition process of a Marx circuit [12]. The capacitor $C6$ facilitates the switch-on process of the second stage by increasing the capacitance to ground. It also acts much like a peaking capacitor. It connects the ground terminal of the third stage of the Marx circuit directly to ground potential via a short current path having a low inductance. The series arrangement of $C6$ together with the capacitor of the third stage ($C5$) thus acts as a peaking stage, with the avalanche transistor of the third stage acting as a peaking switch. The loop of this circuit has been kept small to achieve low inductance. The peaking stage provides a fast rising pulse to the gate of the GaN HEMT via $C7$ and $R22$. It should be noted that the input capacitance of the GaN HEMT GS66508T is according to the data sheet 242 pF [13], much lower than the 1390 pF input capacitance of the SiC MOSFET C3M0075120J [14] used in the previous gate-boosted arrangement according to [12]. In addition, a GaN HEMT requires a lower gate voltage to turn on. $C7$ can therefore be set to a lower value than for a SiC MOSFET at the same drive voltage. For the purposes of the test setup, $C7$ was set to 10 pF.

C. Voltage Measurements and Connection to the Load

For the experiments, the voltages at the gate and drain of the GaN HEMT were measured against ground potential. The signal path for measuring the gate voltage V_g consists of a 50 Ω termination (combination of $R19$ and $R20$), a coaxial cable for connection to the oscilloscope and two 6 dB attenuators. The drain voltage V_d is measured via a fast resistive divider having a low impedance, formed by $R24$ (250 Ω) and $R25$ (2.5 Ω). The capacitor $C8$ in series with the divider blocks the dc voltage applied before the pulse. Voltage measurements were made using an oscilloscope with a bandwidth of 2 GHz and a sampling rate of 5 GS/s.

The GS66508T GaN HEMT used has a rated voltage of 650 V and a rated continuous current of 30 A. To enable operation close to these limits, the characteristic impedance of the load is chosen to be 16.6 Ω, which can be set up as a parallel connection of three 50 Ω cables. The cables are connected using subminiature version A (SMA) connectors. Fig. 3 shows a photograph of the GaN HEMT and the circuit components required for the measurements.

III. Test of a GaN-HEMT as Fast Closing Switch

A. 50 Ω Cable as Pulse Forming Line

The closing switch has been initially tested with an open 50 Ω cable of 1 m length as a load. The open cable as a load causes a traveling wave oscillation with a period T equal

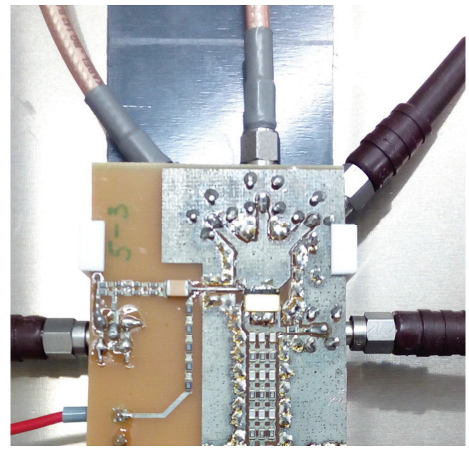
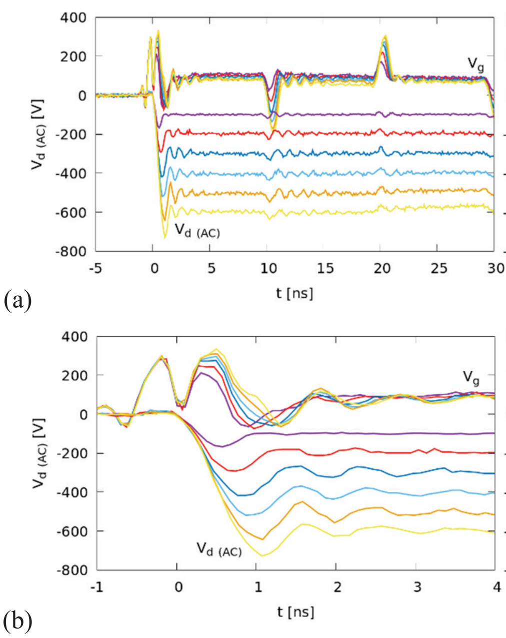


Fig. 3. Detail of the printed circuit board showing the GaN HEMT and the components for measurements of gate voltage V_g and drain voltage V_d.



(a)

(b)

Fig. 4. Measurements of V_g and V_d with an open 50 Ω cable as load: (a) overview and (b) rise of the pulse in detail.

to four times the propagation delay of the cable, giving $T = 4 \times 5$ ns $= 20$ ns. The current through the switch reverses every 10 ns. Thereby, the GaN HEMT conducts the current in both directions. The load was connected to the center SMA connector.

The cable was charged to voltages between 100 and 600 V. The measurement results are shown in Fig. 4. When in the course of the turn-on process the gate capacitance of the GaN HEMT is charged, the voltage at the gate V_g shows an overshoot to a peak of about 16 V before settling to a gate voltage of about 6 V. While the part of the curve before $t = 0$ including the mentioned peak is according to Fig. 4 independent of the charging voltage of the cable, the amplitude of the peak just after $t = 0$ varies with the charging voltage and, hence, with the current through the switch. The signal of the gate voltage exhibits additional peaks approximately every

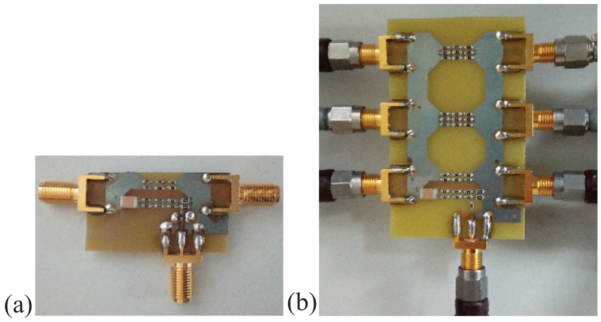


Fig. 5. Printed circuit boards for Blumlein arrangement for (a) Z_C = 50 Ω and (b) Z_C = 16.6 Ω. In the pictures, the pulse-forming lines are connected on the left and right, the downward-facing connection is used for voltage measurement.

10 ns after the initial peak at turn-on. Thereby, the amplitude of the peaks increases with the charging voltage and the polarity changes with the current through the switch.

The current paths through the gate and the drain share a common connection between the source terminal on the die and the ground plane. Although the inductance of the source connection inside the package is only small and the terminal of the GaN-HEMT's package is connected via short path to the ground plane, there will be some voltage drop across this impedance due to the drain current and the gate current while charging the gate capacitance. The peaks visible in the signal for the gate voltage V_g, which vary with the charging voltage of the cable and repeat with alternating polarity every 10 ns correspond to a voltage drop across the inductive component of the impedance in the GaN-HEMT's source path.

The peak in the gate voltage signal V_g before $t = 0$, which is independent of the charging voltage applied to the cable, corresponds to a voltage drop across mostly the inductive component of the impedance in the gate path between the gate voltage measurement position and the gate on die, and additionally the impedance in the source path to ground.

In the test-setup, V_g is measured a few millimeters apart from the gate-terminal of the package. This leads to a slight propagation delay until the signal reaches the gate on die. Moreover, the transistor's input capacitance needs to be charged up to the threshold voltage $V_{\mathrm{gs(th)}}$ before the transistor starts to switch through. Therefore, in Fig. 4 the signal V_d exhibits a delay versus the rise of V_g.

The change of the measurement signal $V_{d\mathrm{(ac)}}$ in the course of the turn-on process resembles the charging voltage of the cable. Unlike the gate voltage signal, the drain voltage signal shows almost no influence from the current flow. In particular, during the moments of polarity reversal of the drain current, the signal is not significantly disturbed.

According to the measurement, the drain voltage $V_{d\mathrm{(ac)}}$ falls from 90% to 10% of its initial value within 0.6 ns, when the curve measured at 600 V charging voltage is considered.

During the pulse the gate voltage V_g decays slightly due to a continuous discharge of the GaN-HEMT's input capacitance.

B. Blumlein Configuration With 50 Ω *Pulse Forming Line*

A Blumlein configuration was set up using two 50 Ω cables of 1 m length as pulse forming lines. The cables are connected

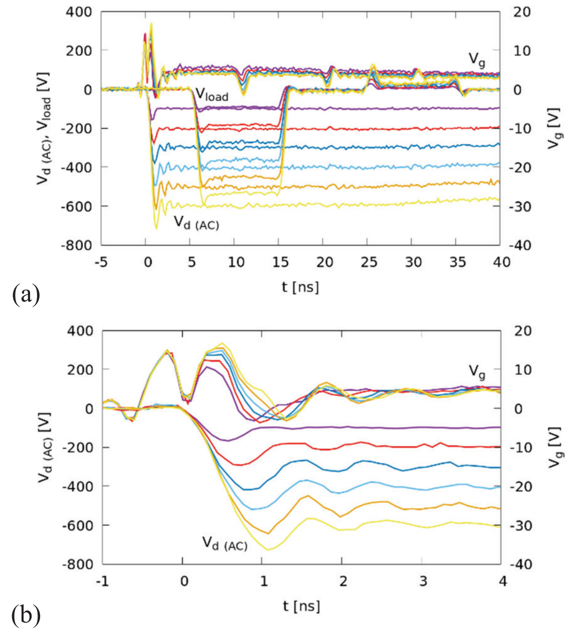


Fig. 6. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 50 Ω pulse forming lines: (a) overview and (b) rise of the pulse in detail.

via SMA connectors and a printed circuit board, which also carries the 100 Ω terminating resistor. The resistor contains a resistive divider for voltage measurements. Fig. 5(a) shows this arrangement and Fig. 6 the measurement results. For the measurements, the charging voltage was varied between 100 and 600 V. At a charging voltage of 600 V, the voltage across the switch falls from 90% to 10% of its initial value within 0.6 ns. The rise time at the load impedance of the Blumlein configuration was measured to be 0.9 ns at 600 V charging voltage. The square wave pulse has a pulsewidth of 10 ns.

There is a slight mismatch in the load impedance. Therefore, the amplitude of the output voltage of the Blumlein generator is lower than the charging voltage and a reflection of the pulse with opposite polarity appears 25 ns after closing the switch.

C. Blumlein Configuration With 16.6 Ω *Pulse Forming Line*

A pulse forming line with a characteristic impedance of 16.6 Ω was assembled as a parallel arrangement of three 50 Ω cables of 1 m length. The cables are connected via a printed circuit board, which also carries the load impedance of 33.2 Ω including a resistive divider for measurements. Fig. 5(b) shows a photograph of the setup and Fig. 7 the measurement results. The charging voltage was varied between 100 and 600 V. At a charging voltage of 600 V, the drain voltage drops from 90% to 10% within 0.7 ns, while the voltage across the load rises within 0.8 ns.

D. Repetitive Operation

As an initial test of the device in repetitive operation, the Blumlein configuration with 16.6 Ω pulse shaping line was operated at a charging voltage of 600 V and a pulse repetition rate of 1.4 Hz for a duration of 6.25 h, resulting in approximately 33000 pulses. A superposition of the first

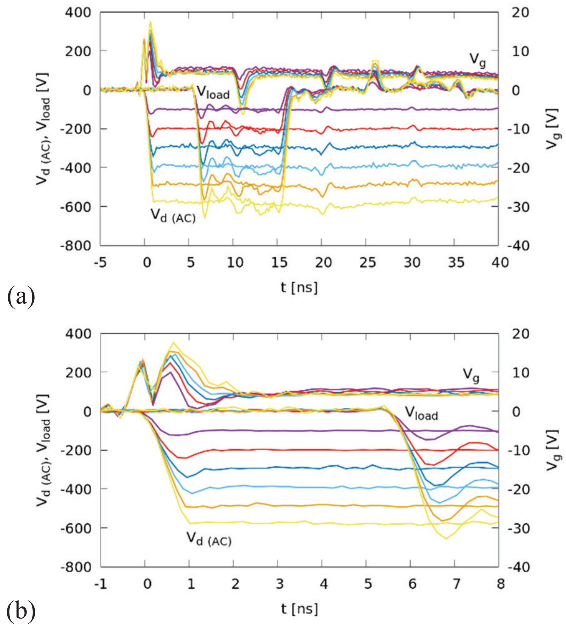


Fig. 7. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 16.6 Ω pulse forming lines: (a) overview and (b) rise of the pulse in detail.

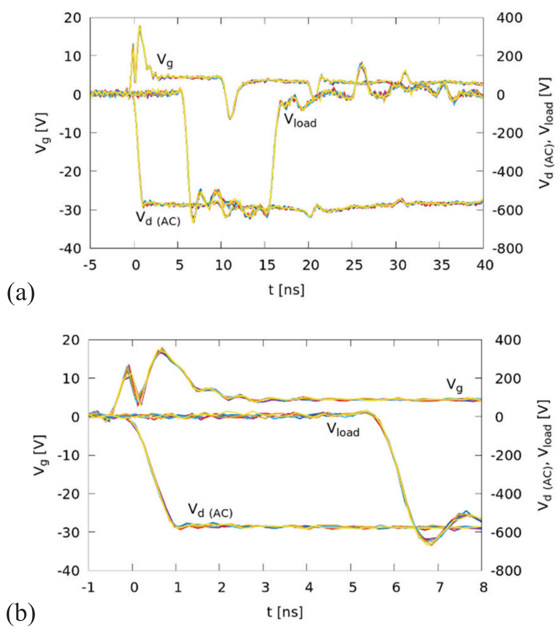


Fig. 8. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 16.6 Ω pulse forming lines, repetitive operation at 1.4 Hz: (a) overview and (b) rise of the pulse in detail.

and last pulse shape of the test together with four randomly selected additional pulse shapes shows no deviation in the pulse shapes (see Fig. 8).

IV. Blumlein Generator Featuring Two Closing Switches

A. Arrangement of Two Closing Switches

A Blumlein Generator equipped with two closing switches, one at the end of each transmission line, has been assembled.

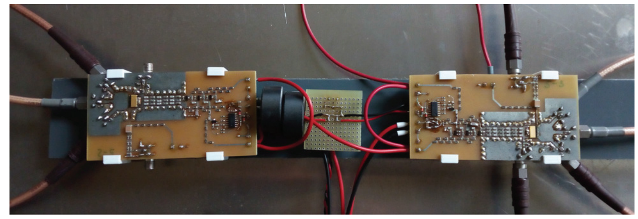


Fig. 9. Arrangement of two closing switches featuring GaN HEMTs in gate-boosted operation.

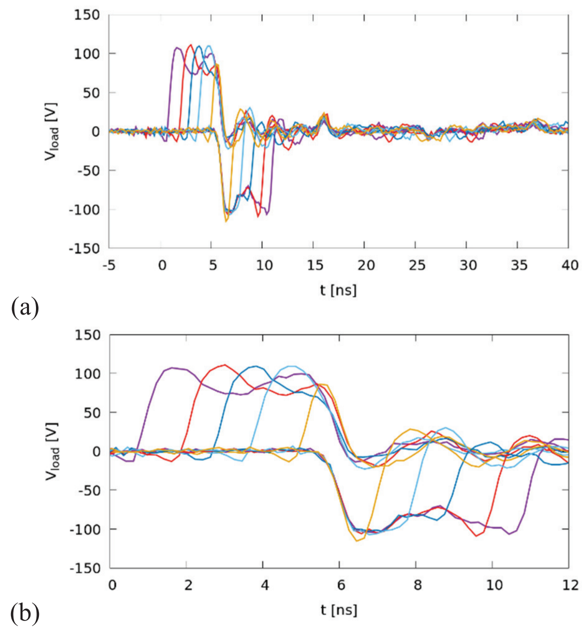


Fig. 10. Measurements of V_{load} at the matched load of a Blumlein generator with a two-switch arrangement operated at 100 V charging voltage: (a) overview and (b) pulses in detail.

Fig. 9 shows the arrangement of the two closing switches to set up the Blumlein generator, allowing easy adjustment of pulselength and polarity. The switch modules are mounted so that their inputs for the auxiliary power supplies and the trigger pulse are adjacent. Both modules are connected in parallel to the same auxiliary power supplies. The module on the left in Fig. 9 is connected to the end of the floating cable of the Blumlein generator. It is therefore transiently isolated from the other module, the auxiliary supplies, and the trigger generator by two ferrite cores acting as a current-compensated choke that blocks the pulse as a common-mode signal. Moreover, seven ferrite cores have been applied to each of the six transmission lines, acting as current-compensated chokes to block common-mode signals.

The perforated grid board between the two switch modules contains two adjustable *RC* low-pass filters acting as delay elements and allowing additional delay between the main trigger signal fed to this board and the signals at the trigger inputs of the two switch modules.

B. Variation of Pulselength and Polarity

Figs. 10 and 11 show the voltage V_{load} measured across the matched load at the output of the Blumlein generator.

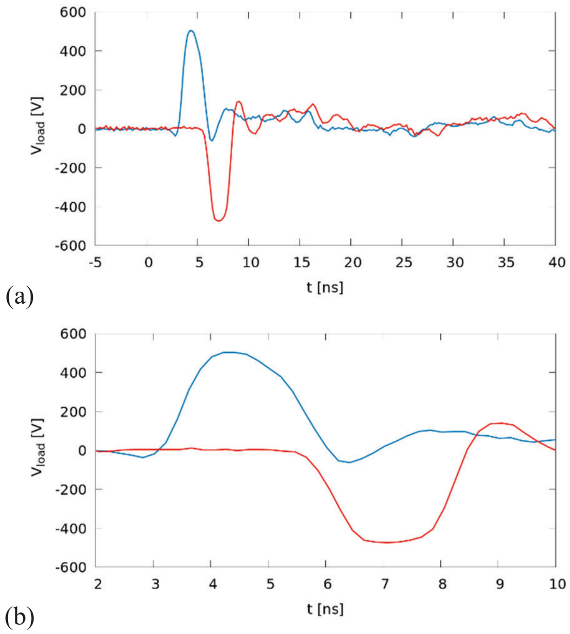


Fig. 11. Measurements of V_{load} at the matched load of a Blumlein generator with a two-switch arrangement operated at 600 V charging voltage, 2 ns pulselength, and varying pulse polarity: (a) overview and (b) pulses in detail.

Different settings for the delay times have been applied to vary the pulselength and the pulse polarity. Thereby, one of both delay elements was kept at minimum delay, while the delay of the other element was varied such that pulses with a length between 1 and 5 ns were obtained. When closing the switch inside the module on ground-side first, a negative output pulse is generated, and vice versa a positive pulse.

Fig. 10 shows the output voltage of the Blumlein generator for a charging voltage of 100 V. Different delay times between the closing of the switches were chosen in the range between −5 and 5 ns (measured at half amplitude), staggered by about 1 ns. An enlarged view of the curves in Fig. 10(b) shows that the rise and fall times measured between 10% and 90% of the amplitude are significantly less than 1 ns. The trigger signal for the oscilloscope was the gate signal from the ground-side switch shown on the right in Fig. 9. The falling edges of the negative pulses are therefore precisely aligned.

Fig. 11 shows the output voltage of the Blumlein generator for a charging voltage of 600 V. The pulse amplitudes are with approximately 500 V smaller than expected. A rectangular pulse of 8 ns length and approximately 100 V follows the desired pulse, which seems to be caused by an imperfect matching of impedances. Further work will be devoted to this detail.

V. Conclusion

A gate-boosting circuit for a GaN HEMT with a three-stage Marx configuration has been set up and tested in a Blumlein configuration. Pulse rise times of less than 1 ns were achieved for characteristic impedances of the pulse forming lines of 50 and 16.6 Ω. In a Blumlein configuration with two closing switches, the pulselength and polarity of the output pulse have been varied by appropriately adjusting the delay between the closing of the two switches. This resulted in output pulse rise and fall times of less than 1 ns. Future work will be devoted to further tests and improvements of the circuit.

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