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Contactless Terahertz Sensing of Ultrafast Switching in Marx Generator Based on Avalanche Transistors

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Abstract—In this paper, we have studied the temporal evolution of switching for each stage of the Marx generator with picosecond temporal and millimeter spatial resolutions employing terahertz measurements. The Marx circuit utilizes collapsing-field-domain (CFD)-based avalanche switches, which are formed in a bipolar GaAs structure and result in the picosecond speed of powerful carrier generation and electrical switching. The application of the CFD-based avalanche switches emitting mm-wave pulsed radiation in the Marx generator provides a unique opportunity to accurately track the switching instants for each of the circuit stages with a picosecond time precision. The collapsing domains cause the sub-THz pulses radiated by each of the avalanche switches, and the same domains generate the electron-hole plasma thus causing simultaneously the electrical switching. In this work, we report the direct measurements of the switching instants for each of the four stages Marx generator and suggest an interpretation of non-trivial experimental results.

Index Terms—Marx generators, avalanche breakdown, solid-state terahertz (THz) pulsed source.

I. INTRODUCTION

Marx circuits are typically used to generate high-voltage pulses [1], but can also be used to significantly increase the peak current across a load [2] and include a broad variety of applications [3]–[5]. They utilize solid-state switches [6] where the switching mechanism is triggered by a voltage, exceeding the threshold, applied between the anode and cathode, or, alternatively, by the \( \frac{dV}{dt} \) effect, when the turn-on is initiated by a sharp voltage ramp. The same physics also works in avalanche transistors [2].

One hypothesis regarding the operation of the Marx generator is that switching happens simultaneously in all stages. However, this claim is difficult to experimentally verify, at least for high-speed ns- and sub-ns switching times, since high-speed oscilloscope probing of individual switching events is complicated by spatially and temporally varying potentials on the ground plane. Alternatively, free space microwave pulsed emission can be used for the switching instants detection but it is very challenging to attribute the pulses to a particular transistor: the characteristic wavelengths of emitted ultrawideband microwave pulses (≈ few dm) typically exceed the size of the entire circuit board, further confounding source localization.

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II. EXPERIMENTAL SETUP AND DEVICE UNDER TEST

Fig. 1 shows a diagram of a pulsed 200 GHz source consisting of mm-size on-chip bow-tie antenna (\( A_i \)) (a) and CFD-avalanching, GaAs transistor (b) [7]. The equivalent circuit of the Marx generator and its printed circuit board (PCB) view are shown in Fig. 1 (c) and (d), respectively. The on-chip antenna can be approximated as an RLC-circuit shown in the inset (e) of the same figure with the following parameters: \( C_a = 85 \ fF \), \( L_a = 8 \ pH \) and \( R_a = 35 \ \Omega \). This low-inductance \( (L_a) \) antenna circuit interacts with CFDs in the avalanche switch thus affecting sub-THz oscillations and the emission, but does not affect the avalanche switching itself due to the small \( C_a \). Capacitors \( (C) \) and inductors \( (L) \) form the circuit loop which operates in a sub-ns avalanche switching regime \( (1-10 \ GHz \ band) \), while 200 \( GHz \) oscillations caused by CFDs cannot penetrate this large inductance \( (L_{total} > 4 \cdot L) \) circuit. Unlike the devices with base-triggering described in Ref. [7], the avalanche switching in the current device is initiated by the avalanche breakdown of the base-collector junction at \( V_b \approx 22 \ V \).
The topside of the PCB with the device (Fig. 1 (d)) is orientated towards the elliptic mirror shown in Fig. 2, thus the Marx generator (MG) is located in the first focal point of the mirror. An X-Y-Z translation stage allows the switches \( S_{1-4} \) to be positioned in the first focus of the elliptic mirror individually. A zero bias Schottky diode detector (170-260 GHz band, VDI WR4.3ZBD with a WR-5.1 conical horn) is placed at the second focus of the mirror and records sub-THz pulses emitted by each of the switches. The signal from the Schottky detector is then amplified \((0.1 - 26\, \text{GHz} / 30\, \text{dB})\) and delivered to the oscilloscope (Femtoscope, Eltesta), which is triggered by the pulse across the load resistor \((R_{\text{load}} = 10\, \Omega)\) recorded at the second input. We have selected an optimized \( R_{\text{load}} \) which is about equal to the output impedance of the entire circuit, provides relatively high current amplitude, and gives as narrow the current pulse as possible but prevents, however, an appearance of relaxation oscillations. The more detailed studies of impedance matching in more complicated Marx generators and their characteristics are provided in Ref. [3], [12], [13]. The biasing voltage of \( V_g = 23\, \text{V} \) is sufficient for periodic self-triggering of the Marx circuit without an external generator with a repetition rate of \( 1.5 - 2\, \text{MHz} \) determined by the bias voltage and \( (R_1 + R_2) \times C \) product.

### III. Results and discussion

Transistor \( S_1 \) (Fig. 1) has a breakdown voltage \( V_{\text{b1}} \approx 21.9\, \text{V} \), while others \( V_{\text{b2-4}} \approx 22\, \text{V} \). Initial charging of the capacitor \( C \) in the first stage within \( t \approx 0.5\, \mu\text{s} \) increases the voltage across \( S_1 \) to the breakdown value, leading to switching of \( S_1 \), and then a negative voltage ramp is applied to the emitter of \( S_2 \), triggers its switching defined by mechanisms discussed above. Then, even higher voltage ramps trigger emitters \( S_3 \) and \( S_4 \). Switching of all four stages results in a series connection of all capacitors \( C \), and the voltage

\[
\sum_{i=1}^{4} V_{S_i} - \text{min residual voltages across } S_{1-4} \text{ is detected at the load resistor } R_{\text{load}}. \text{ The current pulse across the load is shown in Fig. 3, after numerical reduction of parasitic inductance [7].}
\]

The oscillatory behavior of the current pulse rising edge in Fig. 3 is associated with corresponding instants of the transistors \( S_{1-4} \) switching. We attribute the peak in the rising sub-THz pulse intensity emitted by a particular transistor to the moment when the ionization in CFDs results in a significant increase of electron-hole plasma density in the conductive channel, and the voltage across the transistor starts reducing due to the CFDs shrinkage [9], [14]. Then the voltage across other transistors and the load grows, resulting in the rise of the current. For example, the ionization peak in transistor \( S_1 \) can be attributed to the instant at \( t = 120\, \text{ps} \) (with a voltage at the Schottky detector \( V_{\text{d1}}(120\, \text{ps}) = 0.73\, \text{V} \)), and the corresponding increase in the current limited by the inductance lasts till \( t = 180\, \text{ps} \). Further boost of the current between 200 ps and 292 ps is related to the combined effect of \( S_2 \) and \( S_3 \) switching, whereas the final current rise between 350 ps and 425 ps is caused by the switching of transistor \( S_4 \). The significant delays in switching processes between the stages,
ranging between 60 ps and 70 ps, are comparable with the switching time of each transistor. Finally, we attribute the
abrupt break in radiation from switches \( S_{2-4} \) at \( t = 500 \) ps (Fig. 3) to the domains collapse at an extremely high carrier
density [8], [9], [14]. Well pronounced differences in the amplitude of the radiation from \( S_1 \) and other transistors (\( S_{2-4} \)) are
demonstrated below.

The interpretation of inter-cascade switching delays relies on the earlier findings [9], [10], [14] related to the CFD
phenomenon. The first avalanche switching phase caused by the electron injection from the emitter and hole avalanche
injection from the subcollector occurs when the current density exceeds the critical value of 30 kA/cm\(^2\) (for the transistors
with the collector doping of 2 \times 10^{16} \text{ cm}^{-2} \) used here), and the entire emitter-base perimeter participates in the switching
(with the conducting area of \( \approx 10 \) \( \mu \text{m}^2 \)). Thus, a relatively slow (up to 1 ns) transient of the first switching phase occurs
when the current across the transistor exceeds 3 mA.

The second, ultrafast switching phase, accompanied by the CFD formation and filamentation, starts when the current
density exceeds \( \approx 300 \) kA/cm\(^2\) across the filament with an area of \( 2 \mu \text{m}^2 \), which requires the total current of at least 6 mA
across the transistor. When \( V_{be} \) is reached, the resistance \( R_1 \) is large, and the current for the first avalanche switching phase
is supplied only by the capacitors chain \( C_l \), load resistor \( R_{load} \), and switched-off (so far) transistors \( S_{2-4} \). The displacement
current across the barrier capacitances of \( S_{2-4} \) (\( C_l \approx 1.5 \) fF for each transistor and 0.5 fF for the series connection of three transistors \( S_{2-4} \)) provides a current of 3 mA across the
switch \( S_1 \), which supports the first switching phase in \( S_1 \), but cannot provide the current level for the second switching
phase.

The further switching scenario of the Marx circuit is as follows. “Slow” reduction in the voltage across \( S_1 \) within
the first phase redistributes the voltage across the chain \( S_{1-4} \) which causes the avalanche process initiation in the switches
\( S_2, S_3 \) and \( S_4 \). After the delay, slowly switching transistors \( S_{2-4} \) provide a current of more than 6 mA across \( S_1 \) sufficient
for ultrafast filamentary switching. Fast reduction in the voltage across \( S_1 \) increases the voltage across the transistors
\( S_{2-4} \) still further, and then transistor \( S_2 \) reaches the threshold of filamentary CFD-assisted switching. The same process is
repeated then for \( S_3 \) and later for \( S_4 \).

Thus, we attribute the inter-stage switching delays to the time intervals required for the interphase changeover in
each transistor. Namely, \( S_1 \) realizes CFD-based filamentary switching with a limited current supply across \( S_{2-4} \), while \( S_2 \)
starts the ultrafast switching when the voltage across \( S_3 \) and \( S_4 \) exceeds the breakdown level significantly, and the current
supplied by \( S_2 \) is remarkably larger. The more it concerns the superfast switching process of \( S_3 \) and \( S_4 \). All in all, the
ultrafast switching of \( S_1 \), which happens at the strongest external current limitation, should form the area of the switching
filament as small as possible for the CFDs formation. This should result in domains with limited amplitude, and minimal
conductivity in the channels during the entire current pulse. These features can explain the reduced radiation amplitude
due to limited current oscillations in the antenna \( A_1 \), as

IV. CONCLUSION

In summary, a four-stage Marx generator circuit utilizing picosecond-range switches with simultaneous sub-THz emission
has been investigated. Namely, a contactless method for terahertz sensing of ultrafast switching in Marx generator
based on avalanche transistors has been proposed. A unique combination of picosecond temporal and millimeter spatial
resolution has allowed the timing synchronization between the stages to be directly measured.

We have particularly observed that the current pulse generated by the Marx circuit can be approximately five times
longer than the shortest sub-THz pulse (\( \tau \approx 100 \) ps) emitted by the last-switched transistor \( S_4 \). The significant increase in
the current pulse duration across the load resistor is attributed to the following factors: the inter-stage switching delays, and
the different duration of the domain regime in each transistor. The last one is affected by the time-dependent impedance of
the entire circuit. Namely, transistor \( S_4 \) reaches its CFD switching mode when other transistors have already been
switched. Thus, the circuit impedance does not strictly limit the current supplied by the external circuit, and the CFD carrier
generation runs most efficiently that takes the shortest time. On the contrary, transistor \( S_1 \) switches at the highest impedance
of the entire circuit, which reduces the efficiency of the CFD switching process, and the transient takes a longer time.

The discovered results suggest an idea for optimized temporal synchronization of picosecond components combined in
the Marx circuit.

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