Energy Conversion of a High-Voltage Pulse to Electromagnetic Oscillations in a Coaxial Line with a Periodic Structure of Gas Switches[1]

D.N. Bykov, N.M. Bykov, and V.V. Rostov

Institute of High Current Electronics SB RAS, 2/3, Akademichesky ave., Tomsk, 634055, Russia
Phone/fax: 8(3822) 49-21-34, E-mail: Bykoff_23@sibmail.com

Abstract – The paper presents the results of experimental study and computer simulation of the microwave generation through successive breakdowns of a periodic structure of gas switches. The structure is a coaxial line with the inner conductor made in the form of cylindrical sections separated by gas-discharge gaps.

In experiments on breakdown of 15 gas gaps, microwave oscillations at 4–5 GHz with duration ~ 3 ns and amplitude comparable to the supply voltage amplitude was obtained. The experimental results are interpreted using analytical and numerical methods.

1. Introduction

In this work, we study the mechanism of excitation of high-power microwave (HPM) oscillations through successive breakdowns of overvolted gas gaps. Unlike traditional methods of producing HPM pulses, the one proposed in this paper makes no use of an electron beam, thus the problems of beam formation, transport, and bremsstrahlung protection are eliminated.

The mechanism of direct energy conversion of a voltage pulse to electromagnetic oscillations in lines with nonlinear elements is known [1–4]. The authors of [1] used an inductance in the core saturation mode as a nonlinear element. In [2], the nonlinear element was a capacitance dependent on voltage. In the monograph [3], theoretical consideration was given to a line with nonlinear resistances with characteristics dependent on current according to a given law. In the last-mentioned work, it is shown that in these lines, amplification of the sinusoidal supply voltage is possible. All above works discuss nonlinear elements with known and well reproducible characteristics (semiconductor elements, ferrites, dielectrics).

It is expected that the use of gas switches as nonlinear elements in lines can find their niche in designing S-band pulsed sources (1.5–5.2 GHz) with an extremely high power. Clearly, the basic problem of this source design is to provide reproducibility of the switching characteristic for each gas switch.

2. Experimental setup

The periodic structure of gas switches is a coaxial line (Fig. 1) in which the inner conductor is cylindrical sections separated by gas-discharge gaps.

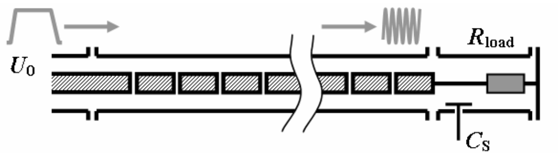


Fig. 1. Schematic of the experimental setup: R_{load} – matched load; C_S – voltage divider; U_0 – supply voltage pulse

The spatial period of the structure $d = 5.5$ cm. The outer and inner diameters of the coaxial line are 6 and 4.2 cm, respectively. The working gas is nitrogen under pressure between 1 and 90 atm. A supply voltage pulse of amplitude $U_0 = 150$ kV, pulsewidth ~ 13 ns, and rise time ~ 0.4 ns is applied to the input of the structure. The line is put under a matched resistive load R_{load}.

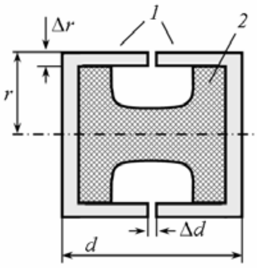


Fig. 2. Geometry of the gas switch: *1* – electrodes; *2* – dielectric

Output signals were measured with a capacitive voltage divider C_S located upstream of the load. The geometry of a gas switch is shown in Fig. 2: r is the radius of inner conductor of the coaxial line, $\Delta d = 0.1$ cm is the width of the discharge gap. Breakdown occurs through interelectrode space with radial dimension $\Delta r = 0.2$ cm.

3. Experimental and simulation results

In experiments on breakdown of 15 gas gaps at a pressure of ~ 20 atm, microwave oscillations at 4–5 GHz with duration of ~ 3 ns were obtained. The supply voltage pulse U_0 was varied between 135 and 150 kV. The lowest frequency corresponded to the lowest voltage. Most stable oscillations were observed at 5 GHz with relative spectrum width of < 10% and signal amplitude comparable to the supply voltage amplitude (Fig. 3).

[1] The work was supported by the Russian Foundation for Basic Research (Grant No. 07-08-00651-a).

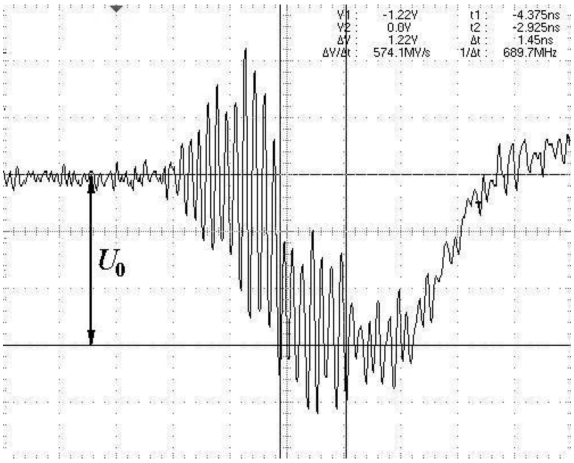


Fig. 3. Experimental time dependence of the load voltage: U_0 – supply voltage

In this work, an attempt was made to explain the obtained experimental results on basis of representing the investigated line as identical cells. Each cell consists of gas switch circuit and a coaxial line section with impedance ρ (Fig. 4). The gas switch in the circuit is described using an RLC-circuit in which the switch *K* turns on as a specified voltage across the interelectrode capacitance *C* is reached. The elements *R* and *L* specify the resistance and the inductance of the gas-discharge gap after breakdown occurs.

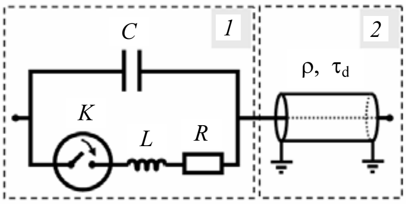


Fig. 4. Model of the cell: *1* – simplified model of the gas switch; *2* – section of the coaxial line with impedance ρ and the electrical length τd; *C* – capacitance of the gas discharge gap; *R* and *L* – resistance and inductance of the gas switch, and *K* – switch

When switch *K* does not operate the capacitance *C* is the only one important in the gas switch circuit. For an infinitely long line, the dispersion relation for the TEM wave was obtained in the form

$$f(\varphi) = \frac{1}{\pi \tau_d} \sqrt{\left(\sin^2\left(\frac{\varphi}{2}\right) + \frac{\tau_d}{2\tau_C} \right)}. \quad (1)$$

Here, *f* is the frequency, $\varphi = h_d$ is the wave phase incursion for a cell, *h* is the longitudinal wave number, τ_d is the electrical length of a cell, $\tau C = 2\rho C$ is the characteristic charging time for the capacitance *C*. Expression (1) was derived in an approximation in which a coaxial line section can be presented as lumped elements. It qualitatively describes the dispersion in the first spectral window.

The dispersion relation for the experimental conditions under consideration is shown in Fig. 5. In this case, there is a frequency range in the first spectral window where the group wave velocity is lower or much low than the velocity of light and the phase velocity approximates the velocity of light.

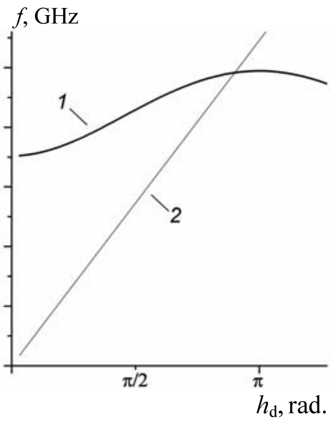


Fig. 5. Dispersion relation for the TEM wave: *1* – in the periodic structure; *2* – in the coaxial line

Numerical simulation by the code KARAT confirms that the dispersion characteristic of the TEM wave has spectral windows (Fig. 6). It is seen from Fig. 6 that the oscillations obtained in the experiments correspond to the second spectral window.

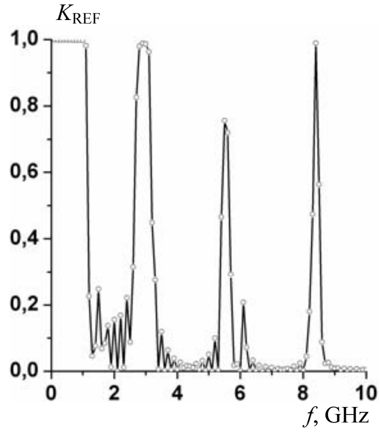


Fig. 6. Reflection factor versus frequency for a periodic structure of 15 cells. Simulation

The main requirement for efficient energy transfer from a supply voltage pulse to microwave oscillations is that the phase of the wave train formed at each gas switch must differ from the phase of the previous wave train by an integer number of periods. This requirement can be written as the phase relation

$$\Delta\varphi = 2\pi f_g (\tau_d + \Delta t) - hd = 2\pi n, \quad (2)$$

where f_g is the frequency of excited oscillations, Δt is the time interval between the instant the pulse arrives in the gap and the onset of switching (delay time), and *n* is an integer.

This expression allows us to estimate the time Δt required for oscillations at a given frequency. According to (2), the oscillations observed in the experiment correspond to a phase difference of 2π between the sources and $\Delta t \approx 0.2$ ns.

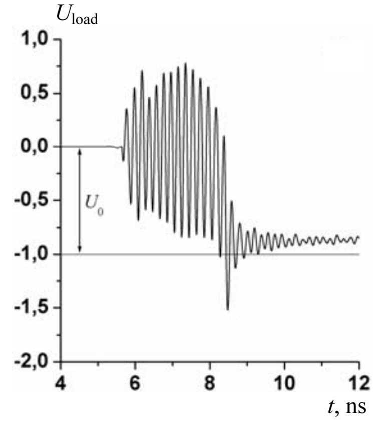
The description of the gas breakdown by the circuit in Fig. 4 is rather simplified. In fact, values of L and R for real breakdown process are time-dependent. Description of these dependences adequate to the experiments is impossible to date. Therefore, a simplified approach is used in which L and R are constant and correspond to the parameters of the gas switch after its breakdown. In this case, as the specified voltage U_{st} is reached across the capacitance C, the switch K is turned on, but with a certain delay. This delay simulates formation time of breakdown.

The choice of values of R, L, C for the elements of the model gas switch circuit is uncertain in a way. We put that L lies in the range 0.068–1 nH where the lower boundary is determined by the inductance of a 22-Ω coaxial line section of length equal to the discharge gap width and the upper boundary is determined by the inductance of a spark of diameter 0.1 mm. The capacitance of the gas switch was varied between 2 and 6 pF. The lower limit (2 pF) corresponds to the calculated capacitance of the discharge gap and the upper limit (6 pF) to the measured capacitance of the entire gas switch. The resistance R was varied between 0.05 and 1 Ω.

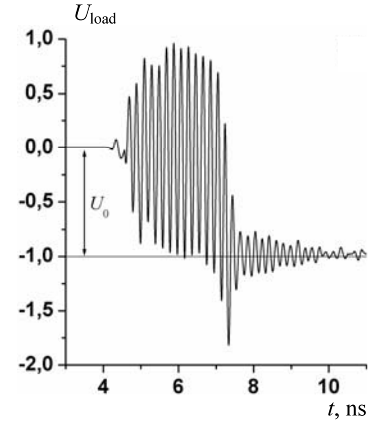
The structure of 15 series-connected cells (Fig. 4) was put under a matched load. A pulse with amplitude of 1 V and a rise time of ~ 1 ns was applied to the structure input. The parameters of the model were varied to obtain specified oscillations at $f_g \approx 5$ GHz with an amplitude and envelope approximating the experimental ones. The time Δt was chosen by selecting the turn-on voltage of the switch K such that phase relation (2) would be met. The most efficient oscillations excitation was observed where the self-resonant frequency of the circuit $f_0 \approx 1/2\pi(LC)1/2$ was close to the frequency f_g.

Figure 7, *a* shows the time dependence of the load voltage for $R = 0.5$ Ω, $L = 0.2$ nH, and $C = 5$ pF. It is seen that the data in Fig. 7, *a* agree qualitatively with the experimental results. The appreciable decrease in the level of the supply voltage pulse at the load, compared with U_0, is likely to be due to repeated passage of the pulse through the resistances R. The oscillations amplitude at the load is comparable to the level of the supply voltage pulse at the load. The decrease in R to 0.05 Ω does not change qualitatively the picture, but increases the oscillations amplitude to U_0 (Fig. 7, *b*).

The simulation show that varying L and C in a wide range exerts little effect on the results providing $f_0 \approx$ const. Fig. 8 shows simulation results for a periodic structure of 45 cells for the following parameters: $R = 0.05$ Ω, $L = 0.11$ nH, $C = 10$ pF. It is seen in the figure that the duration of the excited oscillations increases about three times, compared with the case in Fig. 7. It can be assumed that in the experiment, we actually observed the transient process of the onset of oscillations.



a



b

Fig. 7. Time dependence of the load voltage U_{load} for $R = 0.5$ Ω (*a*) and $R = 0.05$ Ω (*b*). Simulation for 15 cells

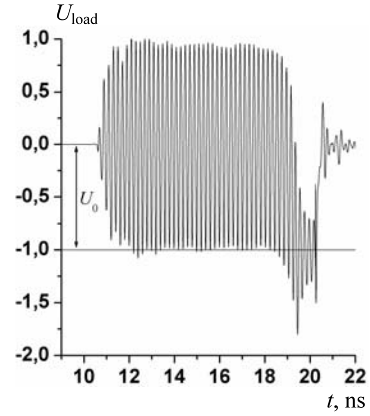


Fig. 8. Load voltage U_{load}, $R = 0.05$ Ω. Simulation for 45 cells

4. Discussion

At this stage of research, we suppose that under the experimental conditions, a multichannel discharge with a resistance R much lower than the line impedance ρ takes place. The shape of the pulse after turns on of the switch K is governed by the oscillatory transient process in the *LCR* circuit. The final high frequency oscillations are result of in-phase summation all sources formed after the breakdown of the gas switches. The excited high frequency fields participate in the initiation of breakdowns of the next gaps, ensuring their synchronization by additional overvoltage over the gaps.

The delay time Δt plays a crucial role in this model, since this time, in the main, determines the oscillations frequency. Owing to the delay time, the high frequency fields participate in the discharge initiation, while hardly participating in ohmic losses.

The excitation of relatively narrow-band (the bandwidth < 10%) oscillations suggests that under the experimental conditions, the gas gaps are broken down with a time delay spread much smaller than the high frequency oscillations period.

5. Conclusion

The work demonstrates the feasibility of the microwave source based on a periodic structure of gas switches. The presented simplest model of this source describes qualitatively the experimental results.

References

[1] A.M. Belyantsev, A.I. Dubnev, S.L. Klimin et al., Zh. Tekh. Fiz. **65**, 132–141 (1995).

[2] A.M. Belyantsev and S.L. Klimin, Izv. Vyssh. Uchebn. Zaved.,Radiofiz. **36**, 1011–1022 (1993).

[3] E. Scott, *Waves in active and nonlinear media in electronic application*, New York, 1970, Translation ed. by L.A. Ostrovskii et al., Sov. Radio, Moscow, 1977, p. 386.

[4] A.M. Belyantsev and A.B. Kozyrev, Zh. Tekh. Fiz. **71**, 79–82 (2001).