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Gaseous discharge plasma switching in oversized interference microwave switches

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Abstract. The first results of the study of gaseous discharge plasma switching in oversized interference switches of X-band active resonant microwave compressors are presented. The switching occured in a mixture of argon and air at atmospheric pressure in the mode of spontaneous breakdown. The breakdown was initiated by a sizable conductive discontinuity represented by a section of thin copper conductor of different lengths not exceeding the working wave length. The section was introduced inside the gaseous discharge quartz tube into the switching arm of the switch through the below cut off circular waveguide. The tube formed the discharge gap in the arm and was located coaxially in the circular waveguide. The tube was located at the antinode area of the electric field standing wave parallel to lines of electric force. The threshold nature of effective switching was proved. The switching efficiency as a function of the conductor length is obtained. The model of the switch was proposed and analyzed by the scattering matrix method within single-wave approximation. The calculation results were in substantial agreement with the experimental data. The operation of two oversized switches in a cascade circuit was studied. It is shown, that in switching circuits of these type formed by one or several oversized H-tees, the switching identical to processes in a conventional switch based on a single-wave H-tee is possible.

1. Introduction

The resonant time compression of relatively long microwave pulses is one of the methods to produce high power nanosecond microwave pulses. The compression procedure is realized by accumulation of the relatively long pulse energy in a cavity and subsequent fast extraction of this energy into a load [1]. Usually, the output unit is a common single-wave H-tee having a gaseous discharge plasma switch in a short circuited side arm. The tee operates like an interference switch. The length of the short circuited arm is chosen to provide the waves radiated from the cavity volume and this arm into the load being opposite in phase that is to eliminate the coupling between the cavity and the load. As a result, the switch gets closed and the cavity coupled with the switch can store the energy. After the storing process is completed the microwave switch is triggered and the length of the short circuited arm is changed so that the waves begin to be combined in phase. Therefore, the switch opens and the accumulated energy of the cavity is transferred to the load and thus the microwave pulse of the width equal to the time of energy transfer is formed. The power gain value is proportional to the ratio of the input pulse width to the formed pulse width.

The effective operation of the X-band interference microwave switch made of moderately multimode rectangular waveguides with the cross section of 58×25 mm^2 in the form of H-tee operating on the TE_{01}

wave mode was demonstrated in [2]. The gain reached 17 dB with the peak power of output microwave pulses of about 2.5 MW. The output pulse power was limited by the input pulse power which was lower than 50 kW. Almost the same result was obtained when the switch designed as a stack of five ordinary H-tees with the cross section of 23×10 mm^2 of its rectangular waveguides was used. The mutual switching arm was the rectangular waveguide section of the moderately oversized cross area of 58×25 mm^2 operating on the mode $TE_{01(p)}$ [3]. Comparison these switches with the ordinary single-mode one showed that they provide higher power gain and output power values at practically equal transient attenuations at the storing mode when the switches were closed [2, 3]. This was due to the higher quality factors of the storing cavities combined with these switches and the larger cross section area of the tee oversized arms.

The operational wave in the oversized rectangular waveguides of switches TE_{01} allows unlimited increasing of the waveguide wider wall size. Therefore, provided the field pattern is not changed this wave can be used in the switch with the large cross-section area meant for operation at the high power levels. At the same time it can be made either as the tee of large oversized waveguide or as a large dimension stack of moderately oversized tees with the common discharge gap arm of large cross section.

With a limiting power flow of 10 MW·cm^{-2} in the gas-insulated waveguide under an excess pressure of up to 10 bar [4] and the cross section area of the X-band switch arms of ~ 15 cm^2 and of the S-band switch arms ~ 150 cm^2 the traveling wave power in the switch arms can be ~ 150 MW and 1500 MW respectively. The cross-section areas in the estimates given were taken for tees which have been tested experimentally. The stack of 3 to5 of such switches used in the design may allow increasing the power, respectively, up to 450–750 MW and 4.5–7 GW. It can be assumed that the tees with the larger cross-section area and, consequently, the higher power will be properly functioning.

However, it is obvious that such switches have their own problems and limitations. But in this work we focused only on the problems of switching in the oversized switches. Despite the demonstration of the successful switching of the oversized H-tee from the accumulation mode over to the extraction mode, the switching mechanism is still unclear. This work presents first results of the study of switching in oversized interference microwave switches, for example, experimental test results and the comparative analysis of theoretical and experimental data. The data obtained in general, can contribute to the increase of energy parameters of formed pulses.

2. Experimental results

The experimental were carried out on the active resonant X-band compressor with the storing cavity cross section of 72×34 mm^2, as in [2]. The tee made of waveguide with the cross-section of 58×25 mm^2 was used as the output port. It was connected to the cavity by a smooth transition. The cavity was excited through the horn transition matching the cross section of 23×10 mm^2 and 72×34 mm^2. It was connected to the inductive iris made as a narrow slot in the central area of the end plate of the waveguide. The cavity working mode was TE_{01} and operational frequency was 8900 MHz. The transition transformed the TE_{10} wave of the standard rectangular waveguide into the cavity working mode. The slot was parallel to the wider waveguide wall and had dimensions of 72×8 mm^2. The measured cavity Q-factor was 1.4×10^4. The calculated double time of wave traveling along the cavity was 3.6 ns. The estimated power gain value was 18.5 dB at these noted values of the working frequency, the Q-factor and the double time travelling.

The magnetron of 50 kW pulse power and 1 μs output pulse width was used for the primary exciting generator. The energy was extracted by switching the output port into the extraction mode by gaseous plasma microwave discharge. The discharge was initiated by illumination of the gap by a laser beam or a spark of the triggering electric discharge. Also the discharge can be spontaneous and initiated by a sizable conductive discontinuity formed by the thin copper wire. The medium for discharge was a mixture of air and argon.

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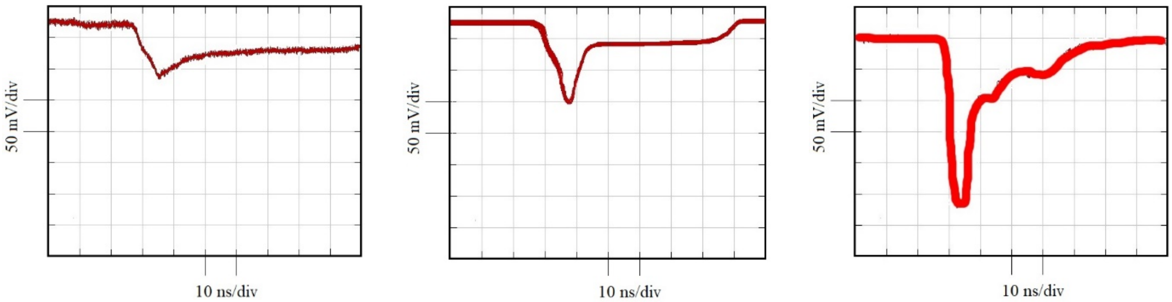

Figure 1. The output pulse envelopes of the active microwave compressor when the interference switch at operated with spontaneous discharge. Oscilloscope scan for the oscillograms: 10 ns/div.

The high efficiency of the switching was observed at all modes of operation but when spontaneous discharges caused by the wire inserted through the circular waveguide into the discharge tube were used some faults of the operation were indicated. In this case it was proved the switching parameters depended on the length of the wire plunged into the discharge tube. The parameters varied from the effective switching ones to a total fault in operation. The output pulse oscillograms for different conditions of the spontaneous discharge operations are presented in figure 1. It is seen the fault operation produced pulses of the power compared to the power values of input pulses. The effective operation produced high power pulses with the width equal to the double time of wave traveling along the cavity.

3. Model of the switching process and analysis of experimental results.

The switching process due to a spontaneous discharge initiated by an irregularity in the volume requires additional explanations. Unlike the initiation in a single-mode cavity, the effective discharge was initiated only at definite dimensions of the inserted irregularity. The discharge was effective when the energy was dump about the double time of wave traveling along the cavity. It seemed that the switching by the oversized interference switch can be explained by three ways.

The first is when the switching occurs due to phase inversion that is the process identical to the switching in single-mode waveguides. Although, this process in the oversized interference switch is practically impossible because the discharge gap length is too large as compared to the plasma discharge channel. At some degree the procedure is undoubtedly present but is not basic.

The second way of switching could be explained by the working mode transformation by the discharge spark and was seemed to be more realistic than the first one. But this switching procedure is not satisfactory for energy extraction during the double time of wave traveling. For achieving the fast extraction time the quantity 100% of the stored energy should be transformed by the discharge spark during the time of wave one way traveling. The estimations of the intermode coupling factor of the discharge spark showed that it was not large enough. So this switching procedure cannot be related to fastest energy extraction and cannot be basic as well.

The third possible procedure was the variation of the eigen frequency of the tee discharge gap arm. The process was really fast and the transition time was the double time of wave traveling along the discharge side arm. This time was much less than the double time of wave traveling along the cavity or the output pulse width. Moreover the process was maintained by a relatively small plasma formation of the discharge spark initiated by a strong field on the surface of the irregularity.

The last process is most efficient and therefore most probable. The switching model was proposed and considered within single mode approximation in order to confirm this statement. According to the model the side arm with the discharge gap was represented by a cavity coupled strongly with the direct arms and loaded by the waveguide stub with the wire section of the length l as shown in figure 2. The wire section is fastened to the insulator and inserted into the waveguide volume. The inserted section of the conducting wire makes the stub a coaxial line with the open circuit ends of the electrical length of $\psi = 2\pi l \lambda^{-1}$, where λ is a free space wavelength. The transmission factor of the element coupling the stub and the arm volume is *h*. Movement of the wire section controlled the electric field level at the input end of the coax section. Injecting the wire with the piece of insulator decreased the radiation losses and kept the Q-factor value of the storage cavity sufficiently high.

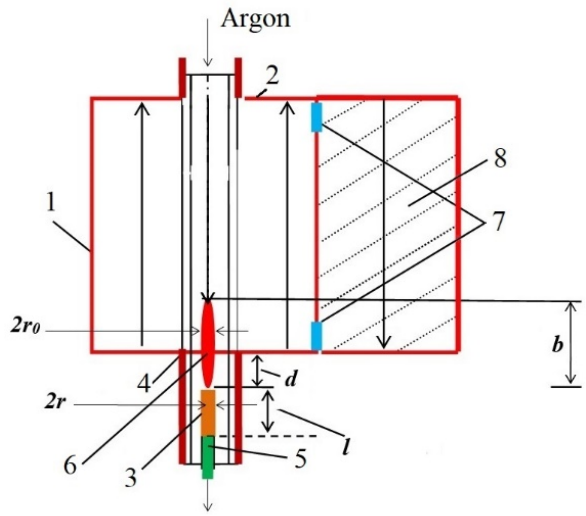

Figure 2. The model scheme of the switching H-tee with the discharge gap in the side arm. 1) longitudinal section of the side arm with the discharge gap; 2) gaseous discharge tube; 3) section of the copper wire of the length *l*; 4) below cut-off frequency waveguide of the stub; 5) insulator; 6) discharge spark; 7) equivalent inductive diaphragm at the input end of the side arm; 8) cross section of the direct arms (shaded area).

It is assumed the model operated similarly to the studied switch. The wire section of the length $l < \lambda$ was moved along the stub axis toward the cavity volume up to the position when the discharge could be formed on the surface of the wire at the increasing electric field strength. The wire section in the stub forms the coax line section open-circuit on both ends. The input impedance of this line depends on its length. If the input impedance is reactive it varies the eigen frequency of the cavity. The frequency variation decreases the field strength in the cavity and, consequently, in the stub. Further, the process depends on the ratio between the rate of the cavity frequency variation and the field variation rate in the stub. If the reactivity is small or practically negligible, the wire section gets a position in the stub where the field exceeds the breakdown level and the discharge spark is generated at the end of the section (see figure 2). The spark quickly (only a few nanoseconds) pulls the resonator frequency beyond the resonance band. In this case, the input impedance of the cavity varies from the large value of the open circuit mode, characteristic to this type of a cavity, to the short circuit mode, characteristic to operation beyond the resonance band. As a result, the phase at the input port of the discharge arm inverts and the tee opens. Otherwise, the wire section shifts the frequency and smoothly lowers the field strength in a way that the field breakdown level is not reached. The cavity either opens partially or does not open at all. It follows that the most effective length of the stub is close to the quarter-wave length and the least effective one – to the half-wave length.

The model operation can be analyzed more strictly. Using the scattering matrix method, it can be shown that a stub of the electric length ψ changes the electric length φ of the cavity or its eigen frequency f_c by $\delta\varphi$ and δf_c respectively which are defined the following expressions:

$$\delta\varphi = 0.5 arctg\left[\frac{(ag - bf)}{(af + bg)}\right] \tag{1}$$

$$\delta\varphi = 4\pi T \delta f_c \tag{2}$$

Here $a = 1 - (1 - h^2)^{0.5} e^{-2\beta} \cos 2\psi$, $b = (1 - h)^{0.5} e^{-2\beta} \sin 2\psi$, $f = (1 - h^2)^{0.5} - e^{-2\beta} \cos 2\psi$, $g = e^{-2\beta} \sin 2\psi$, h – transmission factor of the coupling window between the cavity and the stub, β – wave attenuation at the double time of traveling along the stub, T – double time of wave traveling along the discharge arm. Hence the condition for the frequency shift beyond the resonance band is expressed by:

$$\delta f_c = \delta\varphi / 4\pi T > f_c / Q \text{ or } \delta\varphi > 4\pi T f_c / Q \tag{3}$$

The transmission factor h can be determined from the equation for the coupling coefficient between a stub and a cavity $\beta c = h2/2\alpha = Pr/Pd$, where α is the wave attenuation in the discharge arm during the time of double traveling, P_r – power radiated into stub from the cavity, given by Mandelshtam' formula [5] and P_d – power dissipated in cavity walls, given by the formula $P_d = R_s\int H^2dS/2$. In the latter formula R_s is the surface resistance of discharge arm walls, H – magnetic-field component vector of the operational mode, and the integral is taken over the working surface of the cavity.

So the transmission factor h is expressed by:

$$h(d) = 32a\pi r^3 e^{-2\pi d/2.613r} \cdot 2\pi L\left(\frac{\left(2\pi L\left(1+2b\lambda^2/a\lambda_c{}^2\right)\right)}{\left(3blnr_2 + r_1(L(a+2b)+16a^2z_0{}^2\right)}\right)+ \quad (4)$$

$$32a\pi r^3 e^{-2\pi d/2.613r} \cdot 2\pi L\left(\frac{\lambda^2(L+2b)}{16a^2z_0{}^2}\right)$$

Here r – radius of the coupling aperture of the cavity with the stub; a, b, L – dimensions of the discharge arm; z_0 – free space impedance; λ_c – cut-off frequency of the operational mode. Then, having inserted (4) into (3) we obtain the expression for the frequency shift as a function of the depth d of the stub end location and of the electrical length ψ of the stub. The formation of the discharge spark of the length b brings the additional step-like frequency change by the magnitude determined by the expression [6]:

$$\delta f_c / f_c = -4b^3 z_0 / \left(360Vlg(2b/r_0)\left(1+\lambda_c{}^2/\lambda_w{}^2\right)\right) \quad (5)$$

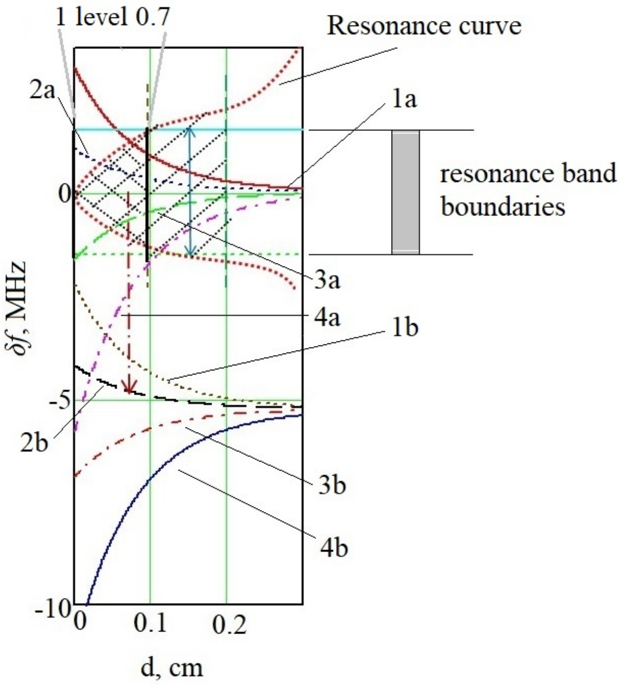

Figure 3. Plots of the discharge arm eigen frequency as a function of the depth of the wire end location and of the wire section length. Upper plots fall within the time before discharge formation, lower plots fall within the period after discharge formation. Red solid line and black dotted line (1a) and (1b) – ψ = 0.6 rad; blue dotted and black dashed lines (2a) and (2b) – 1.1 rad; green dotted and red dash-dotted lines (3a) and (3b) – 2.24 rad; pink dash-dotted and blue solid lines (4a) and (4b) – 2.8 rad. Horizontal dotted blue and green lines are resonance band boundaries. Red dotted line is a resonance curve.

The variation of resonant frequency plotted against the depth of the wire section location in the stub at different electric length values of the wire section is shown in figure 3. The figure shows the frequency variation depends strongly on the depth of insertion d and the length of the wire section l. But the resonance band is limited and only definite values of the wire section length can give rise to the field strength exceeding a breakdown level. Besides, number and values of sought after lengths depend on the field strength amplitude in the cavity. This follows from the plots in figure 3 and is confirmed by the experimental data. For example, if the breakdown field strength in the stub on the wire section surface is reached at a distance of 1 mm from the cavity surface then the discharge will be initiated only at ψ equal to 0.6, 1.1 or 2.24 rad. The required interval of the insertion depth for $\psi = 0.6$ rad will be very narrow, not more than a quarter of 1 mm, but for other values of ψ it will be 0.5 mm. The power level initiating the breakdown in the stub at a distance range from 1 to 2 mm from the working cavity surface is provided by wire sections of all lengths. At the depth values less than 1 mm only three length values of the wire section will be appropriate to develop the discharge spark.

The oversized switches were connected in a cascade circuit and operated at tests experiments. The circuit operational parameters were identical to operation of the single switch.

4. Conclusion

It was shown that the predominant process in oversized microwave switches is the shift of the cavity frequency. The sufficient shift maintains efficient switching of an oversized interference microwave switch.

Development of effective oversized switches can allow the significant increase of the energy characteristics of compressor output microwave pulses.

Acknowledgments

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