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Oversized interference switches of active resonant microwave compressors

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Abstract. Interference switches of resonant microwave compressors made of single mode waveguides provide high coupling factors after switching and rapid energy extraction. The disadvantage of these switches is low electrical strength which limits output power values. Oversized waveguides maintain higher electrical strength due to large dimensions of a cross section but mode transformation disturbs the regular operation of the switch. Operation of interference switches with a gaseous discharge gap as a switching element in oversized rectangular waveguides was studied experimentally. Conditions of their effective switching in active resonant microwave compressors were derived. It was shown that the stable microwave pulses of gigawatt power level in S-band and pulses of 0.1 GW pulse power in X-band can be produced in resonant microwave compressors with oversized interference switches. Possible switch designs are discussed.

1. Introduction

Microwave resonant compressors (MRC) produce pulses by accumulating energy in a resonant cavity during a relatively short time and subsequent rapid extraction of the energy into a load. The ultimate output power of a MRC is equal to a power of the travelling wave component in a resonant volume. So the output pulse power of MRC can reach high values, for example hundreds of megawatts in X-band and several gigawatts in S-band, if large volumes for energy storing are used. According to a method of a switching procedure MRCs come under the passive compressor group or the active compressor group. The energy extraction in a passive compressor is switched on by the phase inversion of an input feeding pulse at relatively low power level, the power gain does not exceed 9. In active compressors the switched power is comparable to the travelling wave power in a cavity and switch operation affects main output parameters such as the maximum power and efficiency. The switch design is the main problem in the course of every active compressor development when the switch invariably should introduce low losses and provide the stable rapid energy dumping from large volume cavities.

Interference switches designed as the H-tee are commonly used for rapid energy extraction. The coupling between a cavity and a load is controlled by the phase shift between the wave radiating from the cavity and the wave transferred from the side arm of the tee. The phase is inverted by the gaseous microwave switch having the trigatron type triggering located in the tee side arm. The limited cross section of the waveguide limits the electrical strength of the elements and the output power value. An increase of gas pressure leads to big energy losses in the discharge plasma and a decrease of efficiency. For example the output pulse power for switches located in S-band waveguides of the cross section of 72×34 mm^2 does not usually exceed 200 MW [1] and the efficiency is within the range of 0.2-0.3 at the losses in the switch of 2-3dB. The switching in oversized cavities involving mode transformation increases the limiting output power [2,3], supposedly up to the gigawatt level in X-band, but the design of the referred compressors was meant to provide output pulsewidth values of tens of nanoseconds and they had low power gain.

This report presents the study of switch designs based on oversized waveguides but intended for fast energy extraction and keeping high values of amplification.

2. Oversized rectangular waveguides in an interference switch

The transition of the cavity from the storage mode to extraction one occurs by use of an additional resonator where the switched wave travels [2]. This resonator is strongly coupled with an output line and its reflection factor from the direction of a storage cavity volume is expressed by:

$$\Gamma \approx -1 + \frac{2\beta}{1+\beta}\frac{1}{1+\dfrac{\delta f^2}{\delta f_l^2}} - j\frac{2\beta}{(1+\beta)}\frac{\delta f}{\delta f_l}\frac{1}{1+\dfrac{\delta f^2}{\delta f_l^2}}, \quad (1)$$

where δf – difference between operational and resonant frequencies, δf_1 – width of resonance curve, β – coupling with the storage volume. As follows from (1) the reflection factor of strongly coupled resonator at the resonant frequency is approximately equal 1. The reflection factor will be – 1 if the frequency will be changed beyond the resonance curve but this means already the phase inversion and switching over to the energy extraction. The reflection factor plotted against the relative frequency change for different coupling values is presented in figure 1.

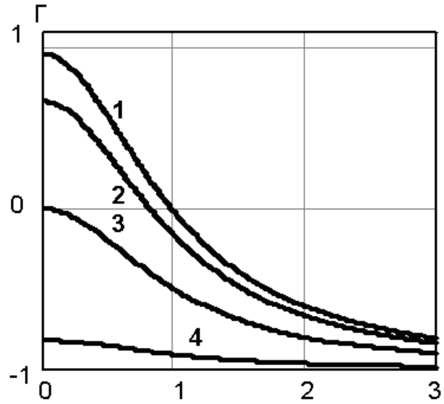


Figure 1. Reflection factor versus relative frequency deviation at following values of coupling: 1 - β = 50; 2 - β = 5; 3 - β = 1; 4 - β = 0.1.

It was assumed the strong coupling between the output line and the switching resonator and the necessary frequency change are enough for developing an effective interference switch no matter what an operational wave mode is used.

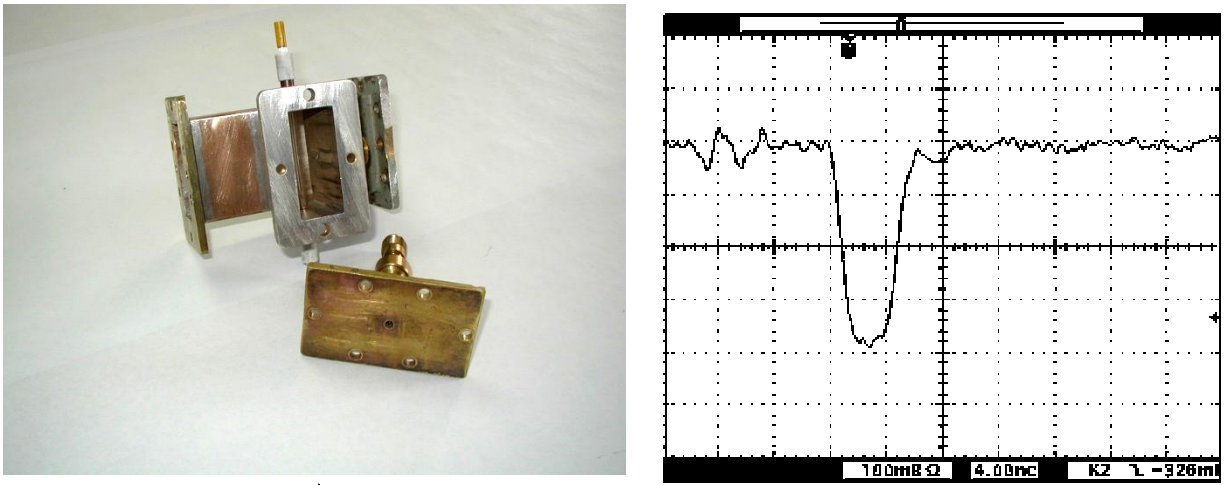
Switching resonators made of single mode waveguides are usually connected to storage volumes by T-junctions or by bridge junctions and demonstrate high switching efficiency. Although the cross section limited by the cut-off frequency value limits the electric strength and the output power.

One possible solution of increasing a waveguide cross section is the use of rectangular waveguides with H_{10} operational wave mode [4]. Corresponding output elements of the tee or bridge design keep the switching parameters of single mode analogues, does not require the special mode transformation into the primary mode of an output waveguide and make the maximum output peak power greater by several-fold. These oversized switches, besides usual requirements to the level of multimode transformation, raise some specific conditions to be provided for effective operation of the switch and the compressor. In order to provide switching over to extraction the phase of wave reflected from the tee arm should be changed by about 180^0 along with the change of the frequency beyond the resonance curve by value of $\delta f \approx nf / Q_a$, where $n \geq 3$ and Q_a - quality factor of the tee arm. Although it was found the dimensions of switching arm should be less some value determined by the ratio of the volume parameter transient time to the double time of wave travelling along the storage cavity *T*.

The expression for the limit of the oversized waveguide narrow wall size at the given arm length of L_{arm} and the size of the broad wall *a* was derived:

$$b_{\max} < \frac{z_0 Q_{arm} l^3}{90naL_{arm} \lg\left(\frac{2l}{r}\right)} = \frac{z_0 Q_{arm}\left(0.2Lv_{pl}/v_g\right)^3}{90naL_{arm} \lg\left(\frac{0.4Lv_{pl}/v_g}{r}\right)}, \qquad (2)$$

where ν_g – wave group velocity, ν_{pl} – plasma propagation velocity, $L_{arm} \approx T v_g / 2$, *l* – length of the plasma spark channel, *r* – cross section radius of the plasma channel. As is clear from (2) the size is proportional to $f^{1.5}$. This means the switches are more efficient for higher frequencies of the microwave band when the relative increase of the wall size is higher at given *T*.



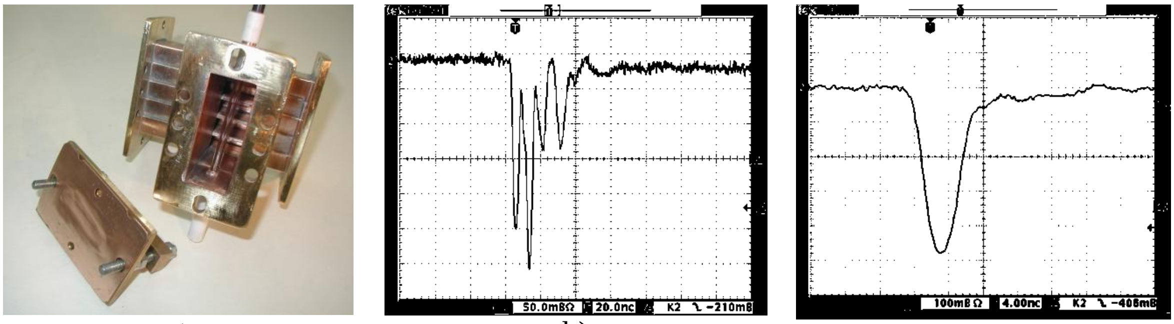
a) b)

Figure 2. Interference switch on the basis of oversized rectangular waveguide (a) and envelope of the formed microwave pulse. Exhibited parameters: pulse width of 3.5 ns, peak power of 2.8 MW, amplification of 17.5 dB.

Experimental study was made in X-band and the tee waveguides had the cross section of 58×25 mm^2. External view of the tee is shown in figure 2a. The longitudinal section of the tee is identical to the single mode one. So when dimensions are precise and operational mode H_{01} is not converted the switch of this type operates similarly to the common switch as there are no physical causes impeding that. It was proved by measuring the transition attenuation in the close state of the switch. The attenuation was 41±2 dB in the frequency range 8800-9500 MHz and that corresponds to the attenuation of a common tee. The tee with H_{01}-mode came to the open state by a slight change of the short-circuited arm parameters. It was verified as well when the switch was installed in the compressor. The calculated double time interval of wave travelling along the storage cavity was 4 ns at the quality factor of 1.6×10^4. That gave the calculated power gain of about 20 dB. The measured gain value was 17.5 dB at the pulse width of 3.5 ns. The primary exciting microwave source was the pulse magnetron generator with the power of 50 kW and so the output pulse power reached 2.8 MW. The switch was triggered by illumination of the discharge gap by an electric discharge spark or by a light beam of the nitrogen laser. The switch discharge was formed in argon at atmospheric pressure in a waveguide volume or in a quartz tube located in the area of maximum electric field and aligned along the electric flux. The typical output pulse envelope is shown in figure 2b. As the figure shows the energy extraction time is equal to the double time of wave travelling along the cavity that is similarly to operation parameters of a singlemode switch.

3. Pack of synchronized switches

Several synchronized switches connected to a single cavity can enable the energy extraction time close to the double time of wave travelling along the cavity volume [5]. The extraction time decreased with increasing the number of switches but the spread of switch triggering was compared to the output pulsewidth recorded at a single switch output. High-level synchronization was reached when the switches were arranged closely to each other i.e. they formed a packet of parallel switches [6]. External view of the switch packet in a rectangular waveguide of the tee, the short-circuit is disconnected, is shown in figure 3a.



a) b) c)

Figure 3. Packet of switches with mutual side arm. a) layout of the tee; b) output pulse envelope when separate side arms were uncoupled; c) output pulse envelope with switching in mutual side arm.

The key problem of synchronous power extraction is maintenance of identical switching conditions in each gap. First, the electric field strength values in the gaps should be equal and this condition depends on the cavity geometrical arrangement, the type of the wave working mode, the waveguide interior surface quality, the coupling between switches and the cavity. For the proposed design the H_{01} mode of a prismatic cavity is most acceptable. The E-field strength along the larger wall is constant and this contributes to equality of field strength values in the switches. The wave modes H_{01} and H_{10} are easily transformed into each other and so combining the energy extracted through all switches does not become difficult.

The second issue is the quantity of switches in the packet which affects the compressor limiting power. The effective switching corresponds to the switching time less than T and if t_f is a characteristic time of the discharge development then the maximum number of switches is given by $n < T/t_f$. For example, in X-band the acceptable number is in the range 2…5 at $T = 5ns$ and $t_f \approx 2ns$ that is the number is not so great. For higher frequencies the usage of the packet may be efficient as $t_f < 1ns$ and, keeping the same T value, the allowable switch number is larger.

The larger number of switches requires hard locking of discharge triggering. The mutual switching area as a joint oscillation system was supposed to be realized as a mutual switching tee arm. The switching process should be controlled by a single discharge and there should not be a need for special synchronization of switches. But the resonant frequency of the arm should be withdrawn beyond the resonant curve during the time interval about *T*. It may be executed by the discharge having the spark channel length much less than the total length of channels when switching proceeds in uncoupled arms. The wave travelling time along the mutual arm is less than the discharge formation time so the phase inversion of waves reflected by the arm is synchronous and so the switches of the packet come to open state also synchronously. The maximum number of switches is estimated by $n < L/b$, where *b*- size of the narrow wall of the tee waveguide.

Experimental tests in X-band proved that the strong coupling between the switching arms is the requirement for synchronous operation. The coupling in the packet was introduced by different ways e.g. by holes in adjoining switch walls, by slots between the short-circuit and flat ends of side arms and by integrating the side arms into a mutual side arm in the form of an oversized regular waveguide section. The level of synchronism rose with increase of the coupling between the arms. The packet with uncoupled arms is responsible for unsteady process of energy extraction characterized by the spread of output pulses as shown in figure 3b. The simultaneous energy extraction during the double time of wave travelling is reached with the strong coupling. The power gain of the compressor with the oversized storage cavity and the mutual side arm of 58x25 mm^2 cross section was 16.5dB at the pulsewidth of 3.5 ns and the corresponding peak power of 2.2MW. According to estimate the energy extraction through a packet with 5…7 switches could form pulses with the peak power of 0.1GW in X-band and the peak power 1GW to 2GW in S-band. The packet of interference switches may combine parallel resonant cavities fed by different sources into a single high power compression system.

4. Conclusion

The microwave interference switch designed as the H-tee of oversized rectangular waveguides with the wave operational H_{01}-mode was experimentally studied. The results proved the possibility of energy extraction from storage cavities by this type of a switch. The packet of single mode switches was developed with a view to provide their synchronous operation for energy extraction. The synchronous operation was demonstrated, the necessary conditions were determined and the number of switches in the packet was estimated. Limiting power values attainable with these switches in X-band and S-band are given.

Acknowledgments

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