Switching of H11 Mode in the Overmoded Circular Waveguide of a Resonant Microwave Compressor[1]

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Abstract – Switching of H11 mode in a circular waveguide of the interference switch improves parameters of high power microwave compressors. The switch can stand more than $3.5 \cdot 10^6$ operations and provides the rms 2% of output pulse amplitude deviation at the repetitions frequency 100 Hz and the switched power about 150 MW. It stands about 106 operations and provides the rms of amplitude deviation less than 12% at the switched power value 600 MW. The tests were carried out for different designs of S-band storage cavities and showed that working H_{11} mode in a circular waveguide doubles the limiting output power of the known versions of a compressor made from rectangular waveguides.

1. Introduction

The gas-filled interference switch made from H-plane waveguide tee meant only for the lowest principal mode is one of the earliest and frequently used output element in microwave compressors [1]. The tee may be a combination of the circular and rectangular waveguide sections the last one being the switching one. Design of the switch and conditions of the process determine the compressor parameters – amplification factor, output power, stability of output pulses, limiting repetition frequency. Small area of a cross section of the rectangular waveguide limits the electrical strength and so, e.g., the output pulse power can hardly exceed 100 MW in S-band for a single cavity compressor.

Obvious means for improving parameters at high power level are not universal and should be used in terms of trade-offs. High pressure of the insulating gas increases the electrical strength of waveguide, decreases the probability of spontaneous breakdowns and limits the region of discharge spark location. For all that, the time the discharge spark formation and the discharge plasma losses increase and this causes falling down of the efficiency and increase of the output pulse width. Usage of safety insulating gas SF_6 is justified only for the increase of the waveguide electrical strength. This gas is not acceptable as a medium for the switching discharge in general. Break down gas molecules decrease the electrical strength, corrosive chemicals are stored in the working volume and promote deterioration of the surface. High gas pressure or highly safety gas makes difficulties in operation of triggering switch used for initiating UV illumination of the waveguide gap. A minor irregularity created intentionally at the area of maximum microwave E-field confines the discharge region binding it to this irregularity and improves output pulses stability but definitely lowers the electrical strength of waveguide.

These considerations account to some extent for making no progress in preservation of the output pulse stability at high values of the working power. Practically this means that there are no effective switches designed for operation at high values of output and switched power. Development of the switches of this type can be considered as an urgent problem.

One way for approaching the problem is using interference switches with working modes characterized by a high degree of electric field pattern nonuniformity that is which have high value of E-field strength in small regions of a resonant volume. These modes can be H_{1m} in a circular cavity or E_{m1}, H_{m1} in a spherical one. The modes have high values of E-field strength in small regions at the cylinder axis or at the sphere center respectively and low on the waveguide surface. For example, the E-field strength value of H_{11} mode in a circular waveguide is about factor of 1.5 higher at the axis than on the cylinder surface. For H_{12} mode, this factor exceeds 7.5 and for H_{13} the factor is 15. For spherical modes, the ratio could be larger than that. Such modes, if used in interference switches, decrease the probability of discharge initiation on the cavity surfaces and increase the probability of initiation in an inner region of the cavity volume with following discharge containing at high E-field location. These switch designs can be developed the output T-junction. The limiting output power can be increased due to extension of cross section area of a waveguide used in the interference switch. The extension can be the factor of 3.5 if the rectangular waveguide with H_{10} mode is substituted for the circular one at working frequency lower than the cut-off frequency for H_{21} mode. Excitation of H_{21} mode could upset operation of the tee as H_{21} is strongly coupled with the principal mode at the region of the waveguide junction. So at the same level of E-field strength the

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maximum output power of a single cavity compressor can exceed 300 MW at S-band if circular waveguides in the switch are used. Confinement of the discharge at the axis of the waveguide at some distance from the wall surface can contribute to the stability of output parameters.

The report presents initial data of experimental study of switching H11 mode in a circular waveguide with confinement of the discharge axis area of the volume.

2. Experimental procedures

The switching was studied using the S-band interference switch designed as H-plane waveguide tee. The tee was made from the circular waveguide of 90 mm diameter which allowed propagation of E01 mode at 2800 MHz besides the principal mode. The E_{01} mode effected negligibly the transitional attenuation of the tee during rejection which was about 52 dB. The circular waveguide had the cross section area 2.5 times as much as the area of a standard rectangular waveguide for the same frequency.

The design of the switching unit is shown in Fig. 1. The unit was fastened either to the side arm of tee or to the direct arm of the tee depending on the cavity design. It could operate with the tube located at a distance one fourth of the waveguide wavelength from the membrane, without tubes, with blowing–through of the switch gap or without the blowing. The symmetry of the section allowed positioning the tube at any angle relatively to the E-field component vector of the working mode.

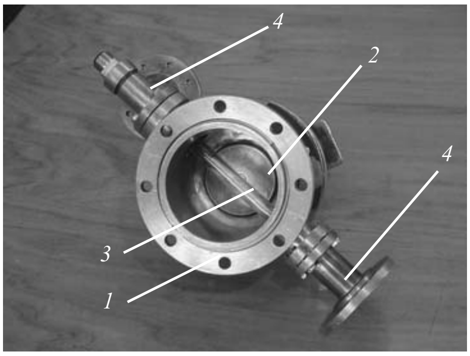


Fig. 1. The circular switch section: *1* – circular waveguide section; *2* – moveable membrane; *3* – quarts tube; *4* – pipe units for gas line

Cavity designs included the traditional one whose cavity was connected to the direct tee arm, the switching unit – to the side tee arm and the energy was extracted through the second direct arm. All elements were made from 90 mm diameters waveguides. Another design of the cavity was the symmetrical one. According one design the excitation and extraction occurred through the hybrid tee and in the other one– excitation through an iris and extraction through the side arm. The switching discharge was in the circular section of one of the direct tee arms. The working modes were $H_{11(5)}$ and $H_{11(10)}$ accordingly, their Q-value – about 2.4–2.5 · 10^4 – could provide the power amplification factor 24 dB. The switching time corresponding to the time of H11 mode – discharge plasma interaction was in the range 3–15 ns.

For studying longer periods about 30 ns the large dimension cavity of 300 mm diameter and 765 mm length was used. Its working mode was $H_{11(14)}$ and the intrinsic Q-value – 7.5 · 10^4. The calculation amplification factor was about 18 dB and the pulse width 30 ns at –3 dB level.

The last experiment involved the two stage series compressor [2] in order to reach maximum output power and study the switching at these compressor parameters. The installation allowed to test switching at different periods of energy storing. Calculation amplification factor was 26 dB and output pulsewidth 3 ns.

The block diagram of the installation was similar to [3]. It operated as follows. The synch pulse was applied to modulator and the magnetron generator produced a microwave pulse which traveled trough the waveguide line, circulator and came to the input element of the compressor cavity. During the time of microwave pulse feeding the cavity was excited and at the end of the process the HV pulse of the HV triggering generator was applied to the triggering switch. The triggering switch operated and initiated the microwave discharge in the section. The discharge turned on the energy extraction mode of the compressor. The process was monitored by the low power probe signals taken from diode units.

The power of magnetron pulses could be adjusted within 0.9…2.2 MW, the pulse width was 3.2 mcs. The magnetron pulse parameters and amplification factors mentioned above provided the switched power of H_{11} mode in the section in the range 100–600 MW. The pulse repetition frequency was step adjusted 25 to 100 Hz.

The measuring procedure was the changing of the switch conditions and checking responses by the parameters of compressor output signals. The stability was determined by statistical processing samples of corresponding parameters. Sample size corresponded to 50 measurements.

3. Switching in circular section

The location of the discharge was visually examined in the symmetric cavity with the hybrid tee. The switch was located in one direct arm of the tee and the transparent window in the short-circuiting membrane of the other. In the rectangular section, the discharge was formed on the surface at the maximum E-field area and looked like a spark of 1 cm length. It strayed around the waveguide surface area of ~ 1.5 cm diameter. In the circular section, the discharge spark was located at the axis region along the E-field line. In repetition rate mode, the discharge glow was fusiform of 1.5 cm length and 1 mm maximum diameter. The glow intensity depended on the gas composition, pressure and switched power level.

The first experiments which proved effective switching in circular sections were carried out on the symmetric cavity with $H_{11(10)}$ mode excited through the iris in one direct arm and the switch – in another. The insulating gas medium was nitrogen, argon, nitrogen – SF_6 and argon – SF_6 mixtures at a pressure from 1.5 to 6.5 bar.

The switching in the regular section filled with nitrogen provided low amplification and produced relatively long pulses with unstable width and amplitude. Typical envelopes of the pulse are shown in Fig. 2. The amplification depended on the gas pressure and did not exceed 17 dB at minimum pressure which was 7 dB lower than calculation one. The amplification decreased by 1–2 dB as the pressure increased from 1.5 to 6.5 bar. The minimum pulse width exceeded the estimated value equal to the period of wave traveling along the cavity and was greater about by a factor of 2.5. The rms value of amplitude and pulsewidth deviation was 10–20%. Maximum output power was 100 MW at the switched power value 300 MW. Those mentioned above shows that the switching of H_{11} mode in nitrogen was inefficient, adding of SF_6 to nitrogen did not help it noticeably.

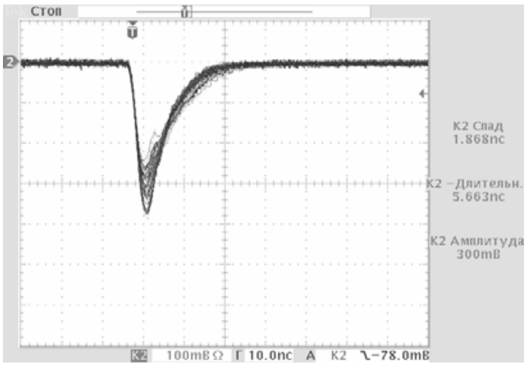


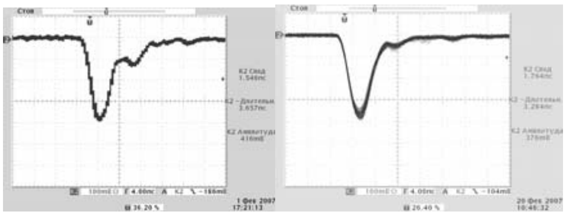
Fig. 2. Overlay of 64 output pulse envelopes at 3.5 bar of nitrogen and 25 Hz repetition rate

The amplification 21.5–22 dB was reached at switching at argon or argon – SF_6 mixture. The pulsewidth was comparable to the time of wave traveling along the cavity. At low frequency rate, up to 25 Hz, the output pulses had stable amplitude and pulsewidth values of rms 6–10%. Stability fell down along with the increase of the repetition rate. But the output parameters were stabilized by adding of 3–5% SF_6 to argon. This gave rms equal 5–7% at repetition rate of 100 Hz and the switched power of 300 MW. Although the compressor amplification fell down by 0.5–1 dB.

In order to implement the blowing through the discharge gap the union pipes were fastened to corresponding opposite holes made in the cylindrical wall as shown in Fig. 1. The nature of switching was similar to no blowing at low repetition rates. The only difference was the decrease of electrical strength of the section. At higher repetition rates, the blowing made for stability of the process. It was especially noticeable when the gas flow was along the electric force line. The usage of the 95% argon – 5% SF6 mixture improved output pulse stability up to rms 3% at repetition frequency rate up to 100 Hz. Maximum output power was 280 MW and the pulsewidth was comparable with the time of wave traveling along the cavity.

Part of experiments was made with blown – through quartz tubes of different diameters 5, 6, 8, 12, and 14 mm and sicknesses 1, 2, and 3 mm. The volume outside tube was insulated by the nitrogen – 15% SF_6 mixture of the pressure higher than the pressure value in the tube by 1–4 bar.

An essential point of the switching in the tube was high efficiency with nitrogen as a medium comparable to argon. The switching in argon had only advantage of providing higher amplification factor by 0.5 dB. But adding of 3–5% SF_6 was required to reach the stability obtained by switching in nitrogen. It seems the tube intensifies the UV illumination of the discharge region due to reflections from its wall and so electron density increases. Typical output pulse envelopes when the switching discharge was confined in tubes of 8 and 12 mm diameter values are shown in Fig. 3.

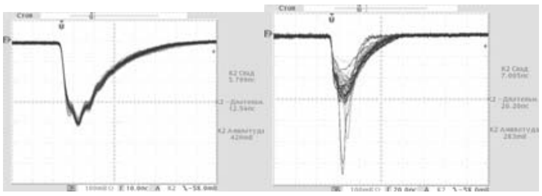


a *b*

Fig. 3. Output pulse envelopes at switching in tubes of 8 mm (*a*) and 12 mm (*b*) in diameter in Ar – SF_6 mixture

At small diameter, the envelope has two noticeable convexities with the time interval between them equal to the twice time of wave traveling along the cavity. It suggests that the reflection of the working wave from the discharge plasma formation of small dimension is not effective. As the diameter increases over 8 mm, the envelope becomes converted into a single convexity shape inherent to higher reflection effectiveness.

The switch section with the tube of 14 mm diameter was installed in positions of different angles relatively to the polarization plane of the working mode. The angle 0° corresponded to the tube parallel to the E-field component of the microwave field, 90° – to H-field component. The tube position causes limitation of the longitudinal dimension of the discharge spark and it affects the process of energy extraction. Fig. 4, *a* corresponds to 90° when the spark length was equal to the tube internal diameter. It corresponded to long extraction times and low amplification. The angle g provides the spark length 1.5 times larger and the extraction time becomes practically equal to the traveling time, Fig. 4, *b* relates to the angle 90° when the spark was formed either in the tube or outside it. The figure shows that compressor output parameters depend on the length of discharge plasma formation.



a *b*

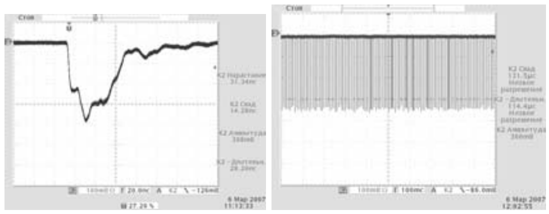
Fig. 4. Output pulse envelopes at location of the switching tube at 90° relatively to E-field force line. Switching in N_2: *a* – switching inside tube; *b* – switching either inside or outside of the tube

The circular switch section was tested with different cavity designs intended for different values of switched power and output pulsewidth. First, it was the 90 mm diameter circular cavity with $H_{11(5)}$ mode where the switch was located in the side tee arm. The switched power was higher than in the symmetrical cavity and reached 400–450 MW at 100 Hz when switching was in the tube blown – through by nitrogen at the pressure 2 bar. The maximum compressor output power was 320 MW at 3 ns pulsewidth and rms 7–8% of parameters deviation.

Formation of relatively long pulses was tested with the overmoded circular cavity of 300 mm diameter and 765 mm length operating at $H_{11(14)}$ mode. Switching was in the side arm of the circular waveguide tee and the switched power was 150 MW. The output pulses had the power of 100 MW and pulsewidth about 30 ns.

The rms of output parameters deviation was less than 2%, the typical oscillograms are presented in Fig. 5.

The maximum switched power that could be provided by used magnetron driver was achieved in the series compression system of two coupled cavities [2]. The first one was overmoded and the second was two-mode cavity with the switch section in the side arm. The second cavity operated under the spontaneous discharge condition. At the input power of 2.2 MW the switched power in the second cavity was 600 MW and the output peak power – 450 MW. At repetition rate 100 Hz the rms of output parameters deviation did not exceed 12%.



a *b*

Fig. 5. Output pulse oscillograms for overmoded storage cavity. Pulsewidth 30 ns, rms less than 2%: *a* – overlay of 64 pulse envelopes, pulsewidth 30 ns; *b* – sequence of 200 pulses, repetition rate 100 Hz

The service life of quartz tubes was estimated at the switched power of 150 MW and output pulsewidth about 30 ns and at 450 MW and 3 ns, respectively. For the first case, the service life period can reach $3.5 \cdot 10^6$ operations, for the second – about 10^6 operations. One of the causes of tube destruction is discharge in gas filled microspaces in tube walls.

The working switched power in all experiments was limited by the input pulse energy provided by the magnetron driver and not in the least by the design of the circular switch section.

4. Conclusion

It was shown that switching of H_{11} mode in a circular waveguide at discharge location in the axis region can be effective for microwave compressors. The switches of the type could be used in compressors with mode transformation as a basic process for energy extraction as well. They could switch the direct intermode coupling or couple an intermediate mode to the load.

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