Analysis of microwave interference switches with distributed power of switched wave and plasma gas-discharge switching

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Abstract. This paper reports on development of effective cascade type microwave interference switches using waveguide H-tees providing total transition attenuation value of about -50dB at the non-transmitting state, the power losses of -2-3dB at the transmitting state, and the working power compared to the one of a regular waveguide. These switches have different types of connections of two or three H-tees. Different designs provide different distributions of switched wave power between tees and provide different power levels of the switched wave. Characteristics of the switches made of tees matched from their side arms and of unmatched ones were calculated using the scattering matrix method. It was shown the matched tees used in the design allow decreasing by several times the power level of the switched wave and that increases the operating power and stability of the switching process. While some definite combination of unmatched tees allow increasing the power level of the switched wave and may provide effective switching of the transmitted wave at decreased power level. It was shown experimentally the cascade switches could be used as effective energy extraction device in an active resonant microwave compressor also.

1. Introduction

Generation and use of the electromagnetic energy of ultrahigh frequency are always accompanied by processes of controlling the fluxes of the microwave energy. The work of devices controlling the fluxes affects the quality and efficiency of a source of microwave radiation. This is especially true for resonant microwave compressors being sources of pulse microwave radiation [1,2].

Resonant microwave compressors operate on the basis of storing the microwave energy in a cavity and following fast extraction into a load. Most compressors use an interference microwave switch for switching the cavity over to the energy extraction mode. This switch is simple and effective; it is designed as a waveguide H-tee, where one direct arm is connected to the cavity and the other direct arm or the side arm is short-circuited and contains the microwave switch.

At the same time, due to the limited electric strength of waveguides used in tees and their limited cross-section area the switch has a limited operating power. Since microwave switch components used in the device reduce the electrical strength of the microwave switch, its operating power level is usually below this limit. Therefore, improving the quality of the switch requires an increase of the electrical strength. Traditional methods of increasing electrical strength (optimization of the design, use of medium with higher insulating qualities etc.) are almost exhausted.

The new design of the switch for systems of microwave compression was proposed in [3], where the value of the phase shift corresponding to inversion of a switched wave was distributed between

tees in the cascade. The distribution of the phase shift makes the tee switches being subjected to a place of relatively weak electrical field strength, allowing thus increasing the maximum power of the transmitted wave.

The work [4] proposes also microwave compressors comprising the cascade connection of switching tees. The increase of the transmitted wave power in such switches is provided by dividing of the wave power between the tees.

This paper presents the results of the study of the switch with distributed power for the series connection where each consecutive H-tee is connected to the side arm of a preceding one (figure 1) and the series connection of H-tees through their straight arms (figure 2).

2. Analysis

The cascade switches were analyzed by the method of the scattering matrix. Here the operation of such switches is shown using cascades made of two H-tees, generally unmatched from the side arm.

2.1. Cascade of H-tees in the side arm

The scheme of such switch is shown in figure 1.
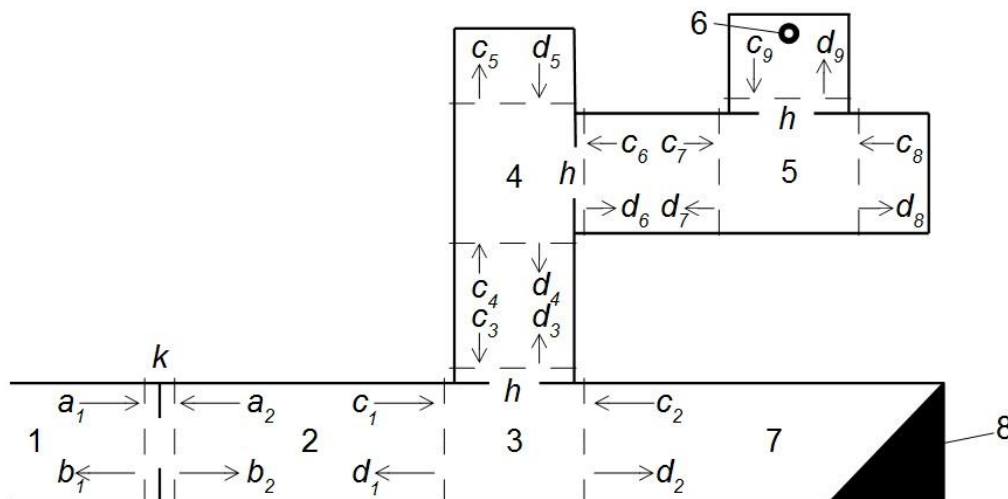
Figure 1. Scheme of compressor with cascade switch in the side arm of H-tee: 1 – input, 2 – cavity, 3-5 – H-tees, 6 – microwave switch, 7 – output, 8 – matched load.

According to the scattering matrix method, the following equations can be written for the wave amplitudes in the studied system:

$$\vec{b} = S_1 \vec{a} \, , \quad \vec{d} = S_2 \vec{c} \tag{1}$$

where S_1, S_2 are scattering matrices of the input window in the connection of the cavity and waveguide H-tee, and the vectors are constituted by the amplitudes of the incident $\vec{a}$, $\vec{c}$ and reflected $\vec{b}$, $\vec{d}$ waves in the components of the system; k and h are the transmission coefficients of the input window of the cavity in the connection of the cavity and the input window of the side arm of H-tee with straight arms . Using (1) for the cascade of two tees, we can obtain expressions for the wave amplitudes in all components of the system: in the cavity b_2, in the output of the switch d_2, in the side arm of the first tee d_3, in the side arm of the second tee d_6, in the short-circuited straight arm of the first tee d_5.
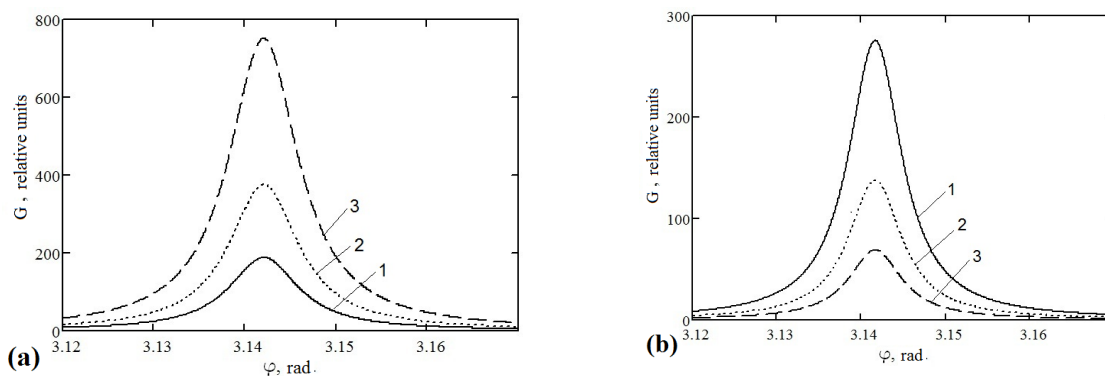
Figure 2. Calculated dependencies of the gain in the components of the compressor with a cascade switch in the side arm of two unmatched H-tees (a, $h = 0.8$), and tees matched from the side arm (b, $h = 1$). 1- amplification into the volume of the cavity, 2 – inside of side arm of the first H-tee, 3 – inside of side arm of the second H-tee.

Figure 2 shows the calculated curves of the gain in the components of the compressor with a cascade switch of two conventional unmatched H-tees (fig.2a; $h = 0.8$), and tees matched from the side arm (fig.2b; $h = 1$). As follows from the curves, effective matching of tees from the side arm is needed to provide the significant reduction of switched power. For example, it is not difficult to deduce the equality of gain factors in cavity and side arms is achieved at $h = 0.95$. This value h provides the reflection coefficient $|\Pi| \approx 0.3$. Further reduction of gain will need a higher degree of matching. Decreasing h leads to a rapid reduction of the transient attenuation of the switch.

2.2. Cascade of H-tees combined in series
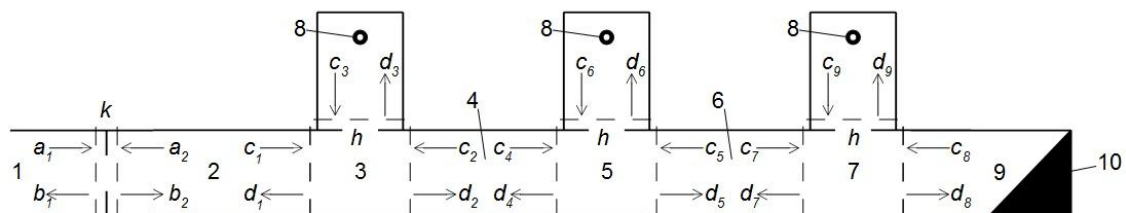
Figure 3. Scheme of compressor with a series cascade switch: 1 – input, 2 – cavity, 3,5,7 – H-tees, 4,6 – common arms of tees, 8 – side arms with microwave switches, 9 – output, 10 – load.

Using (1), the wave amplitudes in all components of the system are expressed in a similar way: in the cavity b_2, in the output of the switch d_8, in the side arm of the first tee d_3, in the side arm of the second tee d_6 and d_9 of the third tee, in the straight arm between the first and second tee d_2 and between the second and third one d_5.

Figure 4 shows the calculated curves of wave amplification in the cavity, side arms and the straight arm between the tees of a cascade of two tees connected in series that were used at experiments. As follows from the curves, the effect of matching is significant.
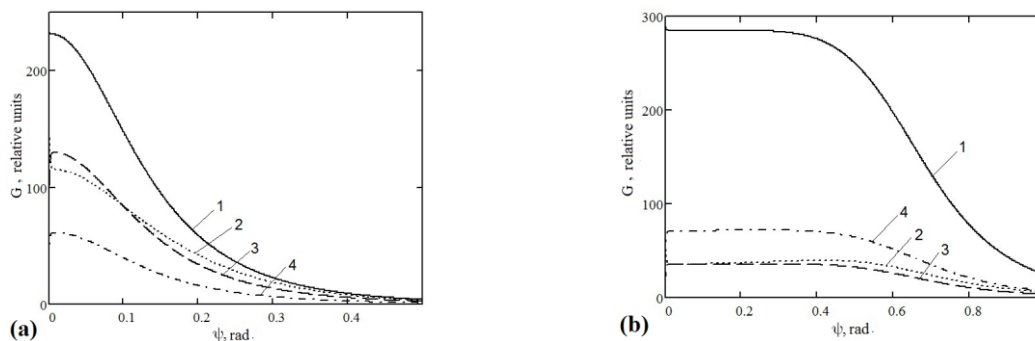
Figure 4. Calculated dependencies of the gain in the components of the compressor with a series cascade switch of two conventional H-tees (a, $h = 0.78$), and the tees matched from the side arm (b, $h = 1$). 1- amplification into the volume of the cavity, 2 – in the side arm of the first H-tee, 3 – in the side arm of the second H-tee, 4- in the straight arm between the first and second tees.

The above plots also imply that the unmatched tees form switches with lower quality performance. High quality performance of the cascade switch is obtained when $h > 0.95$, namely, $G < 0.3$. In the case of unmatched tees we will observe stable decrease of the gain in the side arms of tees less than by two times against four times for the matched tees.

It is reasonable to set the switch with a series cascade to the "open" mode by opening the tees in reverse order, starting with the last tee. In this case, as the tees are opened one by one, the gain will increase in steps in the side arm of each subsequent tee. These microwave switches will work at the field level demonstrably higher than the disruptive level, which will provide their more effective functioning.

The gain in side arms is 2 to 3 times less than in the side arm of a conventional switch (the gain in the side arm of a conventional switch is 140; 35 in a cascade of two tees and 16 in a case of three tees). The loss of energy for charging a conventional switch with the travel time along the arms making around 1/3 of the travel time along the cavity is ~ 0.5 dB, for charging the cascade of two tees also ~ 0.5 dB, and the cascade of three tees – less than 1 dB. For the greater the number of tees in a cascade the range of the phase shift ψ values where the gain in side arms is constancy is broader and the value of gain is less.

3. Experimental studies

Experimental studies were carried out with the compressor having the switches of identical S-band H-tees made of circular copper waveguide. Tees were matched from the side of the side arm, their SWR was ~ 1.02. Operating frequency of copper cylindrical cavity was equal to $f_0 = 2800$ MHz and cavity gain was about 280. The length of input and output pulses was ~ 3 mks and 6-9 ns accordingly.

Plasma microwave dischargers were used as microwave switches. The gas-discharge switches were gas-filled quartz tubes located in the side arms of the tees to the diameter of the waveguide, parallel to field lines of electric field TE_{11} mode [5]. On one end of each tube was the source of illumination.

The first experiments investigated the distribution of gain along the arms of the series switch. The results of these studies confirmed the validity of theoretical analysis data.
In the sequential cascade, after the switch was set on the by-turn spontaneous triggering, one of the switches was set to the controllable triggering mode. In this case, the controllable switch went off first, followed by the spontaneous breakdown of the second switch. This mode of operation was achieved through the distribution of the switched wave power between switches and selecting the composition and pressure of the gas in discharge tubes. The compressor with the switch on the basis of two series connected tees and the oscillogram of output pulses are shown in figure 5a and figure 5b.
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(a)   **(b)**
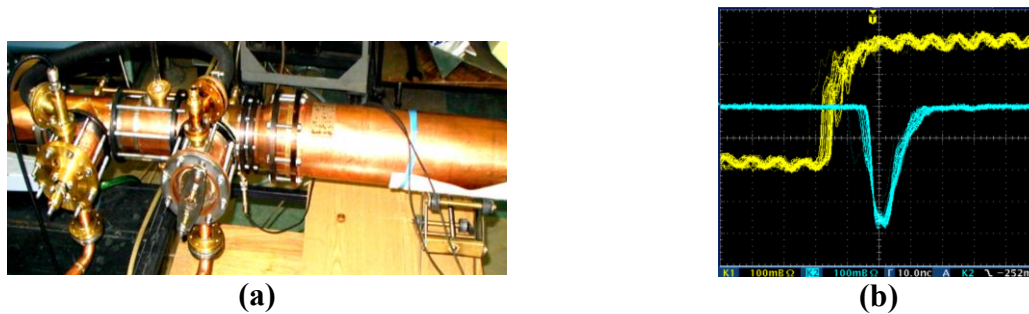
Figure 5. Resonant microwave compressor (a) with a cascade interference microwave switch based on two H-tees connected in series and the envelope of output pulses (b). (Triggering the first switch of the first tee, followed by the second one, with the interval of time equal to the travel time of waves between the tees (synchronization by laser beam)).

During the experiment with a cascade of tees in the side arm, triggering of switches was controllable. The compressor with such switch and the oscillogram of output pulse are shown in figure 6a and figure 6b.

(a)   **(b)**
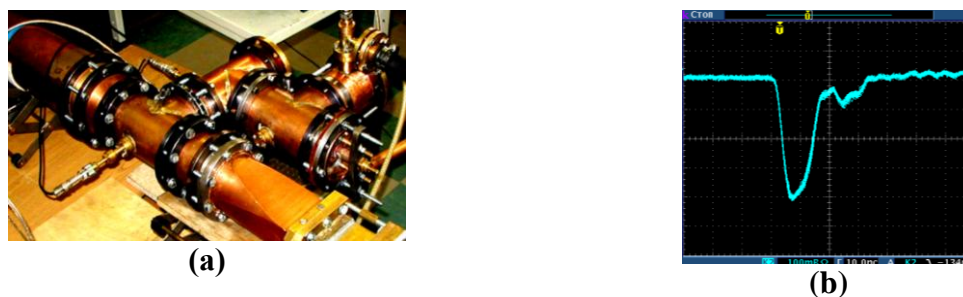
Figure 6. The compressor with a cascade switch of three tees in the side arm (a) and the oscillogram of output microwave pulses (b).

The gain reached in the compressor with a series cascade was ~ 18.5dB when the first switch of the first tee was triggered. When the switch of the second tee was triggered first, the gain was up to~ 20 dB. This is ~ 1 and 2.5 dB below the gain in the control experiment. Gain fall is explained by the partial loss of the prepulse energy. These losses can be reduced to a negligible level by minimizing the length of the tee arms. Almost similar results were obtained on the compressor with a cascade of tees in the side arm.

Losses in the switches do not affect the gain fall. This follows from the experiments in which the cascade switch provided the output of power without prepulse. This conclusion is realized when the switch in the second tee is triggered synchronously with the incoming wave from the cavity (figure 6b). Here the abrupt increase in the amplitude of the field at the delayed switch facilitates synchronization. In this case, pulses are generated, identical to the pulses of the switch with a conventional switch both in terms of form and gain, which confirms that the losses in a cascade and conventional switches are comparable.

The tubes in switches were filled with a mixture of argon and 1-5 % insulating gas under pressure 0-0.05MPa against 0.3-0.5MPa in a compressor with a conventional switch. The power of input microwave pulses rose to 2 MW, and the power of generated pulses reached 200-250 MW. Moreover, the experiments have shown the possibility of operating the switches filled only with argon at a power level of the input pulses ~ 1.5 MW. This means that the power of input pulses and hence the output pulses can be increased with a corresponding increase in pressure in tubes.

4. Conclusion

The maximum output power of an active compressor can be increased by designing the switch as a cascade of H-tees. It is shown that the level of switched power in such a switch can be reduced by factor of $1/2^n$, where n is the number of tees in the cascade.

The cascaded switches may be used in compressors with solid state switches having relatively low operating power. Increasing the number of tees in a cascade can provide the reduction of switched power to a level acceptable for semiconductor switches.

Acknowledgment

References

[1] Didenko A N, Zelentsov V I, Shteyn Yu G, Yushkov Yu G 1972 *Radio Eng. Electron. Phys*. **17** 7 1545-1547 (in Russian)

[2] Alvarez R., Birx D., Lauer E., Scalapino D. 1981 Application of Microwave Energy Compression in Particle Accelerators. *Particle Accelerators*. **11** 3 125-130

[3] Tantawi S G 1999 The design and analysis of multi-megawatt distributed single pole double throw (SPDT) microwave switches. *AIP Conference Proceedings* 472, 959; doi: 10.1063/1.58890

[4] Artemenko S N 2013 Waveguide H-tee T-junction combined in series as the energy extraction device from a cavity. *Izvestiya Vuzov, Fizika* **56** 11/2 238-242. (in Russian)

[5] Avgustinovich V A, Artemenko S N, D'Yachenko V F, Kaminskii V L, Novikov S A, Yushkov Yu G 2009 A study of the switching of the microwave compressor switch in a circular waveguide. *Instruments and Experimental Techniques* **52** 4 547-550