Microwave Resonant Compressors with Energy Extraction Through –3 dB Waveguide Hybrid

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Abstract – The waveguide hybrid as an arrangement for energy extraction in resonant microwave compressors was studied. In particular the results of theoretical analysis of the hybrid operation and experimental data obtained for X-band compressors with energy extraction through the hybrid were presented. It was shown that under some conditions the hybrid can provide a two-fold increase of the compressor output power in comparison with the energy extraction through a waveguide tee.

1. Introduction

The common output element of resonant microwave pulse compressors (RPC) is the interference switch made from the waveguide tee [1]. The switch has the high transition attenuation in the “closed” mode (45 dB and higher) and is easily drives into the “open” mode by initiating the discharge in the short-circuited arm of the tee. Simplicity and efficiency of the tee switch are its advantages considering another known output elements [2, 3].

But the tee switch is limited in working power level which is determined by the electrical strength of the tee and the cross section of its waveguide arms in particular. Par ex. the maximum output power of the compressor with such a switch at the waveguide cross section area ~ 25 cm^2 is ~ 150 MW and if the compressor has two series cavities the maximum power is ~ 1000 MW [4]. At the same time the power attributed to the traveling wave component in a storage cavity of the same frequency band can reach 1…10 GW which is by an order of magnitude greater than the ultimate power of the switch. This means the development of more effective output elements for dumping energy is necessary to bring potential capabilities of a compressor with respect to output pulse power parameter into reality.

The paper presents the study of energy extraction through the hybrid designed as two H-plane tees connected by the mutual side arm and so having the two output channels connected further to the output line in order to add the two output signals together. The single commuter is located in the mutual arm of tees. The design of the hybrid was proposed in [5].

2. Analysis of Hybrid Operation as an Output Element

The outlined drawing of the device is presented in Fig. 1.

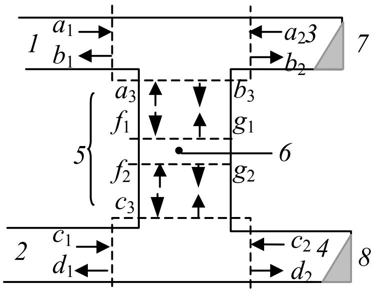


Fig. 1. The hybrid designed as two tees with the mutual side arm. *1*, *2* – input arms; *3*, *4* – output arms; *5* – mutual side arm; *6* – switch; *7*, *8* – matched load

The amplitudes of falling and reflected waves are related by the following equations [6] according to the scattering matrix method

$$\vec{b} = |S_1|\,\vec{a}\,,\ \vec{d} = |S_1|\,\vec{c}\,,\ \vec{g} = |S_2|\,\vec{f}\,, \tag{1}$$

where $\vec{a} = \begin{pmatrix} a_1 \\ 0 \\ a_3 \end{pmatrix}$, $\vec{b} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}$, $\vec{c} = \begin{pmatrix} c_1 \\ 0 \\ c_3 \end{pmatrix}$, $\vec{d} = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}$,

$\vec{f} = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$, $\vec{f} = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$; $|S_1| = \begin{vmatrix} -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \end{vmatrix}$,

$|S_2| = \begin{vmatrix} -\sqrt{1-k^2} & jk \\ jk & -\sqrt{1-k^2} \end{vmatrix}$ – scattering matrices for tees and discharge plasma area respectively.

During the cavity excitation the switch is off and $k = 1$. The waves are scattered at tee areas and following can be derived from (1)

$$\begin{cases} b_1 = -\dfrac{a_1}{2} + \dfrac{a_3}{\sqrt{2}} \\ b_2 = \dfrac{a_1}{2} + \dfrac{a_3}{\sqrt{2}} \\ b_3 = a_1/\sqrt{2} \end{cases},\quad \begin{cases} d_1 = -\dfrac{c_1}{2} + \dfrac{c_3}{\sqrt{2}} \\ d_2 = \dfrac{c_1}{2} + \dfrac{c_3}{\sqrt{2}} \\ d_3 = c_1/\sqrt{2} \end{cases}. \tag{2}$$

Amplitudes in the regular section are related by

$$a_3 = d_3 e^{j\varphi-\gamma}\,,\ c_3 = b_3 e^{j\varphi-\gamma}\,, \tag{3}$$

where φ – phase shift and γ – attenuation constant at traveling along the mutual arm.

If waves coming into hybrid arms have equal amplitudes and are opposite in phase, that is $a_1 = -c_1$, than it can be derived from (2) and (3)

$$b_2 \approx \frac{a_1}{2}(1-e^{-\gamma-j\varphi}),\ d_2 \approx \frac{c_1}{2}(1-e^{-\gamma+j\varphi}). \qquad (4)$$

Equation (4) shows that the condition $\varphi = 2\pi n$ should be satisfied for closing the hybrid. In this case

$$b_1 \approx -a_1, b_2 \approx \frac{a_1\gamma}{2},\ d_1 \approx -c_1, d_2 \approx \frac{c_1\gamma}{2}. \qquad (5)$$

As follows from (5) the hybrid can have the transition attenuation value equal to one of a tee during the excitation process.

During the extraction process the total wave reflection from the discharge plasma can be supposed $k = 0$, $a_3 = d_3 e^{-\gamma/2}$, $c_3 = b_3 e^{-3\gamma/2}$ (for two half wavelengths along the mutual arm) and (1) and (6) are used for expressing the reflected and passing waves

$$b_1 \approx -\frac{a_1\gamma}{4}, b_2 \approx a_1,\ d_1 \approx -\frac{3a_1\gamma}{4}, d_2 \approx c_1. \qquad (6)$$

If the hybrid outputs were terminated by a H-plane tee and the phase of b_2 or d_2 were inverted then, according (1), one would obtain the total output wave amplitude bat the tee output

$$b = \frac{b_2}{\sqrt{2}} - \frac{d_2}{\sqrt{2}} \approx \sqrt{2}a_1 \approx -\sqrt{2}c_1. \qquad (7)$$

According to (7) the power at the tee output is twice as much as the wave power of each output arm of the hybrid. The value of commuted power is kept at the value of power commuted at the tee switch.

Below the effects of wave amplitude and phase disbalance in the input hybrid arms upon hybrid parameters during energy storing and the influence of reflection factor introduced by discharge plasma during energy extraction are considered. The amplitude disbalance can be represented by $a_1 = -(c_1 + \delta c_1)$, and (1) helps us obtain

$$\frac{b_2}{c_1} \approx -\frac{\gamma}{2}(1+\frac{\delta c_1}{\gamma c_1}),\ \frac{d_2}{c_1} \approx \frac{\gamma}{2}(1-\frac{\delta c_1}{\gamma c_1})_1. \qquad (8)$$

So the transition attenuation of each hybrid input will be determined by

$$R_{1,2}^2 = 10\lg\frac{\gamma^2}{4}\left(1 \pm \frac{\delta c_1}{\gamma c_1}\right)^2 = R_0^2 + \delta R_{1,2}^2, \qquad (9)$$

where $R_0^2 = 10\lg\gamma^2/4 -$ attenuation corresponding to balance state, $\delta R_{1,2}^2$ – variation of attenuation due to disbalance.

The variations of attenuation for the hybrid channels plotted against the disbalance value normalized on the basis of attenuation at wave traveling along the mutual arm are shown in Fig. 2.

As Fig. 2 shows at some disbalance value the attenuation of one channel can increase but of another one smoothly drops. At the disbalance $\delta c_1/c_1 \approx 4\gamma$ the attenuations for the channels drop by ~ 10 and ~ 14 dB. That means, p.ex., at typical value $\gamma \approx 10^{-2}$ the difference in power values in the input arms should be lower that –27 dB.

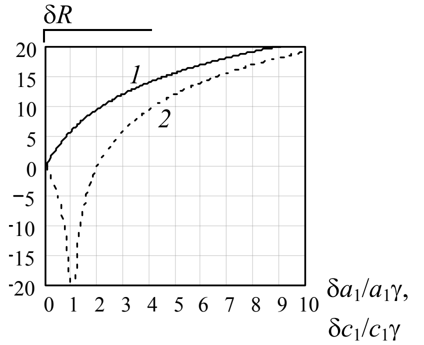


Fig. 2. Plots of variations of transient attenuations for hybrid channel as functions of amplitude disbalance in the input arms. *1* – first channel variation and *2* – second channel variation for the present case $|a_1| > |c_1|$

Now let us consider the effect of phase disbalance. Having assumed $a_1 = -c_1 e^{-j\varphi}$ the equation (1) gives

$$b_2 = \frac{a_1}{2}(1-e^{-\gamma+j\varphi}), d_2 = \frac{c_1}{2}(1-e^{-\gamma+j\varphi}) \qquad (10)$$

and (10) allows to express the attenuation

$$R_{1,2}^2 \approx 10\lg\frac{\gamma^2}{4}\left(1+\frac{\varphi^2}{\gamma^2}\right)^2 = R_0^2 + \delta R_{1,2}^2. \qquad (11)$$

The variation of attenuation plotted against the phase disbalance normalized on the basis of attenuation constant for the wave traveling along the mutual arm is shown in Fig. 3.

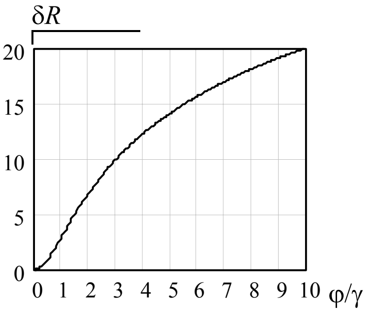


Fig. 3. Plots of variations of hybrid transition attenuations as function of the wave phase disbalance in the input arms

As Fig. 3 shows the requirement for phase disbalance allowances are tough. The difference in lengths of input arms of about, p.ex., one or several tenth of a millimeter causes the disbalance $\varphi \approx 3\div5\gamma$ and decrease of attenuation by 7–14 dB.

Concerning the effects of discharge plasma reflection factor it should be taken into account the discharge introduces additional phaseshift and the phaseshift in turn affects the transition factor k^2 and reflection factor Γ^2 values [6]. Also taking account of (1) the following expression can be derived

$$R_{1,2}^2 = 10\lg\frac{1}{4}[1+\Gamma^2 e^{-2\gamma_1}(2+e^{-2\gamma_1}) - \\ -(1-\Gamma^2)e^{-\gamma_1-\gamma_2}(2-e^{-\gamma_1-\gamma_2})]. \qquad (12)$$

where γ_1, γ_2 – wave attenuation values for wave traveling up to the plasma area from arms 1 and 2. Plots of $R_{1,2}^2$ as a function of Γ^2 are shown in Fig. 4.

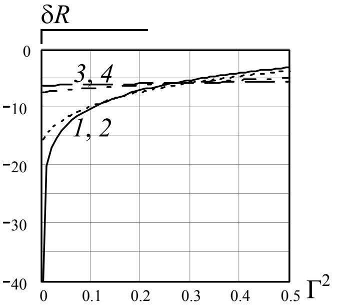


Fig. 4. The transition attenuation of the hybrid at extraction mode against reflection factor Γ^2 for different decay constant γ. Here γ includes γ_1, γ_2 and also losses in plasma. $1 - \gamma \approx 0.01$; 2 – 0.1; 3 – 0.5; 4 – 1

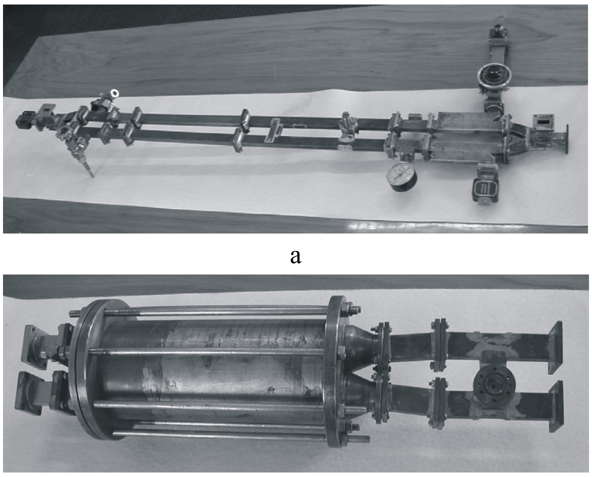
It is seen that $\Gamma^2 \geq 0.5$ and losses should be less 2 dB to make decrease of the amplification factor less than ~ 3 dB. This value is comparable with the decrease of a tee and keeps the extraction process to be still effective.

3. Experimental Testing

All experiments were run in X-band. The transitional attenuation as a function of the phase and amplitude disbalance was determined at low power measurements. Amplitudes in the hybrid input were made equal by attenuators. The ultimate phase balance was achieved by a minor deformations of waveguide walls. The E-plane tee was used for initial dividing power and as it provided input waves opposition phase the length of the mutual hybrid arm was $2\lambda_w$, where λ_w – waveguide wavelength. The experimentally obtained relationships between the transition attenuation and the disbalance of phases and amplitudes practically coinsides with the plots of Figs. 2 and 3.

The energy extraction was tested experimentally at high microwave power level with the singlemoded and multimode cavities shown in Fig. 5. The block diagram of cavity connection is shown in Fig. 6.

The insulating gas and therefore the discharge medium was either air at atmospheric pressure or argon at positive pressure up to 1.5 bar. The output signal envelope and amplitude were checked in each output hybrid arms and at the adding E-plane tee output. The power amplification factor of both compressors was determined by comparing the signal amplitudes at the input and the output of cavities.



a

b

Fig. 5. The storage cavities integrated with the waveguide hybrid serving as an element of energy extraction

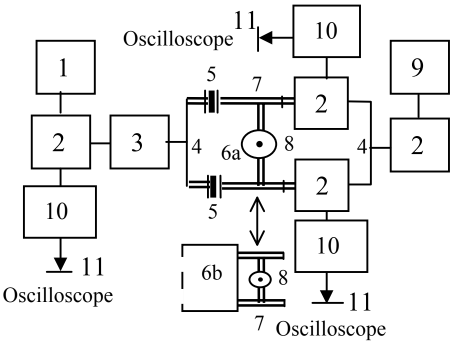
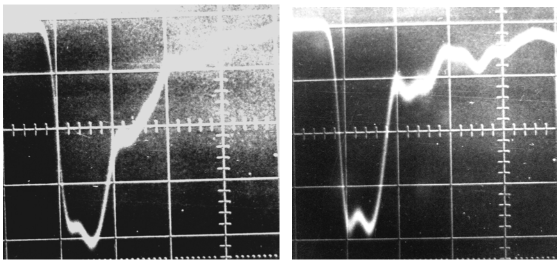


Fig. 6. Block diagram of experimental setup. 1 – magnetron generator with output pulse power ~ 50 kW and pu; sewidth 1 μs; 2 – directional coupler; 3 – circulator; 4 – E-plane tee; 5 – input iris; 6a – singlemoded cavity; 6b – multimode cavity; 7 – hybrid with switch 8; 9 – matched load; 10 – attenuator; 11 – diode unit

The singlemoded cavities had working resonant frequency 9.1 GHz, working mode $H_{10(23)}$ and Q-factor $7.5 \cdot 10^3$. This Q-factor value was equal to Q-factor of the cavities short circuited instead of having the output hybrid. The calculated amplification factor is 14.2 dB at pulsewidth ~ 5.2 ns.



a) P = 440 kW b) P = 440 kW

Fig. 7. Envelopes of singlemoded cavity output pulses (5 ns/div): a) switching in air; b) switching in argon

The envelope of the signal at the output of adding E-plane is presented in Fig. 7a. The switching took place in air so the envelope had a step wise decay and exhibited characteristics of partially opened output element, i.e. longer pulsewidth 8 ns and smaller total power amplification 9.4 dB.

The envelope of the total output pulse when the switching takes place in argon are shown in Fig. 7b. In this case the extraction time is equal to the time of round traveling along a cavity and the envelope is similar to those usually obtained by extraction through a tee. The amplification factor for each channel was ~ 9.5 dB and for the total pulse it was ~ 12.5 dB.

Similar results were for energy extraction out of the multimode cavity which operated at the frequency 9.12 GHz, had $H_{01(13)}$ working mode and Q-factor $\sim 7.5 \cdot 10^4$. The estimated power amplification factor is ~ 13 dB at the output pulsewidth ~ 30 ns.

When the switching was air the pulsewidth in each output channel was ~ 130 ns and the power amplification 5.5 dB. When the switching was in argon the pulsewidth values for separate channels were ~ 45 ns and ~ 50 ns and for the total pulse at the adding E-plane tee output was 30 ns. The corresponding amplification factors were 7.5 dB and 10.5 dB.

The should be mentioned that the switching may be effective in air [7] but at power levels by an order greater that the pulse power at this run of experiments.

4. Conclusion

So the study proves that the waveguide hybrid made from two H-plane tees with a mutual side arm can be used as advantageous output element. It has the transition attenuation over 40 dB during the excitation period and provides effective energy extraction through two channels when the extraction process is controlled by a single switch.

References

[1] A.N. Didenko, Yu.G. Yushkov, *High power nanosecond microwave pulses,* Moscow, Energoatomizdat, 1984, pp. 32–41.

[2] Z.D. Farkas, H.A. Hogg, G.A. Loew, P.B. Wilson, *in: Proc. 9th Int. Conf. on High Energy Accelerators*, 1974, pp. 576–583.

[3] S.N. Artemenko, V.L. Kaminsky, Yu.G. Yushkov, Letters to J. Tech. Physics **7***,* 1529 (1981).

[4] S.A. Novikov, S.N. Artemenko, A.V. Avgustinovich et al., "Microwave pulse compression in system of cavities connected in series", presented at *13th Symposium on High Current Electronics*, Tomsk, Russia, 2004.

[5] S.N. Novikov, S.V. Razin, P.Yu. Chumerin, Yu.G. Yushkov, *Author Certificate SU 1302995*, 1985.

[6] J.L. Altman, *Microwave Circuits*, London, Nostrand Company, 1964, pp. 159–184.

[7] S.N. Artemenko, A.V. Avgustinovich, Rus. Radiotechnique and Electronics **45**, 125 (2000).