Frequency-Agile High-Power Resonant Microwave Compressors[1]

S.N. Artemenko, V.A. Avgustinovich, and A.S. Shlapakovski

Nuclear Physics Institute, 2a, Lenina ave., Tomsk, 634050, Russia
Phone: 8(3822) 72-31-76, Fax: 8(3822) 42-39-34, E-mail: novsa@npi.tpu.ru

Abstract – The problem of creating high-power resonant microwave compressors capable of wide-band frequency tuning is considered. Results of the theoretical analysis are presented for the compressor configuration including a storage cavity and output interference switch based on a waveguide H-tee and, also, for the configuration comprising a symmetric storage system and input-output coupler in the form of double waveguide tee. Experimental results are presented for the two elaborated prototypes of tunable X-band compressors. It has been shown that the operating frequency hopping is possible due to the transition to neighbor cavity modes, and the range of hopping can be as wide as the band of a single-mode waveguide. In experiments, the gain of ~ 16 dB at ~ 1.6 MW output power was achieved for 2 frequencies distanced at ~ 230 MHz from each other; compressor operation at 4 frequencies within the band of ~ 550 MHz was demonstrated. At a certain degree of the H-tee "sub-opening", frequency variation is possible without mechanical tuning; this was also shown experimentally.

1. Introduction

The resonant pulse compression technique based on the microwave energy storage in a cavity with its following fast release allows one to produce microwave pulses of nanosecond duration and megawatt-to-gigawatt peak power level from rather compact and relatively inexpensive devices. At the same time, resonant pulse compressors are, in their nature, narrow-band devices. This limits attractiveness of compressors as high-power microwave sources for laboratory research.

Meanwhile, a frequency-agile compressor would be a best candidate for an RF drive source of a relativistic amplifier with 10^8–10^9 W output power. First, a compressor meets a requirement for the RF drive to have a pulse length much shorter than electron beam pulse duration (i.e., 10–100 ns) that provides phase stability of an amplifier output signal. Second, it easily provides the power level of and above 1 MW that significantly exceeds the noise level typical for beams produced from explosive emission cathodes and is most proper for amplifiers with relatively low gains (20–30 dB). Thus, using a multi-frequency (wideband) compressor would make possible a stable operation of an amplifier with a control of output radiation frequency, power, and phase.

Another application of high-power frequency-agile compressors could be testing electronic hardware. To the investigations typically performed with the usual compressors [1], frequency-agile compressors can add the studies of the effects of not only the frequency, but also the waveform of irradiation pulses, namely, the influence of microsecond prepulse level on critical power and energy fluxes for an irradiated device.

In addition, it seems probable that frequency-agile compressors find some applications in radar systems.

In this paper, possibilities of frequency tuning are considered for the compressors with a storage cavity and waveguide tee-based interference switch. Results of theoretical analysis and experimental testing are presented for the X-band compressors.

2. Storage cavity spectrum and interference switch frequency dependence

Usually, for a compressor storage cavity, a waveguide section is employed, whose length $L >> \lambda_w$, where λ_w is the wavelength in the cavity. Accordingly, the operating cavity mode has a large axial index $p >> 1$. The formula for cavity eigenfrequency is well known:

$$f = \frac{c}{\lambda_c}\sqrt{1+\frac{p^2\lambda_c^2}{4L^2}}, \tag{1}$$

where λ_c is the cutoff wavelength for the operating cavity mode. The key characteristic of a resonant compressor is the double transit time of the operating wave along the cavity T_r. For a compressor with an ideal switch, at ideal matching with a load, this time coincides with output pulse duration. T_r is expressed through the operating frequency and cavity length as

$$T_r = \frac{4L^2 f}{c^2 p}. \tag{2}$$

Using (1) and (2), one can estimate the interval Δf between neighbor cavity modes:

$$\Delta f \approx T_r^{-1}. \tag{3}$$

Within the band of a single-mode waveguide, e.g., for $T_r = 5$ ns, in the X-band, there can be about ten cavity modes differing by their axial index. It should be noted that Δf is approximately the same as the typical spectral width determined by the compressor out-

[1] The work was supported in part by the Russian Foundation for Basic Research (Grant No. 05-08-01150). The authors are grateful to Dr. Yu.G. Yushkov for his interest and stimulating discussions.

put radiation pulse length. Evidently, the minimum tuning range for a compressor operating frequency should be of the order of Δf.

If the operating frequency is changed, the closing frequency of the switch must be changed accordingly. Usually, the switch is the waveguide H-tee with the short-circuited arm, in which the gas discharge plasma commutator is placed. The closing frequency is changed by the variation of the short-circuited arm electrical length using, say, a movable membrane. The compressor with the short-circuited side arm of the tee is schematically shown in Fig. 1. The input signal enters into the storage cavity through the coupling hole; the output signal, after the commutator switches the tee over from the closed to open state, goes through the tee straightforward arm to the load.

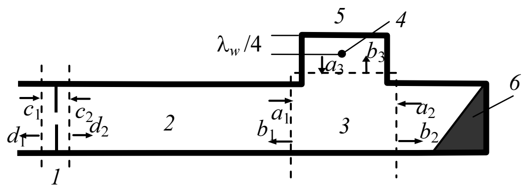

Fig. 1. Resonant compressor with an H-tee-based interference switch: *1* – input diaphragm; *2* – storage cavity; *3* – H-tee; *4* – microwave commutator; *5* – movable short-circuiter; *6* – matched load. Arrows designate incident and reflected waves

Determine the H-tee band-pass properties to compare them with characteristic interval (3) of cavity spectrum. The amplitudes of the waves are shown in Fig. 1. According to the method of scattering matrix [2], in the H-tee region, they relate as:

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}, \quad (4)$$

In the short-circuited arm, $a_3 = -b_3 \exp(-\beta - i\psi)$, where β is the attenuation constant and ψ is the phase incursion at the arm double transit time. For an ideally matched load ($a_2 = 0$), one can easily get from (4) the following formula for the tee transition attenuation:

$$R^2 = \frac{|b_2|^2}{|a_1|^2} = \frac{[1-\exp(-\beta)]^2}{4} + \exp(-\beta)\sin^2\frac{\psi}{2}. \quad (5)$$

It is convenient to rewrite (5) in terms of the deviation from the closing frequency δf and cavity characteristics. Assuming the cross-sections of the tee waveguides and cavity are the same and using the relationships $\psi = 2\pi T_r \delta f/n,\ \beta = \alpha/n,\ \alpha = \pi f T_r/Q_0$ where n is the ratio of the cavity length to the tee side arm length, α is the attenuation constant at the cavity double transit time, and Q_0 is the quality factor of the cavity operating mode, one can obtain for $\beta \ll 1$

$$R^2[\text{dB}] = 20\lg\frac{\pi f T_r}{2nQ_0} + 10\lg\left(1 + \frac{4n^2Q_0^2}{\pi^2 T_r^2 f^2}\sin^2\frac{\pi T_r \delta f}{n}\right),$$

where the first term is the transition attenuation of the closed tee. For the frequency deviation determined by (3), the second term is $\approx 20\lg(2Q_0/T_r f)$. For typical parameters (f = 10 GHz, $Q_0 = 10^4$, T_r = 5 ns), its value exceeds 50 dB that is very high. The transition attenuation falls down to values unacceptable for a compressor operation very rapidly; it becomes less than 40 dB at δf of ~ 10 MHz.

Nevertheless, for a short side arm, compensating the frequency deviation (to close a tee again) does not require big changes of the side arm length. One can easily show that such a change $\delta l = -\lambda_w T_r \delta f/2n$. At the minimum possible length of the side arm, for the transition to the neighbor cavity operating mode, the needed length change $\delta l \approx \lambda_w/2p$; for the X-band and T_r = 5 ns, this value is of the order of 1 mm.

3. Compressor characteristics at tee "sub-opening"

Let us now consider the compressor of Fig. 1 as whole. The relation of the wave amplitudes in the diaphragm region is given by its scattering matrix

$$\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = \begin{pmatrix} -\sqrt{1-k^2} & ik \\ ik & \sqrt{1-k^2} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}, \quad (6)$$

where k is the coupling coefficient. In the cavity region, the amplitudes relate as

$$a_1 = d_2 \exp[(-\alpha - i\varphi)/2],\ c_2 = b_1 \exp[(-\alpha - i\varphi)/2], \quad (7)$$

where φ is the phase incursion at the cavity double transit time. Adding to (6) and (7) already written relations for the tee region and making some simple algebra, one can obtain the general formula for the cavity gain

$$M_r^2 = \frac{|d_2|^2}{|c_1|^2} = k^2\left\{1 - \sqrt{1-k^2}\, e^{-\alpha}\left[\cos\varphi + e^{-\beta}\cos(\varphi+\psi)\right] + \right.$$

$$\left. +0.25\left(1-k^2\right)e^{-2\alpha}\left(1 + 2e^{-\beta}\cos\psi + e^{-2\beta}\right)\right\}^{-1}. \quad (8)$$

Hence, the gain of the cavity with the tee reaches maximum if φ satisfies the following equation:

$$\text{tg}\varphi = -\frac{\exp(-\beta)\sin\psi}{1+\exp(-\beta)\cos\psi}. \quad (9)$$

This formula defines, in fact, the compressor operating frequency, which, at the sub-opened tee, is not exactly the same as the cavity eigenfrequency. The difference δf is given by the relation $\varphi = 2\pi T_r \delta f$. Let us now consider the interval (0, 2π) of ψ variation that means the tee is sub-opened, then fully opened, and closed again. At the ends of this interval, δf = 0. Thus, assuming $\beta \ll 1$, one can get from (8) and (9) the expression for the maximum cavity gain

$$M_r^2 \approx \begin{cases} k^2\left[1-\sqrt{1-k^2}\exp(-\alpha)\cos\frac{\psi}{2}\right]^{-2}, \ \psi\in(0,\pi); \\ k^2\left[1+\sqrt{1-k^2}\exp(-\alpha)\cos\frac{\psi}{2}\right]^{-2}, \ \psi\in(\pi,2\pi). \end{cases} \quad (10)$$

The gain can be further optimized by adjusting the input coupling. For the closed tee ($\psi = 0$), the optimal value of the coupling coefficient is

$$k_0^2 = 1-\exp(-2\alpha) = 1-\exp\left(-2\pi f T_r/Q_0\right). \quad (11)$$

The calculation results for maximum cavity gain (10) at fixed input coupling (11) are shown in Fig. 2 along with the operating frequency deviation from the tee closing frequency. The Q-factors here are typical for a single-mode (curve 1) and moderately oversized (curve 2) X-band cavity. It is seen that with sub-opening tee, the cavity gain abruptly decreases at the operating frequency changing by 10–15 MHz. With opening tee, the wave amplitude in the cavity becomes less than the amplitude of the incident wave. When the tee is fully open, the frequency jumps, and then, the gain starts increasing, and the frequency returns to its initial value, just from the opposite side.

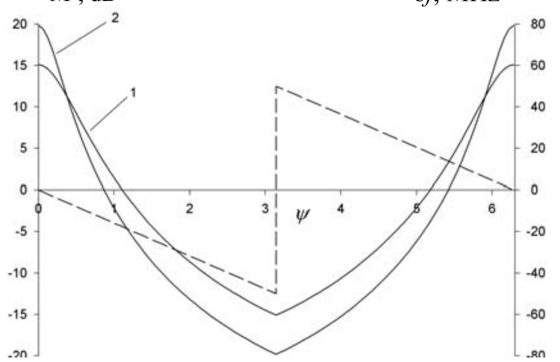

Fig. 2. Cavity gain vs the tee state at the fixed input coupling optimal for the closed tee. The dashed curve shows the difference between the operating frequency and the tee closing frequency: $f = 10$ GHz, $T_r = 5$ ns, $Q_0 = 1 - 10^4$; $2 - 3 \cdot 10^4$

So, the gain in the given operating cavity mode decreases when the tee side arm length changes from the value that corresponds to $\psi = 0$. At the same time, the gain increases for the neighbor cavity mode. Its eigenfrequency equals the tee closing frequency at $\delta l \approx \lambda_w/2n$ that corresponds to $\psi = 2\pi/n$, so that the gain in the neighbor mode is given by Eq. (10), in which ψ is substituted with $\psi - 2\pi/n$. Fig. 3 shows so calculated values of the gain and frequency for the three cavity modes with decreasing axial index. It is seen that the gains in two neighbor modes become equal at tee sub-opening when the phase change with regard to the tee closed state reaches π/n for both frequencies, so that operating frequency jumps at $\delta l > \lambda_w/4n$ as shown in Fig. 2. Further increasing the tee side arm length leads to a further jump; so one can overlap a single-mode waveguide passband.

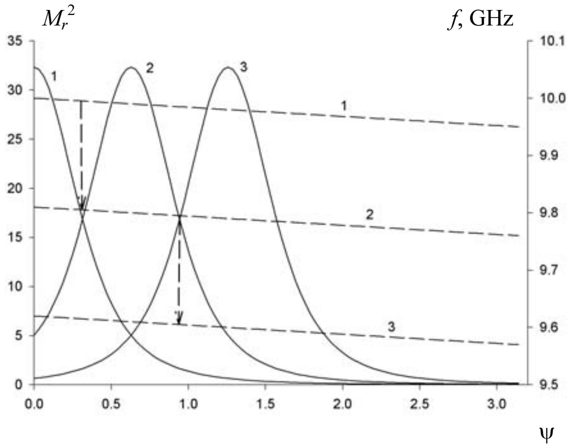

Fig. 3. Cavity gain for three neighbor modes at the changing length of the tee short-circuited arm. $\psi = 0$ corresponds to the length, at which the tee closing frequency $f = 10$ GHz. Dashed lines show the operating frequencies for each mode, arrows indicate a transition to a neighbor mode increasing the gain. $n = 10$, $T_r = 5$ ns, $Q_0 = 10^4$

It should be also noted that when the degree of tee sub-opening is the same for two neighbor cavity modes, switching over between them is possible, i.e., one can change the compressor operating frequency without any change of geometry. Such possibility is achieved at the expense of gain decreasing; though, the said decreasing is smaller at larger n. Furthermore, switching over without changing geometry is possible between three modes as well; for instance, at $n = 20$ and other parameters of Fig. 3, the gain at the centered frequency, at which the tee is closed, would be only twice as much as that at both side frequencies, at which the tee is identically sub-opened.

Let us finally write formulas for the direct characteristics of the compressor output radiation: compressor gain M_c^2 and prepulse power (related to incident wave power) M_p^2. One can easily show that

$$M_p^2 = \frac{1}{4}M_r^2 e^{-\alpha}\left[\left(1-e^{-\beta}\right)^2 + 4e^{-\beta}\sin^2\frac{\psi}{2}\right];$$

$$M_c^2 = \frac{1}{4}M_r^2 e^{-\alpha}\left[\left(1-e^{-\beta}\right)^2 + 4e^{-\beta}\cos^2\frac{\psi}{2}\right]. \quad (12)$$

Evidently, the compressor gain is less than the cavity gain because of the tee "sub-closing" during energy release; however, the difference is negligible if the gain is considerable ($\psi < 0.5$). On the contrast, the prepulse power strongly changes in this range. For parameters of Fig. 3, the ratio of output pulse power to the prepulse power calculated from (12) changes from 62 to 12 dB. Thus, the compressor is able to form widely variable combinations of a long (microsecond), relatively low-power prepulse and short (nanosecond) high-power pulse. The prepulse energy can be much less than that of nanosecond pulse, or can be significantly greater. Such combined signals may be required in research on testing electronic hardware [1].

4. Compressor with a symmetrical storage system

Symmetrical configuration of microwave compressor is based on the double waveguide tee. If its side arms are short-circuited forming a storage cavity, which is separated from the input arm by the diaphragm with the coupling hole, a signal does not enter into the output arm when the side arm lengths are equal. If they differ by quarter wavelength, the double waveguide tee opens, and a stored energy is released.

It is important that operation of such compressor does not put any requirement on the frequency, unlike the traditional compressor. Hence, it is capable of discrete frequency tuning due to transition to neighbor cavity modes without any change of geometry. Also, it is capable of continuous frequency tuning by an identical changing the length of both side arms, which is much easier to realize than non-identical changing the lengths of cavity and tee short-circuited arm needed for continuous frequency tuning in the traditional compressor configuration.

Using the method of scattering matrix, as in the previous section, one can obtain the following formula for the maximum cavity gain in the symmetrical case:

$$M_r^2 = \frac{k^2}{2}\left[1-\sqrt{1-k^2}\exp\left(-\frac{\alpha}{2}\right)\cos\frac{\psi}{2}\right]^{-2}. \quad (13)$$

Here, ψ is the phase incursion due to inequality of the side arm lengths. For the closed tee ($\psi = 0$) and optimal coupling coefficient k, formula (13) gives, in fact, the same cavity gain as in the traditional compressor ($M_{r\ \max}^2 \approx 1/2\alpha$ at $\alpha << 1$). At the same time, the compressor gain in the symmetrical system is almost twice higher since energy is released from both storage arms simultaneously, and the output pulse duration is twice shorter since it is determined by the double transit time of just one side arm.

5. Experimental results

Two frequency-agile compressor prototypes, both of traditional configuration, were elaborated and tested. In the first prototype, the storage cavity was made of ∅49 mm copper tube that is moderately oversized in the operating frequency range of the employed pulsed magnetron (9.0–9.5 GHz). The H-tee was made of single-mode circular waveguide sections with a smooth Chebyshev-type matching transition. Its side arm of ~ λ_w in length was short-circuited by a deformable membrane allowing variation of the tee closing frequency within the range of 300 MHz. The $TE_{11(31)}$ and $TE_{11(32)}$ cavity modes were chosen to be operating. For these modes, the eigenfrequencies of 9.156 and 9.388 GHz and the Q-factor of ≈ $2.8 \cdot 10^4$ were measured at low-power level, and the calculated compressor gain is ~ 19.5 dB at ~ 4 ns cavity double transit time. Switching at high-power level (input signal of 30–40 kW, 1 μs) occurred either in air or in argon-air mixture at atmospheric pressure.

In Fig. 4, the output pulses are shown. Changing operating frequency required ~ 2.5 mm displacement of the tee side arm membrane. For both operating modes, the maximum gain was 16.2 dB at ~ 1.6 MW output power and ~ 4 ns FWHM pulse duration. The gain and prepulse power at tee sub-opening were measured; the results qualitatively agreed with calculations using expressions (10)–(12). Minimum possible gain needed for RF discharge initiation was ~ 7 dB, so the prepulse power increased by ≥ 20 dB remaining order of magnitude less than output power.

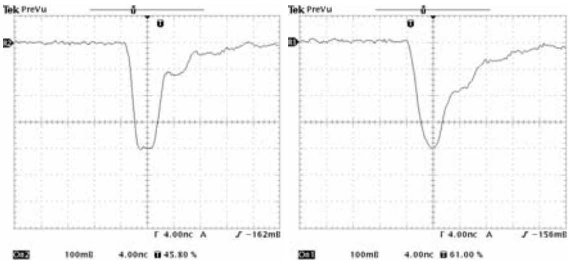

Fig. 4. Output pulses of the compressor with the multimode cylindrical cavity. Left: f = 9.156 GHz, mode $TE_{11(31)}$. Right: f = 9.388 GHz, mode $TE_{11(32)}$. The tee is adjusted for maximum gain in each case

The second prototype was made with minimum possible length of the tee side arm ~ $\lambda_w/2$. The single-mode rectangular waveguide (23 × 10 mm) was used for the cavity. The tee membrane deformation within ~ 2.5 mm provided the cavity adjusting for the four, TE10(22) to TE10(25), eigenmodes. Therefore, this compressor was capable of switching over the frequency without mechanical tuning when operating in three mode pairs: $TE_{10(22)}$–$TE_{10(23)}$, $TE_{10(23)}$–$TE_{10(24)}$, or $TE_{10(24)}$–$TE_{10(25)}$. In the experiments, maximum gain of ~ 11.5 dB was obtained at 9.212 and 9.396 GHz; the output pulses were the same as in Fig. 4 (0.55 MW power and 5.5 ns duration). At tee sub-opening, the gain reduced down to 6–7 dB, and the prepulse appeared (see Fig. 5, the successful demonstration of the frequency hopping).

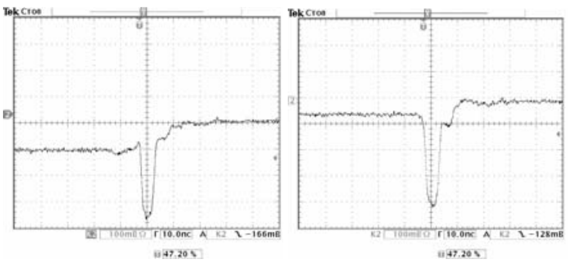

Fig. 5. Output pulses at operating frequency changing in the compressor with the rectangular cavity. The tee membrane position is fixed. Left: f ≥ 9.212 GHz, mode $TE_{10(23)}$. Right: f ≤ 9.396 GHz, mode $TE_{10(24)}$.

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