Microwave Pulse Compression in System of Cavities Connected in Series

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Abstract – The report studies the resonant microwave pulse compression system comprising two storage cavities connected in series. The first cavity is high-Q multimode, the second one is cylindrical singlemoded. The process of energy transfer from the first cavity into the second one affects the output system parameters considerably. Electric field strength values in the S-band cavities were determined as functions of time and transition factor for the periods of excitation and energy transfer. Experimental data are presented.

1. Introduction

The output microwave pulse of a resonant pulse compressor (RPC) can be subjected to compression once more and transformed into one of higher power and shorter pulsewidth. The process is the series compression and it allows to increase output power in comparison with the maximum power achieved by a singe cavity.

In order to increase output parameters of the series compression RPC the output pulse power and pulsewidth of a primary microwave exciting source should be increased as well as the first cavity should be designed high-Q and multimode. The energy extraction from such a cavity can not be executed in a fast manner even into a matched load and the pulsewidth of microwave pulses at its output is usually from several tens to hundreds of nanoseconds. During energy transfer from the first cavity into the second one the mutual coupling reaches a steadystate high value and initiate the transient process characterized by the time constant comparable or exceeding the output pulsewidth of the first cavity.

Parameters of the system comprising two S-band coupled cavities were estimated at different values of the transition factor between the cavities and some experimental data are presented.

2. Cavity Excitation and Energy Transfer

The series connection of two cavities can be presented by the schematic shown in Fig. 1.

The introduced factor h corresponds to the integrated transition attenuation of the first cavity output element and the second cavity input element.

The cavities *1* and *2* are excited by a single primary source, its pulses having the amplitude of $|a_1|$. The value $|a_1|$ is normalized on the primary source power P_g basis $P_g = \frac{1}{2}|a_1|^2$. The energy extraction comes sequentially: at first the transition factor h increases and the transfer begins and then only after the second cavity is excited its output factor m increases to couple the cavity and a load.

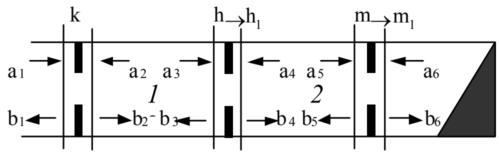

Fig. 1. Simplest schematic for series compression in two cavities. *1* – first cavity; *2* – second cavity; *k*, *h*, *m* – transition factors of corresponding discontinuities

Differential equations for the excitation period can be derived from matrix equations relating the wave amplitudes $a_1 \ldots a_6$, $b_1 \ldots b_6$ of the discontinuity areas [1] assuming that double traveling times T_1 and T_2 along cavities *1* and *2* respectively are small in comparison with the time of the process in question:

$$\begin{cases} \dfrac{db_2(t)}{dt} + \dfrac{b_2(t)}{\tau_1} = \dfrac{2jka_1}{T_1\sqrt{1-k^2}\sqrt{1-h^2}e^{-\alpha_1}} + \\ + \dfrac{2jh\sqrt{1-k^2}\sqrt{1-m^2}e^{-\alpha_1/2-\alpha_2}}{T_1(1+\sqrt{1-k^2}\sqrt{1-h^2}e^{-\alpha_1})} b_4(t); \\ \\ \dfrac{db_4(t)}{dt} + \dfrac{b_4(t)}{\tau_2} = \dfrac{2jhb_2(t)e^{-\alpha_1/2}}{T_2\,(1+\sqrt{1-h^2}\sqrt{1-m^2}e^{-\alpha_2})}. \end{cases} \quad (1)$$

The output signal envelope is determined by

$$b_6(t) = jmb_4(t)\,e^{-\alpha_2/2}\,. \quad (2)$$

Here τ_1 and τ_2 – time constants; α_1 and α_2 – wave decay constants at double traveling along the cavities *1* and *2* respectively; j – unit imaginary number.

Calculated plots for the traveling wave amplitude as a component of the standing wave in the first and second cavities are presented in Fig. 2 for the time interval $0 \le t \le t_g$ when $a_1 = 1$ and the width of exciting pulse $t_g = 6 \cdot 10^{-6}$ s. Besides the plots apply to following parameters $T_1 = 5.23 \cdot 10^{-9}$ s, $T_2 = 3.43 \cdot 10^{-9}$ s,

$Q_{01} = 7 \cdot 10^4$; $Q_{02} = 1.9 \cdot 10^4$; $\omega = 2\pi \cdot 2.8 \cdot 10^9$ s^{-1}; $\alpha_1 = \omega T_1/(2Q_{01})$; $\alpha_2 = \omega T_2/(2Q_{02})$; $k = 0.5$ and $m = 10^{-2}$.

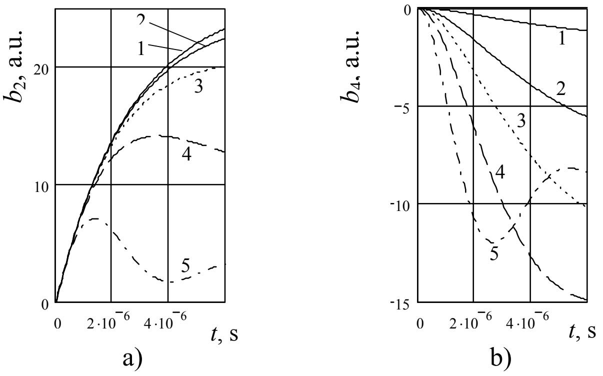

Fig. 2. Traveling wave amplitudes in the first a), and the second b) cavities respectively during excitation. 1 – $h = 10^{-4}$; 2 – $5 \cdot 10^{-4}$; 3 – 10^{-3}; 4 – $2 \cdot 10^{-3}$; 5 – $5 \cdot 10^{-3}$

Plots of Fig. 2 prove that the isolation between cavities is necessary during first cavity excitation by the primary microwave source. In this particular case when h exceeds $2 \cdot 10^{-3}$ the resonant energy transfer from one cavity to another starts without switching and that decreases the stored energy in the first cavity.

Values $b_2(t_g)$ and $b_4(t_g)$ are used as initial conditions for the differential equations of the energy transfer process when the transition factor h acquires the new value h_1. Additional phase shifts φ and ψ can be taken into account in the relationships for traveling wave amplitudes in regular sections of both cavities and also one can assume that the second cavity is decoupled from the matched load during the process. The differential equations for the energy transfer period are also derived from the matrix equations and are justified when T_1 and T_2 are small:

$$\begin{cases} \dfrac{db_2(t)}{dt} + \dfrac{b_2(t)}{\tau_1} = c_{11} \cdot b_4(t) - c_{21} \dfrac{db_4(t)}{dt}; \\ \dfrac{db_4(t)}{dt} + \dfrac{b_4(t)}{\tau_2} = c_{12} \cdot b_2(t) - c_{22} \dfrac{db_2(t)}{dt}. \end{cases} \tag{3}$$

Here c_{11}, c_{12}, c_{21}, c_{22} – coefficients which are functions of the system parameters T_1, T_2, h_1, k, α_1, α_2, ψ, φ.

The plots of the calculated time dependant wave amplitudes in the second cavity when the stored energy of the first cavity is being transferred is plotted in Fig. 3. At h_1 increasing the character of energy transfer process varies from aperiodic into periodic one along with increase of the beat amplitude. Within the interval under review the amplitude in the second cavity is higher when the transfer period of the resonant mode process is smaller.

The energy transfer efficiency and transfer period plotted against h_1 value are presented in Fig. 4.

The efficiency was estimated as the ratio of the maximum energy reached in the second cavity to the energy value in the first cavity in a moment of its switching over.

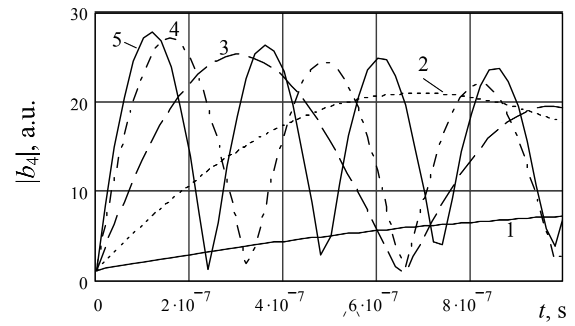

Fig. 3. Wave amplitude in the second cavity during energy transfer process for 1 – $h_1 = 1.5 \cdot 10^{-3}$, 2 – $0.8 \cdot 10^{-2}$, 3 – $2 \cdot 10^{-2}$, 4 – $4 \cdot 10^{-2}$, 5 – $5 \cdot 10^{-2}$ and phase shift values $\psi = \varphi = h_1/2$

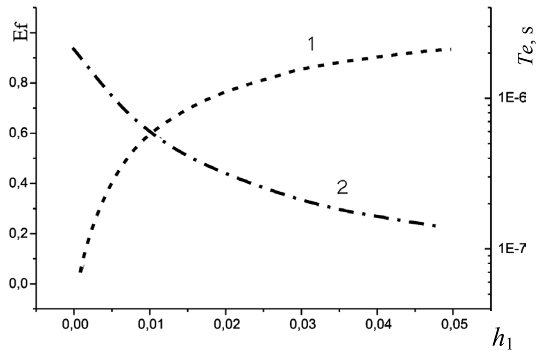

Fig. 4. Plots of the energy transfer efficiency E_f (1) and the transfer period transition (2) against the T_e factor h_1

The output pulse envelope $b_6(t)$ was calculated according (2) where the factor m takes on the value $m_1 \geq 0.5$ when the wave amplitude in the second cavity (see Fig. 3) reaches its maximum value. The calculation showed:

– the total power amplification factor of the series compression exceeds the value of RPC with a singular cavity; power amplification over 25 dB can be obtained in RPC with a singular cavity only with respect to the field inside a multimode cavity but, as has already been mentioned, the energy extraction during the double traveling time is not attainable;

– assumed low values of the loaded Q-factor and the time constant of the second cavity as a cavity of the last compression stage correspond to a singlemode overcoupled cavity which allows to form short microwave output pulses with the pulsewidth of several nanosecond in S-band to hundreds of picosecond in X-band.

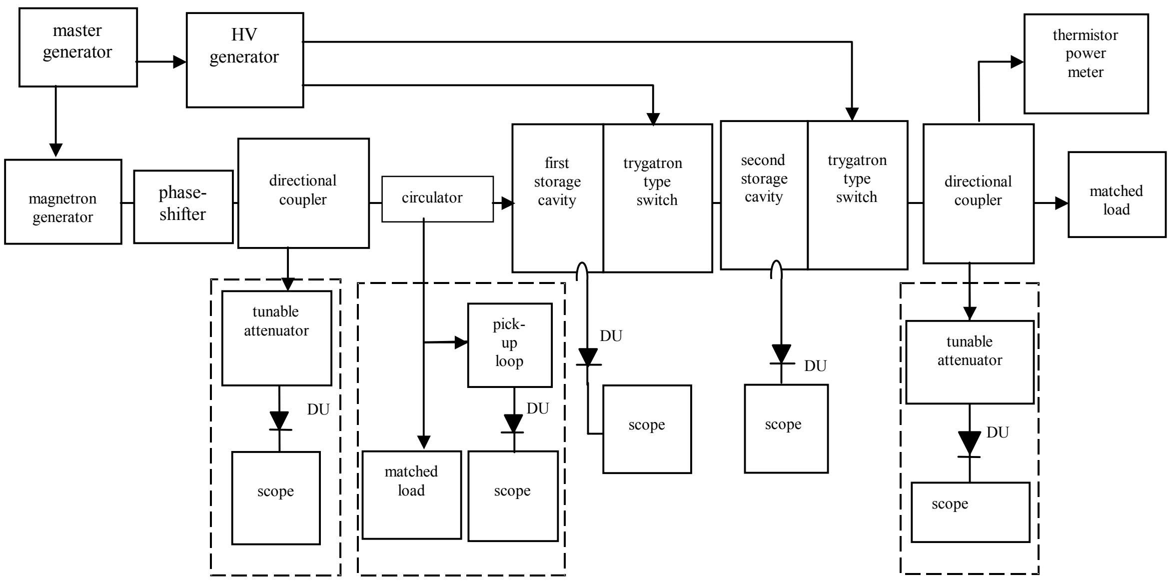

Fig.5. Block-diagram of the set-up with the series compression of microwave pulses. DU- diode unit

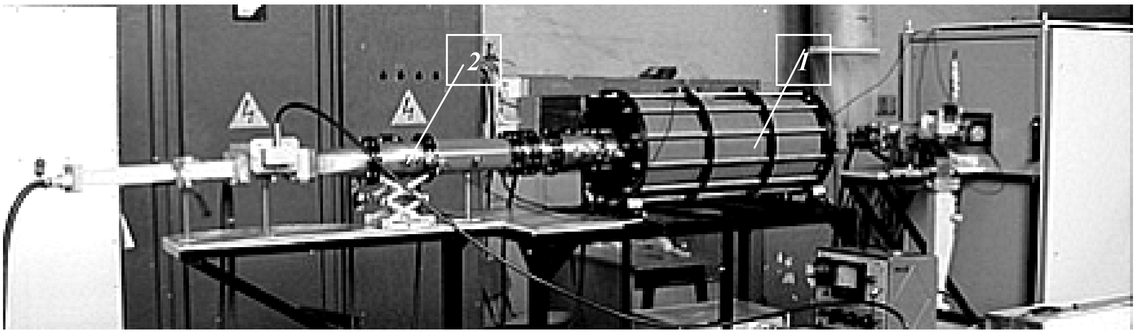

Fig. 6. Layout of with two cavities connected in series. *1* – first cavity; *2* – second cavity

3. Two Stage Compression RPC

The objective of the development of the experimental set-up was the testing of RPC operation in the resonant mode of energy transfer into the second cavity with the output parameters surpassing parameters of already reported RPC [2]. The typical block-diagram of RPC with two series connected storage cavities is shown in Fig. 5. The device operates as follows. The magnetron generator produces a microwave pulse exciting the first cavity. After the delay equal approximately to the microwave pulsewidth the HV pulse of the triggering generator initiates the commuting discharge in the first cavity switch. The energy of the first cavity is transferred into the second one and after the latter is excited the second HV pulse drives its switch into action leading to extraction of the energy in a form of a short nanosecond microwave pulse. The output power is measured by the method of comparison using the circuit comprising a calibrated waveguide coupler, calibrated coax variable attenuator, diode unit and oscilloscope.

The two cavities S-band RPC with series compression is shown in Fig. 6. The exciting microwave source is the adjustable magnetron generator having a working frequency tunable in the range 2.795…2.806 GHz, maximum pulse power 2.7 MW, maximum pulsewidth 6 μs and maximum repetition frequency 200 Hz during 1 min bunch operation. These parameters produce the stored energy value in the first cavity exceeding 6 J but the energy density should not be higher than 0.1…0.2 J/m^3. Considering this and taking account of the local spectrum density of natural frequencies the cavity of the first compression stage had diameter of 300 mm, length 766.5 mm and the working mode $H_{11(14)}$. The unloaded Q-factor was $Q_0 \approx 8 \cdot 10^4$ and the power amplification factor was estimated as $M^2 \approx 64$ if the losses in the switch were neglected. For the short output pulsewidth of about 3 ns the length of the second cylindrical cavity should be approximately 370 mm at the diameter of the cross section 90 mm and the working mode $H_{11(5)}$.

The energy transfer is defined by

$$W_2 = W_1 e^{-t/2\tau_2} \sin^2 \Omega t ,$$

where W_1, W_2 – stored energy values of excited field in the first and the second cavity respectively, $\Omega = \dfrac{h_1}{\sqrt{T_1 \cdot T_2}}$. At the moment to $t_0 \approx \pi\sqrt{T_1 \cdot T_2}\,/\,2h_1$ the energy is extracted from the first cavity but

$W_2 \approx W_1 e^{-t_0/2\tau_2}$ and W_2 is higher when t_0 is smaller or h_1 – larger.

The oscillogram of the signal envelope showing the field strength variation in the first cavity when the switching is brought up and the energy is extracted is presented in Fig. 7. The oscillogram of the signal picked up from the second cavity when the resonant transfer of energy takes place without switching and within energy extraction is shown in Figs 8, *a*, *b* shows the signal but when the switching occurs at the moment the field strength comes to its maximum value of the first period of beats.

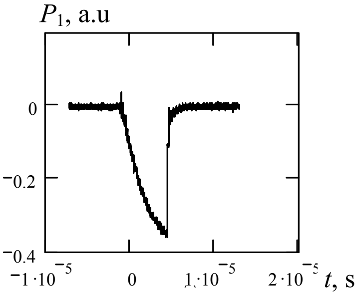

Fig. 7. The envelope of the first cavity signal when the energy is transferred

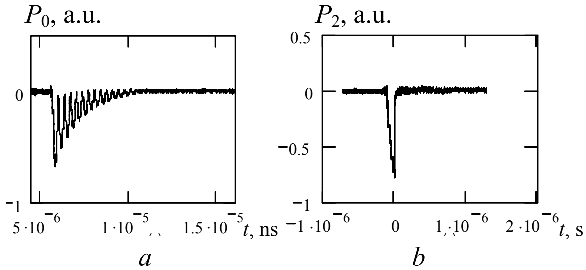

Fig. 8. The envelope of the second cavity picked up signal: *a* – energy is transferred but is not extracted from the cavity; *b* – when energy is extracted

The output pulse envelope is presented in Fig. 9. The maximum pulse power value was P_{out} = 1.2 GW measured by the method of comparison. The pulse-width determined at –3 dB peak power level was close to 3 ns.

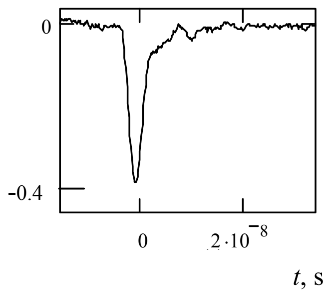

Fig. 9. The envelope of the output pulse

So calculations and experimental showed high efficiency of the resonant energy transfer from the first cavity into a subsequent one at forming short microwave pulses in RPC. In RPC presented above the transfer efficiency was about 80%. Application of this process may allow the development of microwave sources having the pulsepower exceeding 1 GW and operating in the pulse repetition mode.

The authors thank V.F. Dyachenko, L.D. Butakov for fruitful help in experiments and V.A. Vizir and his team of High Current Electronic Institute SD RAS for manufacturing and fixing the HV modulator for magnetron generator.

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