Installations Using Resonant Pulse Compression for Generating Ultra-Short High Power Pulses in X-, K- and Q-band

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Abstract – The report reviews the designs of devices built on the basis of commercially issued magnetron transmitters and meant for generation of high power nanosecond microwave pulses in X-, K- and Q-band. The experimental data of their testings are presented.

1. Introduction

Studying the interaction of an electromagnetic field with matter, electronic devices, biological objects, etc., requires high-power sources of single-pulse and repetitively pulsed microwave radiation with a duration of 10^{-11}–10^{-6} s [1–3]. One of the most promising trends in the development of such sources is associated with the technique of obtaining ultrashort pulses by the resonant pulse compression of the energy of continuous or periodically pulsed radiation of microsecond duration [4].

This paper presents results obtained at development of resonant pulse compressors in X-, K- and Q-band and designs of devices for generation of high power microwave pulses with the output pulsewidth stepwise adjustment

2. K-Band Device with Output Pulsewidth Stepwise Adjustment

The application of this technique gives way to development of the devices with output pulsewidth adjustment in the range from one cycle of carrier frequency oscillations to CW mode. Radiation pulses with a minimum duration of 50–100 ns are provided by conventional microwave sources based on classical vacuum tubes and modulators with partial discharge of the energy storage. Using these devices for resonant pulse compression allows one to obtain microwave pulses t_p out at the tube and modulator outputs that are shorter than the pulses generated by them with durations t_b. At the same time, he peak power increases by a factor of $\eta_н \cdot \eta_b \cdot t_p/t_b$ out, where $\eta_н$ is the storage efficiency and η_b out is the outputting efficiency. The value of η_b is 70–90%; this is determined by the efficiency of switch operation. The value of $\eta_н$ can be determined through the parameters of the resonance system (the intrinsic quality factor Q_0, the coupling factor β relative to the excitation channel, and the resonator time constant

$$\tau = 2Q_0 / (\omega(1 + \beta))$$

and the oscillator parameters (the carrier frequency of oscillation ω and the pulse duration) using the relation [6]

$$\eta_i = 2\frac{\beta}{1+\beta}\frac{\tau}{t_p}\left(1-\exp\left(\frac{t_b}{\tau}\right)\right)^2. \qquad (1)$$

A simplified diagram of the facility is shown in Fig. 1. The magnetron transmitter 1 provides three generation modes whore parameters are presented in Table 1. To control the pulse duration and repetition rate in steps, the transmitter utilizes a modulator designed for the partial discharge of the capacitive energy storage.

Table 1

Parameter	Microwave transmitter	Facility with a single compressor	Facility with a 2.5-ns compressor	Facility with a 1-ns compressor	Facility with two-stage compression	
Pulse duration, ns	1500,800,300	10	2.5	1	2.5	1
Peak power, kW	58	1624	300	580	3300	10000
Pulse repetition rate, Hz	200, 600, 1500	200	1500	1500	200	200
Power amplification factor, dB		14.4	7.14	10	17.5	22.4
Compression efficiency, %		18.7	4.31	3.33	9.5	11.5
Compression factor		150	120	300	600	1500
Power consumed from the mains, W ~ 115 V,						
400 Hz	1400	1800	1800	1800	1800	1800
+27 V	200	200	200	200	200	200
Weight, kg	80	99.7	99.7	98.9	100	99.9
Volume, m^3	0.166	0.213	0.213	0.213	0.213	0.213

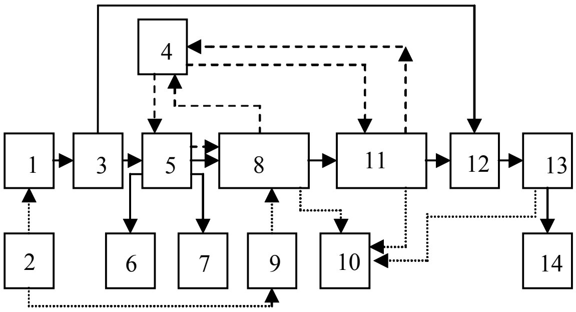

Fig. 1. Block diagram of the facility: 1 – microwave transmitter; 2 – control unit; 3, 12 – waveguide electromechanical switches; 4 – gas filling system; 5 – phase circulator; 6, 7 – circulator loads; 8 – first-stage compressor; 9 –spark-gap triggering unit; 10 – system for signal indicators and parameter measurements; 11 – second-stage compressor; 13 – coupler; 14 – dummy antenna

Two waveguide electromechanical switches 3 and 12 allow the facility to be operated in either a microsecond or nanosecond operating mode. In the microsecond mode, the radiation generated by the magnetron is fed to the input of directional coupler 13 and, from its output, to the antenna or dummy antenna 14. In the nanosecond mode, magnetron pulses arrive at the input of phase circulator 5, designed to match the magnetron to resonance pulse compressor 8. Loads 6 and 7 absorb the power of the waves reflected from the compressor input during the excitation of its resonance system.

To achieve a pulse-periodic mode of radiating nanosecond pulses, three compressors are used.

The design selected for the first compressor was determined by the possibility of obtaining pulses with the maximum peak power at the facility output. For this purpose, the microwave transmitter was switched to the emission mode with a pulse duration of 1500 ns and a pulse repetition rate of 200 Hz. Analyzing relationship (1) shows that, in order to obtain a compression efficiency > 10–20%, the resonance system of the compressor must include a superdimensional high-Q resonator. The possibilities for increasing the resonator Q-factor by increasing its volume are limited by problems in selecting oscillation modes. Taking this limitation into account, a compressor with a resonance system having an intrinsic Q-factor of 35000 was built. The detuning between the working and the closest parasitic oscillation modes was 50 MHz.

This compressor utilizes a principle of generating ultrashort pulses that is based on the extraction of energy from a superdimensional cavity resonator using an interference switch that operates due to changes in the coefficient of intermode interaction in the coupling window between the resonator and the switch [4].

The resonance system of the compressor consists of a cylindrical copper resonator with an inner diameter of 44 mm and a switch based on an H-plane waveguide tee, which is made of copper waveguides of standard cross section 16×8 mm^2. $H_{12,11}$ and H_{10} oscillation modes are excited in the resonator and the tee junction, respectively. The switch is triggered by high-voltage pulses arriving from a spark-gap initiation unit 9. The setup parameters corresponding to this mode are presented in Table 1.

To further increase the peak power of the pulses at the facility output and to overcome the problems related to the breakdown strength of the compressor structural elements, we used the well-known scheme of two-stage sequential compression [5]. The first compressor 8 performed the preliminary compression of the generator pulse energy. One of two compressors 11 was connected to the output of the first compressor and further shortened the generator-produced pulses to the required duration. This scheme was used in the facility to realize two emission modes with different pulse durations. The two additional compressors provided emission modes with pulse durations of 2.5 and 1 ns, respectively. These compressors were based on H-plane waveguide tees. The resonance system of the compressors was manufactured from standard copper waveguides with a cross section of 16×8 mm^2. When 2.5- and 1-ns pulses are formed, the operating oscillations occur at the $H_{01,10}$ and $H_{01,5}$ waves. The intrinsic Q-factors of the compressors' resonance system are 3300 and 3200, respectively. The setup parameters corresponding to this mode are presented in Table 1.

The facility also allows the emission of nanosecond pulses with a repetition rate of up to 1.5 kHz. In this mode, the magnetron generator produces pulses of 300-ns duration. One of the additional pulses of 300-ns duration. One of the additional compressors is installed at the circulator output. The setup parameters corresponding to this mode are presented in Table 1.

Nitrogen was used to ensure the breakdown strength of the circulator and the compressors of the first and second compression stages. The operating pressure in the first-stage compressor and circulator was 3–4 atm. The operating pressure in the second-stage compressor was 1–2 atm. Lavsan windows transparent to radio waves were positioned at the outputs of the first and second compression stages and provided the necessary pressure difference. The gas admission, depressurization, and gas-pressure monitoring were executed using gas system 4.

The processes of energy storage in the compressors' resonance systems and the output-radiation parameters were monitored using coupler 13 and indicator system 10.

So the study of the installation shows that it is possible to develop the microwave pulse sources with stepwise pulsewidth adjustment from several nanosecond to several microseconds on the basis of pulse magnetron transmitters integrated with resonant compressors. For the first time the K-band compression system was developed to procedure pulse radiation of 1 ns pulsewidth and 10 MW pulsepower. The study of the compressor operational parameters prove that the extension of abilities by adding the nanosecond pulse radiation mode increases the mains power consumption by 12.5%, weight by 25% and volume by 28.6%.

3. Two Channel Set-up for Generation of X- and Q-Band Ultra-Short Pulses

Possibility of synchronizing several common vacuum microwave tubes and resonant pulse compressors allows to create devices which radiate in a few frequency bands at the same time. The structural scheme of the device forming the sequence of nanosecond pulses with different carrier frequencies is presented in Fig. 2.

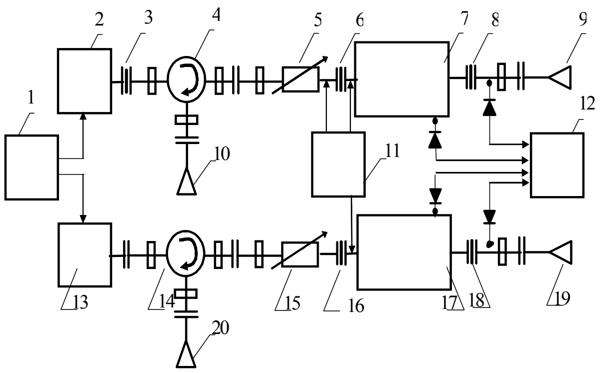

Fig. 2. Block diagram of the facility: 1 – control unit, 2 – microwave transmitter Q-channel, 3, 6, 8 – dielectric window, 4 – circulator Q-channel, 5 – phaseshifter Q-channel, 7 – compressor Q-channel, 9 – dummy antenna, 10 – circulator loads Z-channel, 11 – gas filling system, 12 – system for signal indicators and parameter measurements, 13 – microwave transmitter X-channel, 14 – circulator X-channel, 15 – phaseshifter X-channel, 16, 18 – dielectric window, 17 – circulator loads X-channel

The device operation is supported by the standard microwave magnetron generators combined with the resonant pulse compressors. The device radiates microwave pulses of nanosecond pulsewidth in three modes:

– fixed frequency of Q-band,

– fixed frequency of X-band,

– simultaneously in Q- and X-band.

The magnetron transmitter of Q-channel – 2 generates pulses of pulsewidth 380 ns at –3 dB peak power level and pulse power 51.17 kW following with repetition rate 1000 Hz. The prefabricated circulator – 4 and adjustable phaseshifter – 5 were used in order to match the magnetron and the resonant pulse compressor 7. The load – 10 absorbed the wave power reflected from the compressor input during the process of exciting its resonant system.

The pulse repetition mode of nanosecond pulse radiation was implemented by the resonant compressor including the multimode cavity with unloaded Q-factor equal 50000. The tuning of the working mode frequency out of a nearest stray mode was 100 MHz.

The basic procedure of ultra-short pulse generation in the Q-channel compressor was similar to the setup of K-band. The compressor resonant system comprises the circular copper cavity with the interior cross section diameter 30 mm and the switch made from the H-plane tee. The symmetrical arms of the tee are circular, the side arm has a cross section 5.2×2.6 mm^2. The working mode was $H_{(12)11}$. The wave mode H_{11} was excited in symmetrical arms, the side arm has a wave mode H_{10}. The compressor switched operated in a self breakdown mode.

The circuitry of the X-channel is similar to the circuitry of Q-channel. The circuitry included magnetron transmitter having following radiation parameters: pulsewidth 850 ns at –3 dB power level, pulse power 6 kW and repetition rate 500 Hz.

The mode of nanosecond pulse radiation was implemented by the resonant pulse compressor including the multimode cavity connected by the smooth transition with the singlemoded waveguide tee. The compressor resonant system is the circular copper cavity with the interior cross section diameter 58 mm combined with the switch made from the waveguide *H*-plane tee made from the waveguide of standard cross section 23×10 mm^2. In the cavity and the tee the modes $H_{11.6}$ and H_{10} were excited respectively. The switch was located in the side arm of the tee and operated in the self breakdown mode.

The insulation of the microwave system with Q- and X-channels was supplied by filling cavity volumes with argon up to давления $6 \cdot 10^5$ Pa and $1 \cdot 10^5$ Pa respectively. The waveguide line from the magnetron output to the input Q-channel compressor window was filled with nitrogen up to $3 \cdot 10^5$ Pa. The waveguide line of the X-channel was filled with air at atmospheric pressure. The dielectric microwave windows made of mica were at the inputs the outputs of compressors to provide necessary pressure drop. Filling with gas, pressure release and pressure monitoring was executed by the gas system.

Required modes of radiation were provided by the control and synchronization block. The radiated energy was directed to a load or antenna equivalent.

Radiation parameters were monitored by the system of indication. The process of energy storing in the compressor resonant systems of both channels and envelopes of generated pulses were monitored using the diode units. Main setup parameters are presented in Table 2.

The data obtained during creation and studying of the setup show that using commercially issued microwave transmitters with pulse magnetrons and resonant compressors its is possible to develop setups for generating of nanosecond pulse sequence with different carrier frequencies. For the first time the Q-band compressor was developed which produced pulses of 5 ns pulsewidth, 1.6 MW peakpower and 1 kHz repetition rate. The power amplification factor of the compressors was 15 dB.

Table 2

Parameter	Q-chan-nel	X-chan-nel
Peak power, kW	1600	60
Pulse duration, ns	5	2
Pulse repetition rate, Hz	1000	500
Power amplification factor, dB	15	17
Efficiency,%	41.14	11.8
Compression factor	76	425
Time spread between pulses in the mode of Q- and X-band simultaneous operation, ns	≤ 50	
Power consumed from the mains, W ~115 V, 400 Hz +27 V	2162 52	
Overall dimensions: length × width × height, mm	970×810×1110	
Weight, kg	150	

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