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A Facility with Resonant Pulse Compression for Generating High-Power Ku-Band Microwave Pulses

A. N. Man'ko, V. N. Slinko*, P. Yu. Chumerin*, and Yu. G. Yushkov***

** GNU Research Institute of Nuclear Physics, Tomsk Polytechnical University, pr. Lenina 2a, Tomsk, 634050 Russia*
*** Fifth Central Research and Testing Institute, Krasnokazarmennaya ul. 153, Voronezh, 394052 Russia*
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Abstract—A generator of high-power Ku-band microwave pulses with resonant pulse compression is described. It allows thestepped control of output-pulse durations from 1 ns to 1.5 μs at a pulse repetition rate of 0.2–1.5 kHz and a peak power of 58 kW to 10 MW. This source can be used for investigating the interaction of electromagnetic radiation with various objects.

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 [1–4]. 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 [5]. Employing this technique, it becomes possible to use a single device that yields pulses whose duration is controlled over the range of continuous radiation to a single oscillation period of the carrier frequency.

Radiation pulses with a minimum duration of 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_{out} at the tube and modulator outputs that are shorter than the pulses generated by them with durations t_p. At the same time, he peak power increases by a factor of $\eta_{st}\eta_{out}t_p/t_{out}$, where η_{st} is the storage efficiency and η_{out} is the outputting efficiency. The value of η_{out} is 70–90%; this is determined by the efficiency of switch operation. The value of η_{st} 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]

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

This paper describes the prototype of a facility developed on the basis of resonant pulse compressors and the commercial magnetron transmitter of a Ku-band radar station. The facility controls in steps the duration of electromagnetic radiation pulses over the range of 1 to 1500 ns.

A simplified diagram of the facility is shown in Fig. 1. Magnetron microwave transmitter *1* provides oscillation modes with the following output parameters: pulse durations of 1500, 800, and 300 ns; pulse repetition rates of 200, 600, and 1500 Hz, respectively; and a pulse power of 58 kW. 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.

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*. The circulator has a direct loss of 0.2 dB and ensures a 30-dB decoupling between the arms connected to the compressor and the magnetron output. 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

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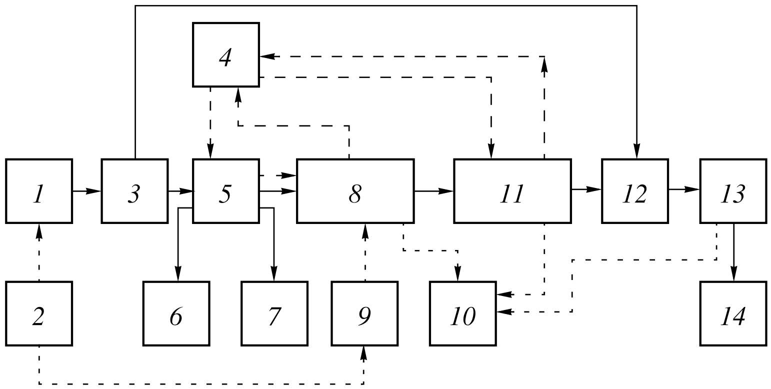

Fig. 1. Block diagram of the facility for resonant compression of the microwave energy: (*1*) microwave transmitter; (*2*) control unit; (*3, 12*) waveguide electromechanical switches; (*4*) gas filling system; (*5*) phase circulator; (*6, 7*) circulator loads; (*8*) first-stage compressor; (*9*) spark-gap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

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 [5].

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 side arm of the tee terminates in a short-circuited wall. A trigatron switch of the type described in [7] is positioned in the waveguide at a distance of one-quarter of the wavelength from the short-circuited wall. The switch is triggered by high-voltage pulses arriving from a spark-gap initiation unit *9*.

With the first compressor, the facility allowed the emission of pulses with a duration of 10 ns, a repetition rate of 200 Hz, and a peak power of 1624 kW. The gain was 14.4 dB, and the compression efficiency was 18.7%. The field strength in the compressor structural elements was >100 kV/cm.

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 [7]. 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. An inductive diaphragm, through which the resonance system of the compressor was excited, was set up in one arm of the tee junction. The second arm was connected to the load, while the third arm terminated in a short-circuited wall. The principle of forming ultrashort pulses in this compressor is based on the extraction of the energy stored in the segment of the waveguide line between the diaphragm and the axis of symmetry of the tee junction after the coefficient of coupling to the load is changed by the interference switch [5]. The duration of the formed pulses is determined by the time of the wave round trip along this line. The design of the switch is similar to that used in the first compressor.

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.

Using one of the additional compressors, 2.5-ns pulses with a peak power of 3.3 MW or 1-ns pulses with a peak power of 10 MW were formed at the output of the facility with the two-stage compression system. The gain of the two-stage compression system, the compression efficiency, and the field strength in the structural elements were 17.5 and 22.4 dB, 9.5 and 11.5%, and <140 and <250 kV/cm, respectively.

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 compressors is installed at the circulator output. The pulse peak powers measured at the output of the facility when operating in this mode were 300 and 580 kW; the gains of the compres-

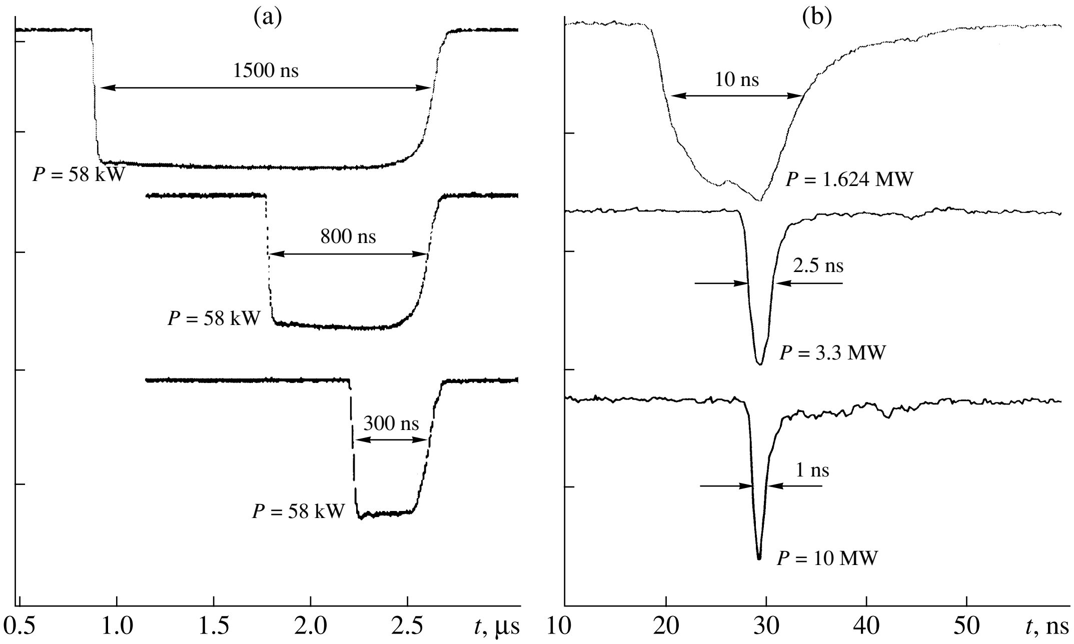

Fig. 2. Oscillograms of pulses in the modes for forming (a) microsecond and (b) nanosecond pulses.

sors were 7.14 and 10 dB, and the compression efficiencies were 4.31 and 3.33%, respectively.

The calculated values of the compressors' gains in this excitation mode are 11.5 and 15.4 dB, respectively. The difference between the calculated and measured gain values is explained by the fact that the design of the compressors does not allow control of the input coupling upon a change in the duration of the excitation pulse.

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*. The pulse profile, duration, and repetition rate were measured using a TDS-3 oscilloscope. The peak power at the facility output was determined from the mean power, measured by an M3-22 wattmeter with an M5-43 thermistor head.

A Д3-34A variable attenuator was used to measure the peak power of the pulses yielded by the facility, which was designed for realizing radiation conditions that presuppose the use of two-stage compression. For this purpose, we compared the amplitudes of these pulses to the amplitudes of the pulses measured at the output of the first-stage compressor. Figure 2 shows the envelopes of microwave pulses at the outputs of the

Table

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 consumed from the mains, W	1600	2000	2000	2000	2000	2000
Mass, kg	80	99.7	99	98.9	100	99.9
Volume, m^3	0.166	~0.213	~0.213	~0.213	~0.213	~0.213

magnetron generator (Fig. 2a) and the first- and second-stage compressors (Fig. 2b).

Structurally, microwave transmitter *1* (Fig. 1), control unit *2*, and spark-gap triggering unit *9* are arranged in a separate rack. Gas system *4* is designed as a separate unit. Circulator *5*, first- *8* and second-stage *11* compressors, and electromechanical switches *3* and *12* are placed on the outer supporting elements of the rack.

The facility is powered from supply lines of ~115 V (400 Hz) and +27 V. The main parameters of the facility are listed in the table.

The results of our tests show that facilities with a controlled pulse duration of from several microseconds to single nanoseconds can be created on the basis of resonance compressors and the microwave transmitters of a Ku-band radar station. An additional mode of emitting nanosecond pulses is provided by the introduction of resonance compressors and auxiliary equipment that ensures their operation. This increases the energy consumed by the facility by 12.5%. It also increases the facility's mass by 25%, and its volume by 28.6%.

The use of the sequential-compression technique in the Ku band has made it possible for the first time to obtain microwave pulses with a duration of 1 ns and a peak power of 10 MW. In this case, the compression coefficient of the generator pulse was 1500, the peak-power gain was 23 dB, and the compression efficiency was 11.5%.

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