Compact Relativistic Millimeter-Band Microwave Oscillators [1]

M.I. Yalandin,* V.G. Shpak,* V.V. Rostov**

*Institute of Electrophysics UB RAS, 106, Amundsen Street, Ekaterinburg, 620016, Russia,
Phone: +7343-2678785, Fax: +7343-2678794, E-mail: yalandin@iep.uran.ru
**Institute of High-Current Electronics, 2/3, Akademicheskii Prosp., Tomsk, 634055, Russia

Abstract – The report presents a brief review of research and developments, which made it possible to create during the number of years a series of the pulse-periodic millimeter wave range nanosecond and subnanosecond relativistic HPM generators. The devices are based on a compact high-current electron accelerators and possess a peak power in the range from tens of megawatts to the gigawatt.

1. Introduction

Since pioneering studies into high-power microwave generation, efforts of researchers have resulted in a comprehensive theoretical understanding and advanced practical applications of X-band relativistic backward wave oscillators (BWO) [1,2]. However, the first attempt to project the obtained results to the millimeter wavelength band [3] showed that it was necessary not only to miniaturize BWO electrodynamic systems, but also to develop specialized high-current accelerators [4]. The energy of the accelerator beam (power x pulsewidth) was difficult to convert fully to the energy of a microwave pulse in the existing experimental setups. It is with this situation in mind that the work was initiated in 1980 aimed at creation of HPM millimeter-wavelength oscillators employing small-size accelerating equipment.

The RADAN series accelerators [4] have been developed at the Institute of High Current Electronics (Tomsk) and then at the Institute of Electrophysics (Ekaterinburg). For modern versions of devices of this series, capable of off-line operation and having the lifetime $>10^7$ shots, provision has been made to control the output parameters. The RADAN-303 accelerator [5] and the microwave devices based on this accelerator have been brought to the level of systems having no world's analogs. With these devices, a number of pioneer studies have been performed. Relativistic BWO's operating in the frequency region 37-140 GHz at a multimegawatt power level, the first millimeter-range relativistic Cherenkov amplifier, and a 70-GHz BWO with a permanent-magnet-based focusing system have been developed [6-8]. In these studies, emphasis was made on improving the performance of microwave devices and increasing their pulse repetition rates. The advancement of wideband oscillography and diagnosing equipment has provided the possibility to perform more extensive studies on generation of subnanosecond high-voltage pulses and electron beams [9]. As a result, the first subnanosecond wideband microwave pulse sources providing fullness of the millimeter range and capable of operating in the superradiative (SR) mode [10] have been created.

The current work on high-voltage pulsed power and accelerator technology as applied to relativistic high-frequency electronics involves the use of new solid-state nanosecond high-voltage pulse generators with inductive energy stores and semiconductor opening switches [11]. These generators, developed in the pulsed power laboratory of the Institute of Electrophysics, feature "solid-state" stability of parameters, long lifetimes ($> 10^8$ shots), and pulse repetition rates (PRF) in excess of 3 kHz at an output voltage of several hundreds of kilovolts across loads of some tens or hundreds of ohms.

2. Compact high-current accelerators

The RADAN-303B unified pulse generator is a double pulse-forming line (PDFL), switched into a load with a gas spark gap, which is combined with a Tesla transformer [5]. The breakdown voltage can be controlled in the range from 10 to 200 kV. Its stability (rms deviation ~5%) is typical of untriggered spark gaps. The pulse duration is 5 ns and the voltage risetime is 1-1.5 ns. The pulse power across a matched 45-ohm load is 0.8 GW. The load may be an explosive-emission-cathode based, magnetically insulated coaxial vacuum diodes (MICD's).

To shorten the accelerating voltage pulse to 200-300 ps, a device is used whose principle of operation is that a short pulse is cut out of a longer pulse with the use of peaking and chopping spark gaps [9]. An inductive-capacitive unit with a gas spark gap has been developed which provides for additional compression of the energy of nanosecond generator. When charging a short capacitive energy store in the traveling wave mode, an increase in output voltage from 150 to ~200 kV has been achieved, which corresponds to an increase in pulse power by a factor of 1.75.

Analysis of the modes of stabilization of the breakdown of subnanosecond spark gaps gave rise to a

---

[1] This work was supported in part by RFBR, Grants: 05-02-08016; 04-02-16576; 05-02-08240.

precision-triggered three-electrode spark gap for DPFL-based RADAN generators [12]. The jitter was no longer than the duration of the trigger pulse equal to 300 ps. Nanosecond generators with triggered spark gaps were used in developing module high-current systems. Double-channel synchronized generators with subnanosecond peakers as loads were also tested. The module-built system offer possibilities to perform investigations in microwave electronics on intricate synchronizable complexes such as relativistic amplifiers with subnanosecond beams, setups intended for studying the scattering of microwaves by relativistic electron flows [13], and systems with coherent microwave power summation.

3. Magnetically insulated electron beams

High-current magnetically insulated electron beams of nano- and subnanosecond duration are widely used in studies concerned with mechanisms of generation of a strong microwave radiation and development of HPM generators with an extensive energy-exchange space. Magnetic isolation is necessary for both the formation of the beam in the accelerating gap and the beam guiding in the drift chamber of the accelerator. When the length of accelerating pulses is 3-5 ns, which is typical of nanosecond pulse generators of the RADAN type, the formation of electron beams in a magnetically insulated vacuum diode encounters the same problems as in systems with pulses 10-100 ns long. They differ in compactness of the short-pulse vacuum diode and a small cross size of the drift chamber of the accelerator. This is because of the strength of the vacuum insulation of the MICD is enhanced at nanosecond and subnanosecond exposure times. In particular, a permanent magnet (NdFeB) can be used for a compact vacuum diode with the drift chamber 10 mm in diameter [8].

Usually, a capacitor bank-powered pulsed magnetic coils are used for focusing of nanosecond and subnanosecond high-current beams. Superconducting magnetic coils and liquid-cooled dc magnetic coils are used too. In the latter case, stabilized power is supplied from a bank included molecular capacitors and a transistor IGBT switch operating in the pulse-width modulation regime [14].

When the accelerating pulse is subnanosecond long, the formation of a high-current magnetized beam has some specific features arising from the longitudinal dynamics of electrons and a finite initiation time of the cathode emission [9].

4. Millimeter-range relativistic HPM generators

During the period from 1980 to 1986, a microwave oscillators (relativistic BWO's) with high-current e-beams of energy 150-200 keV have been created [6]. The MG1, MG2, and MG3 oscillators that operated at wavelengths of 8 and 4 mm (E_{01} mode) with a pulse repetition rate of 0.1-10 Hz were capable of producing up to 10 MW of output power.

The electron efficiency was increased to 10-15% (with a RADAN-303 accelerator, 250-300 keV), and for the (35-38) - GHz BWOs (MG4, MG5 generators) the output power attained 60 MW (1991, [7]). Later on (in 2004), a numerical optimization of the 38-GHz BWO allowed us to increase an output microwave power of up to 80-100 MW [13].

The compact vacuum diode of the MG6 oscillator served as a prototype for the MICD of a relativistic BWO with a focusing system based on Nd-Fe-B permanent magnets [8]. The magnetic system embraced the diode case. This made it possible to shift the region of magnetic field reverse from the cathode toward the insulator, and the slow-wave system was in a uniform field of ~14 kOe. Because of the optimum excess of the operating current over the starting one was not attained in these experiments, the output power of the 70-GHz BWO reached 1 MW only. The pulse repetition rate (100 Hz) was limited in this case by the accelerator.

With a 3-4-ns duration of the oscillation in a 70-GHz BWO (MG6) the microwave energy flux in a single-mode slow-wave (SWS) electrodynamic system was ~0.5 GW/cm^2 and the electric fields at the SWS walls reached ~2 MV/cm [7]. We believe that these high specific parameters directly result from the increased electric strength of the electrodynamic channel at the short time of exposure to microwave fields. The MG series oscillators represents up to now the most compact commercially - available relativistic microwave devices. Their pulse repetition rate (~10 Hz) is limited by the coolable pulsed solenoids.

It takes to note, that the highest peak generation power for Ka-band BWOs equipped with a conventional single-mode SWS was obtained for the rare-repetitive operation in the conditions of e-beam focusing by a strong (exceeding the cyclotron-resonant value) guiding magnetic field (~5 T). For the regime of particles interaction with microwave fields in conventional quasi-stationary Ka-band BWO the ejection of beam to the walls of the slow-wave structure (SWS) occurs [15]. This effect is more pronounced for a low e-beam guiding magnetic field of ~ 2 T (below the cyclotron-resonant value). It leads to the periodic disruption of microwave generation and resembles in appearance self-modulation of the radiation power. With that, in the repetitive operation the BWO electron efficiency averaged over the pulse duration is 3-5 times less as compare to the effectiveness of quasi-stationary single-shot gene-ration, when e-beam is guided by strong B-field [7].

The latest numerical simulations and experiments demonstrated the highly effective beam-to-wave energy exchange for the Ka-band BWO under conditions of decreased guiding magnetic field. In a

Table I. Millimeter band HPM oscillators realized on the base of high-current compact electron accelerators

Year	Type; Oscillator	Basic high-voltage pulser	PRF; Bz (solenoid type)	λ ; pulsewidth	P_{max}; power conversion
1983	MG3; BWO	RADAN-220	Single; 5 T (pulsed)	8 mm; 3 ns	~10 MW; ~5%
1984	MG2; BWO	RADAN-220	Single; 2.5 T (pulsed)	4 mm; 3 ns	~10 MW; ~5%
1991	MG4; BWO	RADAN-303	Single; 5.5 T (pulsed)	8 mm; 4 ns	~60 MW; ~15%
1992	MG5; BWO	RADAN-303	10 Hz; 1.8 T (pulsed)	8 mm; 3 ns	~15 MW; <5%
1992	BWO	RADAN-303	100 Hz; 1.8 T (NdFeB)	4 mm; 2 ns	~1 MW; /-/
1997	SR BWO	RADAN-303+slicer	100 Hz; 5-8 T (dc, He)	8 mm; 0.3 ns	~60 MW; ~20%
1998	SR BWO	RADAN-303+slicer	Single; 4.5 T (pulsed)	8 mm; 0.3 ns	~150 MW; ~30%
2002	SR BWO	SM-3NS+slicer	3500 Hz; 2 T (dc, oil)	8 mm; 0.3 ns	~300 MW; ~50%
2003	SR BWO	RADAN-303+slicer	Single; 6.5 T (pulsed)	8 mm; 0.2 ns	~1 GW; ~150%
2004	SR Scattron	2xRADAN-303+slicer	Single; 2.5 T (pulsed)	2 mm; 0.2 ns	~1 MW; /-/
2006	BWO	RADAN-303	10 Hz*; 1.7 T (pulsed)	8 mm; 2.5 ns	~100 MW; ~20%
2006	SR BWO	RADAN-303+slicer	10 Hz*; 1.7 T (pulsed)	8 mm; 0.3 ns*	~450 MW*; ~100%*

*-project / simulated parameters

full-scale PIC - modeling [16] Ka-band BWO scheme with modified SWS [17] were investigated. Improved SWS has increased cross section and resonant reflector for the microwave extraction instead of waveguide cutoff neck. Special shaping of B-field lines of the guiding solenoid ensured the decompression of magnetic flux. As a result, for quasi-stationary BWO model (frequency band of 38 GHz; guiding magnetic field of ~ 1.7 T; pulsewidth of 3 ns) the calculated efficiency attained 37% (peak power of up to 150 MW). In the experimental realization the power 60-100 MW was confirmed up to date.

5. Generation of high-power picosecond microwave pulses

Picosecond high-current accelerators [9] made it possible to study non-stationary HPM generation in various devices that was realized in the experiments since 1995. The mechanisms of induced radiation of a short dense fluxes of moderately relativistic electrons represented a coherent single-pass amplification of the initial signal that arises at the sharp front of the beam current pulse, and possesses some similarities with a well-known superradiation phenomena (R.H. Dicke, [18]). From the practical standpoint, these investigations solve the problems of generating microwave pulses with a duration less than 1 ns and of enhancing the level of power conversion of e-beam to electromagnetic radiation.

The theory of the cyclotron mechanism for non-stationary generation of picosecond microwave pulses by short electron fluxes was firstly proved experimentally in [10]. Similar operation modes were then studied for devices based on the undulator and Cherenkov mechanisms of radiation [19]. By now, the first experimental results have been obtained on realizing the mechanism of backward induced microwave scattering by a picosecond electron beam [13].

Most progress in obtaining the high-power picosecond electromagnetic pulses of the millimeter-wavelength range (the frequencies of 38 GHz, 70 GHz, and 140 GHz) was attained in the experiments (1996-2001) with the Cherenkov mechanism of non-stationary HPM generation where a rectilinear high-current e-beam passes through a periodic SWS, provided that electrons were synchronous to the backward spatial harmonics of the wave TM_{01}. In experiments [20], a quadratic relation was shown between the radiation pulse peak power and the charge of the electron beam, which proved the coherent character of radiation from the entire volume of a spatially limited electron flux. If a superconducting dc magnet was used for focusing the beam, such a microwave source operated at the repetition frequency 25-100 Hz. In the 8-mm wavelength range, a conventional scheme of a moderately relativistic BWO yields considerably high microwaves peak power of the order of 60-150 MW [21], although the beam-to-radiation power conversion factor did not exceed 0.3.

Later on, in 2001, the modified periodic slow-wave structures of BWOs with increased transverse dimension were applied for the superradiative BWOs. In this case, the spatial charge of the beam does not critically affect the process of electron bunching, the dispersion of a broadband wave packet is reduced, and the SWS represents a convenient channel for the beam transportation. The last factor is of particular importance at a reduced magnitude of the focusing magnetic field. This gave the possibility to perform the experiment [14], where high-current electron accelerator based on a hybrid picosecond voltage pulsed generator [11] was equipped with a oil-cooled dc solenoid (B_Z=2 T). Pulses in the 38 GHz range with the peak power up to 300MW were generated at the repetition frequency 1-3.5 kHz in the packets with the duration of 1 s. The radiation power averaged over the packet was as high as 200 W.

The subsequent theoretical study of non-stationary modes of energy exchange in moderately relativistic BWOs, numerical PIC-simulation, and the first experiments with a superradiative X-band oscillators showed (2002, [22]) the possibility of generating picosecond microwave pulses with a peak power that would not principally be limited by the power of driving electron beam. In the experiment (2003, [23]) optimized SWS of superradiative Ka-band BWO and a strong guiding B-field (pulsed solenoid, 6.5 T) provided a proper energy exchange conditions and the power conversion factor from a 1-ns e-beam to the 200-ps long microwave pulse attained ~1.5 at the output radiation power up to 1 GW. The efficiency of energy conversion from the beam to electromagnetic wave was estimated to be of the order of 20-25%. The radiation power density in the SWS was 1.5 GW/cm^2, which is a record value for HPM devices up to date.

6. Conclusion

The experience obtained in the researches and development of the compact relativistic Ka-band oscillators demonstrates that the time scale of units of nanoseconds makes a certain advantages in creation of powerful quazi-stationary pulsed-repetitive HPM sources of radiation possessing a high specific parameters.

The further shortening of the generation down to the picosecond time scale exhibits numerous evidences that such a non-stationary HPM oscillators are characterized by highest electric strength in a wide aspect. The devices operating at pulse duration of 0.2-1 ns are not critically sensitive to a whole class of phenomena (emission processes at the walls in SWS, secondary emission resonance discharges, etc.), which in high-power “long-nanosecond” electronics conventionally limit the duration of generated radiation pulses.

References

[1]. N.F. Kovalev, et al., Pis'ma v ZhETF, **18**,4, 232 (1973)

[2]. A.V. Gunin, et al., IEEE Trans. on Plasma Sci., **26**, 3, 326 (1998)

[3]. V.S. Ivanov, et al., Pis'ma v ZhTF, **14**, 4, 817 (1978)

[4]. G.A.Mesyats, et al., Proceedings of the IEEE, **92**, 7, 1166 (2004)

[5]. G.A. Mesyats, et al., *in Proc. 8 th Int. Pulsed Power Conf.*, 1991, pp.73-77.

[6]. A.S. Elchaninov, et al., *in Proc. 6th Int. Conf. on High-Power Part. Beams*, 1986, pp. 552-555.

[7]. M. I. Yalandin, et al., *in Proc. 9th Int. Pulsed Power Conf.*, 1993, pp. 388-391.

[8]. V.G.Shpak, et al., *in Proc. 11th Int. Conf. on High-Power Part. Beams*, 1996, pp. 473-476.

[9]. G.A Mesyats, M.I. Yalandin, Phys. Usp., **48**, 3, 211 (2005)

[10]. N.S.Ginzburg, et al., Nucl. Instr. & Meth. in Phys,. Research-A, **375**, 1-3, 553 (1996)

[11]. M.I.Yalandin, et al., IEEE Trans. on Plasma Sci., **30**, 5, 1700 (2002)

[12]. M.I.Yalandin, V.G.Shpak. IET, **44**, 3, 285 (2001)

[13]. A.G. Reutova, et al., // Pis'ma v ZhTF, **82**, 5, 295 (2005)

[14]. V.P. Gubanov, et al., *in Proc. 14th Int. Conf. on High-Power Particle Beams*, 2002, pp.263-266.

[15]. M.I. Yalandin, et al., *in Proc. Int. Pulsed Power-Plasma Science Conf.*, 2001, pp. 544-547.

[16]. V.P. Tarakanov, *User's Manual for Code KARAT*, Berkeley Research Associates, Inc., VA, USA, 1992.

[17]. S.D. Korovin, et al. Izv. Vuzov. Radiofizika, **42**, 12, 1189 (1999)

[18]. R.H. Dicke, Phys. Rev., **93**, 1, 99 (1954)

[19]. N. S. Ginzburg, et al., Izv. Vuzov: Applied Nonlinear Dynamics, **6**, 1, 38 (1998)

[20]. N.S. Ginzburg, et al., Phys. Rev. E, **60**, 3297 (1999)

[21]. M.I. Yalandin, et al., IEEE Trans. on Plasma Sci., **28**, 5, 1615 (2000)

[22]. A.A. Eltchaninov, et al., Laser and Particle Beams, **21**, 187 (2003)

[23]. S. D. Korovin, et al., Techn. Phys. Lett., 30, 2, 117 (2004)