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Microwave generators with passive mode-locking

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Abstract. We present the results of experiments on the generation of periodical trains of subnanosecond Ka-band pulses in the electron generator, which is based on passive mode locking. The experimental scheme includes a helical-waveguide gyro-TWT and a saturable absorber which is based on cyclotron resonance interaction with an initially rectilinear electron beam. Saturation of absorption is caused by relativistic dependence of the gyrofrequency on electrons energy. In good agreement with theoretical predictions, periodical trains of 0.4 ns pulses with peak power of 100 kW and repetition period of 2.5 ns were measured. In addition, we describe an alternate scheme of the pulse generator with passive mode-locking which feature using of two parallel electron beams formed by a single cathode and transported in common vacuumized interaction space that should simplify the practical implementation.
Keywords: ultrashort pulses generation, passive mode-locking, multi-beam oscillators.

1. Introduction

Passive mode-locking as a method for generating periodic sequences of ultrashort optical pulses (USPs) is well known in laser physics [1, 2]. This effect is achieved by incorporating a saturable absorber into the laser resonator. The theoretical studies carried out [3–5] have shown the possibility of transferring the described method to microwave electronics. The key point for the development of electronic USP generators with passive mode-locking was the development of an absorber that should provide saturable absorption in the microwave range at a power level of tens and hundreds of kilowatts. For this purpose, it was proposed to use cyclotron resonant absorption of radiation by an initially rectilinear electron beam, when the absorption saturation is caused by the relativistic dependence of the gyrofrequency on the particle energy. At this moment we suggest two scheme of microwave USP generator. This first one is based on two separated sections which connected by microwave transmission line. One section serves for the amplification of radiation while the second one is used as a nonlinear absorber. At this moment such a scheme have been realized experimentally and is discussed in Section 2. An alternative scheme described in Section 3 is based on two parallel electron beams formed by the single cathode and transported in common vacuum interaction space.

2. Experimental setup. Observation USP generation

Fig.1a shows of experimental setup of the Ka-band USP generator powered by the helical-waveguide gyro-TWT and mode-locked by cyclotron resonance absorber with parameter given in Table 1. The external quasi-optical (QO) transmission line Fig.1b connects the amplifying and absorbing section and also contains a coupler for outputting radiation (see also [6]) Both devices, the amplifier and absorber, use the cyclotron resonance interaction which is polarization dependent with respect to the left-handed or right-handed circularly polarized waves. This fact along with the use of the passive polarizers converting the linearly polarized wave into the circularly polarized one (and vice versa) ensures a situation when the incoming wave having a certain linear polarization propagates upstream the electron beam flow practically without the interaction. While propagating downstream (after being reflected by a sub-cutoff narrowing), the wave actively interacts with the e-beam (resulted in the amplification or absorption) and leaves the tube through the same window in the form of a wave with the same transverse pattern but with the orthogonal polarization as shown in Fig.1b. For both tubes, just after or before the polarizer, the wave has the form of the TE_{11}

circular waveguide mode. In order to convert it into the Gaussian beam, a specially profiled taper is used for each tube. In the experiments the Gaussian beam outgoing from the amplifier had the RF electric field parallel to the *x*-axis (*x*-polarization) (Fig.1b). It is focused and successively directed by focusing mirrors MF1 and MF2, wire-grid G1, plane mirror MP, wire-grid G2, focusing mirrors MF3 and MF4 to the input/output port of the absorber. After the interaction, the wave leaves the absorber in the form of *y*-polarized Gaussian beam (blue ray in Fig.1b). This wave beam is focused and directed by mirrors MF4 and MF3, passes through wire-grid G2 and reflected by mirror MC having the sinusoidal corrugation, the orientation of which can be varied by the mirror rotation around its axis as shown in Fig.4b. Due to the corrugation, the *x*-polarized component occurs in the specular reflected beam (magenta ray in Fig.1b). The relative power of this *x*-polarized beam can be varied from zero to almost 100% depending on the MC orientation angle. This beam is then reflected by the wire-grid G1 to the dummy load while the rest of the power is propagated in orthogonal polarization through G1 and is successively directed by MF2 and MF1 to the input/output of the amplifier in the form of a *y*-polarized beam.

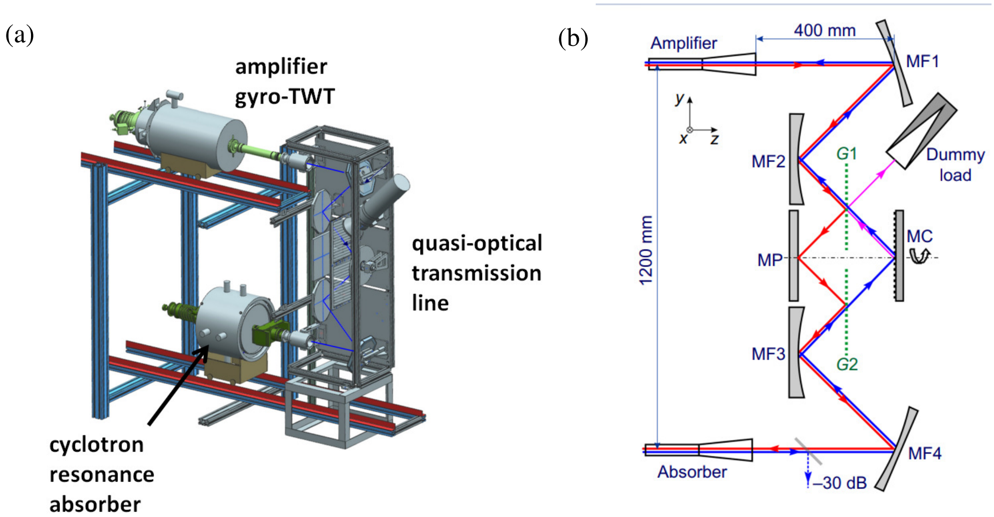

Fig.1. Experimental setup of the Ka-band USP generator. (a) Three-dimensional visualization; (b) QO system scheme: *1* – gyro-TWT (amplifier); *2* – cyclotron resonance absorber; *3* – focusing mirror (MF1); *4* – polarization splitter in the form of grid of horizontal wires (G1); *5* – rotating mirror with a corrugated surface (MC); *6* – dummy load. The red (magenta) and blue arrowed lines correspond to Gaussian beam paths with mutually orthogonal linear polarizations; red and magenta are for x- polarization.

Table 1. Main parameters of the experimentally realized Ka-band USP generator

	Amplifier	**Absorber**
Electron energy	50 keV	40 keV
Beam current	6.7 A	1 A
Pitch factor	~1	0
Interection length	244 mm	91 mm
Waveguede radius	3.57 mm	2.96 mm
Corrugation period	11.6 mm	–
Cirrugation amplitude	0.45 mm	–
Operating mode	TE_{21} / TE_{11}	TE_{11}
Magnetic field	~0.65 T	~1.1 T

The RF monitoring equipment allows the pulse waveforms to be recorded with maximum resolution (Fig.2b) for the time interval of 2 μs, during which the average power is quite stable, and all the pulses have a FWHM of (0.43±0.03) ns and a repetition period of 2.57 ns. The level of maximum peak power (P_{max} in Fig.2a) corresponds to 100 kW. Notably, this value significantly exceeds the saturation level of the stationary amplification of 30 kW, which is achieved in the gyro TWT without the cyclotron absorber.

The evaluated spectrum of the 2-μs pulse train (Fig.2c) is fairly reproducible from shot to shot. Its total width of nearly 2.5 GHz corresponds to the single-pulse duration, whereas the distance between the main lines of 0.39 GHz corresponds to the pulse repetition period. The measured width of each spectral line of about 0.5 MHz is determined by the record duration of 2 μs. This narrow width of spectral lines, together with equal distances between them, provides the most evident verification of the very good coherence of the generated pulses, i.e., long-term stability of the frequency and the phase of oscillations. The latter fact is also confirmed by calculating the autocorrelation function (Fig.2d) using the recorded RF-filled signal.

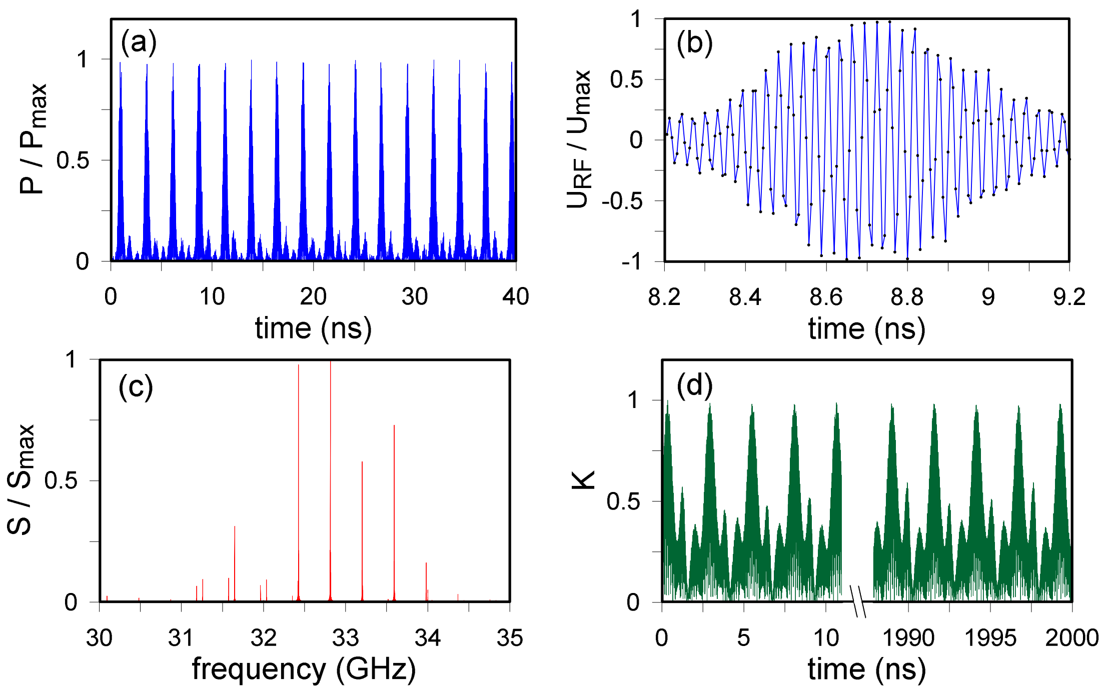

Fig.2. The UPS observation. Squared normalized rf signals recorded with 6.25-ps time step for the operating regime (a). Profile of a typical single pulse in the operating regime (b). Fourier transform of the recorded USP train with 2 μs duration (c). Corresponding autocorrelation function (d).

3. Modeling of USP generator with two parallel electron beams

It should be noted that practical implementation of the previous scheme of USP generator requires developing a rather complicated scheme capable of ensuring signal transfer between sections and the extraction of radiation. For this reason, in [7] we propose an alternative scheme of USP generator, a distinctive feature of which is the use of two parallel electron beams formed by a common cathode and transported via a common vacuum channel. One of these beams ensures the amplification of radiation while the other beam accounts for the nonlinear cyclotron-resonance absorption. Analysis of the dynamics of USP generators showed that pulses of maximum amplitude, the wave group velocity in the amplifier section must be different from the translational velocity of electrons, so that the generated electromagnetic pulse can take energy from various fractions of the electron beam. On the contrary, the nonlinear absorber section should operate in the optimum regime of group synchronism ensuring minimum mutual influence of various fragments of the electromagnetic pulse via the electron beam. Under these conditions, the absorber ensures maximum contrast between the absorption of low noise background and almost full transparency for the transmission of large-amplitude fragments of an electromagnetic pulse.

Fig.3 shows a schematic diagram of the double-beam USP generator. In this system, the external electron beam provides the amplification of radiation during Cherenkov interaction with slow wave propagating in the cylindrical waveguide with periodic corrugation of side walls. Saturable absorption is ensured by the internal (paraxial) electron beam, for which the conditions of cyclotron resonance with radiation are provided by variation of the guiding magnetic field in certain region in the absorbing unit. In addition, the electrodynamic system of USP generator includes two reflectors situated on the cathode and collector sides of interaction space. The internal paraxial electron beam propagates at a rather large distance from the slow-wave system and is almost not involved in the Cherenkov interaction because of radial decay of the slow wave amplitude. Experimental testing of the proposed scheme of USP generator in the 8-mm microwave range is planned on the basis of the SATURN microsecond thermoemission accelerator (IAP RAS, N. Novgorod).

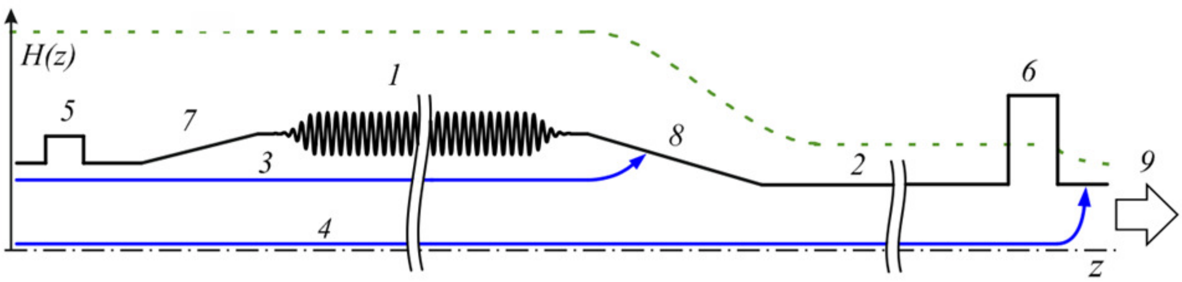

Fig.3. Scheme of USP generator with two coaxial electron beams: *1* – amplification section based on a corrugated waveguide, *2* – cyclotron absorption section, *3* – external amplifying beam, *4* – internal absorbing paraxial beam, *5* and *6* – input and output reflectors, *H*(*z*) – profile of the leading magnetic field, *7*, *8* – matching cone-shaped waveguides, *9* – radiation output to the payload.

Table 1. Parameters of the 8-mm range USP generator with two parallel electron beams

Parameter name	Value
Electron energy	210 keV
Beam current of of external / internal beam	6 A/4.4 A
Interection length of amplufiug / absorbing unit	240 mm / 150 mm
Waveguede radius of amplufiug / absorbing unit	6.15 mm / 3.3 mm
Corrugation period	1.5 mm
Cirrugation amplitude	1.16 mm
Coupling impedanse for operating mode HE_{11}	1.3 Ohm
Radius of external / internal beam	4 mm / 0 mm
Magnetic field	0.93 T

Modeling carried out for the aforementioned system parameters confirmed (Table 1) the possibility of realization of the regime of periodic USP generation in the proposed scheme. The peak power of pulses with duration of 0.6 ns and carrier frequency of 37.5 GHz reached up to 540 kW. The period of pulses in the train was 3.3 ns. It should be emphasized that the USP generator exhibits self-excitation is a soft regime, so that oscillations develop starting with low initial noise level. Thus, the results of analysis demonstrate the working capacity of the proposed USP generator based on two parallel radiating and absorbing electron beams.

It should be noted that there are several well-known successful experimental realizations of oscillator schemes with two parallel electron beams, which have been used primarily for the selection of modes with respect to transverse indices – see, e.g., [8]. The present work showed that analogous electron optics can also be used for fundamentally different purposes – in particular, periodic USP train generation.

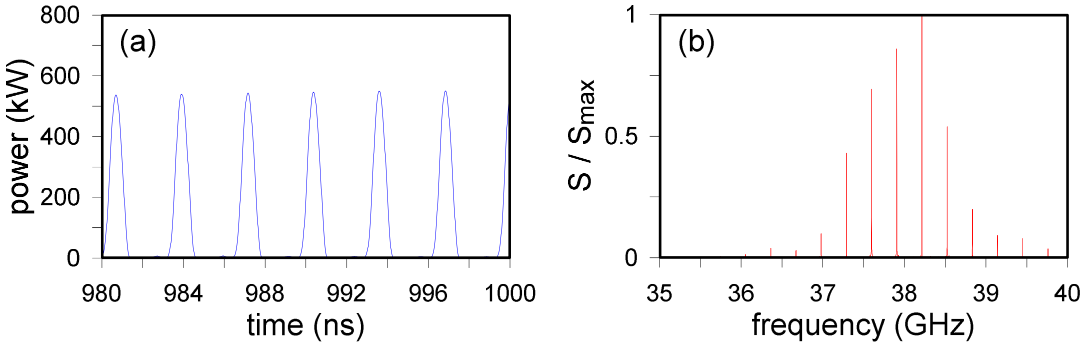

Fig.3. Results of the simulations: (a) profiles of output microwave pulses; (b) radiation spectrum.

4. Conclusion

For the first time in high-power vacuum microwave electronics the USP generator based on passive mode locking effect was realized. Also we propose an alternate scheme of the pulse generator with passive mode-locking which feature using of two parallel electron beams formed by a single cathode and transported in common vacuumized interaction space that should simplify the practical implementation. Such sources of microwave radiation in the form of periodic trains of USPs can find application in radar, spectroscopy, and communication.

Acknowledgement

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3. References

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