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Development of W-band short pulse generator with passive mode-locking

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Abstract. Based on a time-domain model we demonstrate that a periodic train of powerful ultrashort microwave pulses can be generated in an electron oscillator consisting of two coupled helically corrugated gyrotron travelling wave tubes (gyro-TWTs) operating in regimes of amplification and saturable absorption, respectively. Mechanism of pulse formation in such an oscillator is based on the effect of passive mode-locking widely used in laser physics. Saturable absorption can be implemented in a gyro-TWT in the Kompfner dip regime by a proper matching of the guiding magnetic field. According to simulations with the parameters of an experimentally realized Ka-band gyro-TWT, the peak power of generated pulses with duration of 60 ps can achieve 400 kW
Keywords: passive mode-locking, ultrashort pulses, gyrotron-TWT, Kompfner dip.

1. Introduction

In laser physics, there exists a well-known principle for production of ultrashort optical pulses (USP), based on the effect of passive mode-locking [1, 2], which is achieved by incorporating a saturable absorber into the laser resonator. As it was shown in [3–5], a similar method of ultrashort pulse generation can be realized in a two-section microwave oscillator consisting of an amplifier and a nonlinear absorber in the feedback loop.

The basic requirement on the amplifying unit is a broad frequency bandwidth that is needed for effective amplification of ultrashort microwave pulses. In the millimeter wave band, it is attractive to utilize a novel type of gyro-TWTs with a helically corrugated waveguides operating at a harmonic of gyrofrequency [6]. Such devices have a number of unique characteristics, including an extremely broad frequency bandwidth up to 20%.

The key problem for development of a mode-locked electron oscillator is realization of the nonlinear absorber applicable to the microwave frequency band and suitable for operation at a high-power level. In this paper we suggest to use for this purpose the additional section with independent electron beam where interaction also takes place in a helically corrugated waveguide at the harmonic of gyrofrequency. In such a system the saturable absorption realizes for magnetic field slightly exceeding the resonance one. In fact, this area corresponds to a so-called Kompfner dip regime, which was originally studied for Cherenkov TWTs [7]. We demonstrate that after proper matching of parameters, the Kompfner dip regime with saturation of absorption can be realized also in a gyro-TWT with a helically corrugated waveguide.

2. Time-domain model of a mode-locked electron oscillator

The scheme of the considered microwave USP oscillator with passive mode-locking is presented in Fig.1. This oscillator includes two gyro-TWT sections with helical corrugation one of which is used as an amplifying unit, while another operates in the regime of nonlinear absorption.

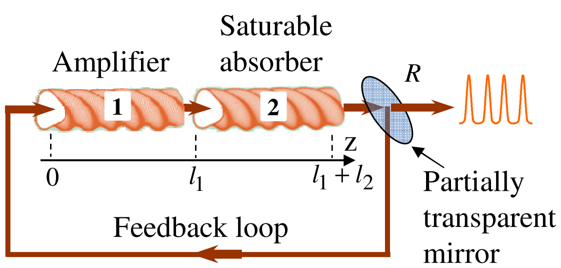

Fig.1. Scheme of a mode-locked microwave oscillator consisting of two coupled helical gyro-TWTs.

Multi-fold helical corrugation of a waveguide wall

$$r = r_0 + \tilde{r}\cos(\bar{m}\varphi - h_d z) \quad (1)$$

provides the coupling of two partial $TE_{m,n}$ modes: near-cutoff mode A and a far-from-cutoff traveling mode B, where r_0 is the waveguide mean radius, $\bar{m}$ is the number of corrugation folds, $\check{r}$ is the corrugation amplitude, d is the corrugation period, $h_d = 2\pi/d$. In both sections the electron-wave interaction is described by the equations [8]:

$$\begin{aligned}
&\frac{\partial^2 a}{\partial z^2} - 2i\frac{\kappa_A}{c}\frac{\partial a}{\partial t} - 2\sigma\kappa_A^2 b = i\frac{4eI_b}{\pi mc^3}\frac{\kappa_A^2}{\beta_{\|0}\sqrt{N_A}}\frac{s^s}{2^s s!}\int_0^{2\pi} p_+^s d\theta_0, \\
&\frac{\partial b}{\partial z} + \frac{1}{V_{gr}}\frac{\partial b}{\partial t} - i(h_d - h_0)b - i\frac{\kappa_A^2}{h_0}\sigma a = 0, \qquad (2) \\
&\frac{\partial p_+}{\partial z} + \frac{1}{V_{\|0}}\frac{\partial p_+}{\partial t} + i\frac{\kappa_A}{2\beta_{\|0}}\frac{p_+}{s}(\varDelta + |p_+|^2 - \beta_{\perp 0}^2) = \frac{s^s}{2^s s!}\frac{\kappa_A}{\beta_{\|0}\sqrt{N_A}}a(p_+^*)^{s-1}.
\end{aligned}$$

Here p_+ is the transverse electron momentum, $a = eA(N_A)^{1/2}/mc^2\kappa_A$ and $b = eB(N_B)^{1/2}/mc^2\kappa_B$ are the normalized amplitudes of partial waves, $\sigma = (\tilde{r}/2r_0)(\nu_B^2 - m_A m_B)/[(\nu_A^2 - m_A^2)(\nu_B^2 - m_B^2)]^{1/2}$ is the wave coupling parameter [3], N_A and N_B are the dimensionless norms of the partial waves, $V_{gr} = h_0 c/\kappa_A$ is the group velocity of the traveling wave b, $V_{\|0} = c\beta_{\|0}$ is the longitudinal velocity of electrons, I_b is the beam current, $\Delta = 2(\omega_A - s\omega_H)/\omega_A$ is the cyclotron resonance detuning, $\omega_H = eB/mc\gamma_0$ is the gyrofrequency, $h_0 = h_B(\omega_A)$ is the longitudinal wave number of the traveling wave b for the frequency ω_A, $\kappa_A = c\omega_A$ and $\kappa_B = c\omega_B$ are transverse wave numbers for partial waves a and b, correspondingly, s is the electron cyclotron harmonic number.

We assume that the amplifying and absorbing sections are coupled via the traveling partial wave B in accordance with the scheme shown in Fig.1 boundary conditions can be presented in the form

$$b_2(t, l_1) = b_1(t, l_1), \qquad b_1(t, 0) = Rb_2(t - T, l_1 + l_2), \quad (3)$$

where $R < 1$ is the reflection coefficient, T is the time delay.

3. Results of simulations

Simulations were performed for the parameters presented by Table 1.

Table 1. Main parameters of W-band USP generator

	Amplifier	Absorber
Electron energy	68 keV	54 keV
Beam current	10 A	5.8 A
Pitch factor	1.2	0.5
Interection length	60 mm	3.8 mm
Waveguede radius	1.1 mm	1.2 mm
Corrugation period	3.7 mm	3.1 mm
Cirrugation amplitude	0.25 mm	0.31 mm
Operating mode	$TE_{2,1}$ / $TE_{1,1}$	
Number of corrugation folds	3	
Magnetic field	1.96 T	1.91 T

In the amplifying section we choose parameters of corrugation in such a way that the intersection between the beam line and the dispersion curve of the normal mode is provided (Fig.2a). In this case the wave group velocity substantially differs from the axial velocity of the electrons. As a result, due to slippage of *em* pulse over the electrons it effectively accumulates the energy from different fractions of the electron beam. On the contrary, in the absorbing section, for minimization of the absorber relaxation time the grazing incidence of dispersion characteristics of the electron beam and the normal wave of a corrugated waveguide is beneficial (Fig.2b).

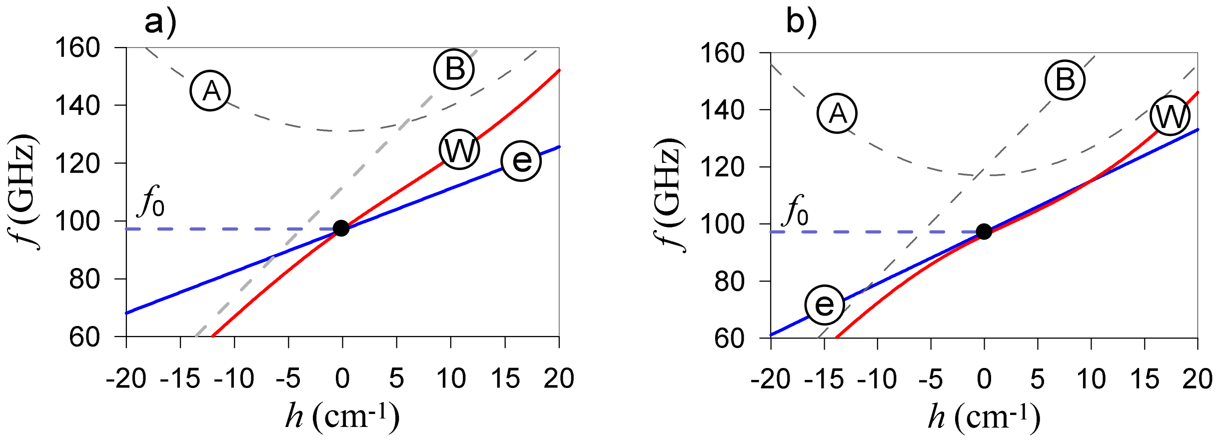

Fig.2. Dispersion diagrams of the partial (A, B), normal (W) and electron cyclotron (e) waves in the amplifier (a) and absorber (b) sections for operating frequency 100 GHz. f_0 = 97 GHz.

Due to incorporation of a saturable absorber (a helical gyro-TWT operating in the Kompfner dip regime, see Fig.3) in the feedback loop of the oscillator, similar to lasers, spikes with small amplitudes are strongly suppressed, whereas large amplitude signals are transmitted practically without attenuation.

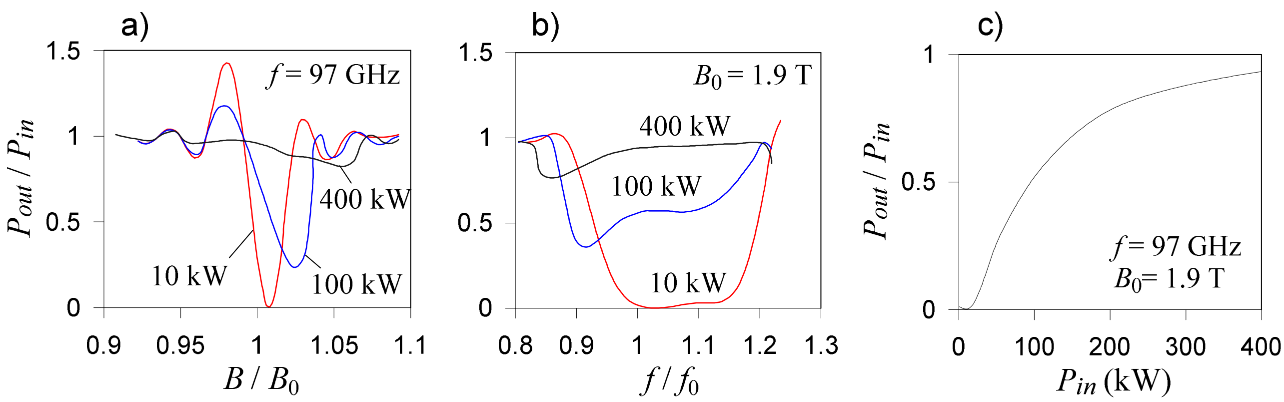

Fig.3. Operation of a helical gyro-TWT in the Kompfner dip regime. Dependences of the transmission coefficient on the value of guiding magnetic field (a), the frequency (b) and the power (c) of the incident signal.

As a result, the output radiation represents a periodical train of short electromagnetic pulses (Fig.4). In spectral domain, the process of pulse formation can be interpreted as synchronization of a large number of longitudinal resonator modes (the effect of mode-locking). For chosen parameters the duration of the generated pulses is 60 ps with distance between them of 1.2 ns. It is important to note that the generated pulses are coherent, i.e., they have correlated phases, which is confirmed by calculations of a correlation function $K(t)$ (Fig.4b).

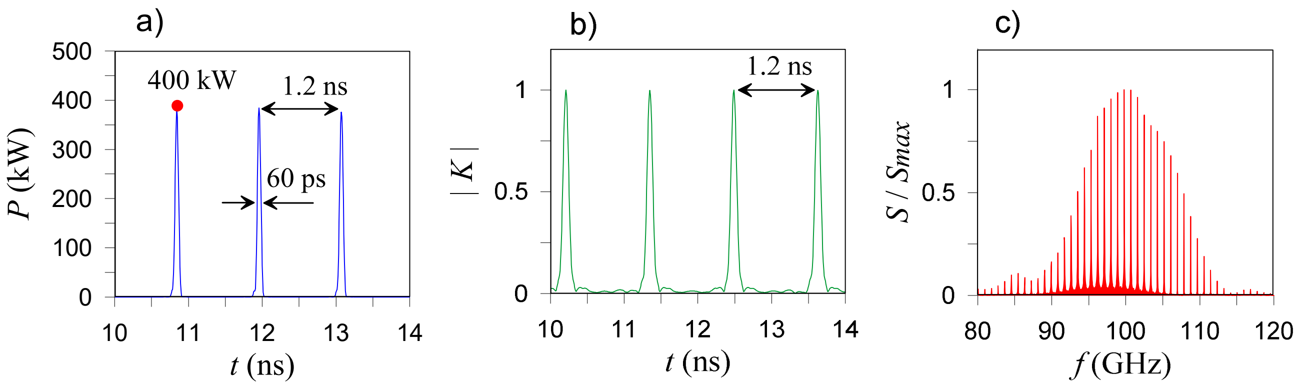

Fig.4. Simulations of USP generation. (a) Profile of microwave pulses, (b) absolute value of correlation function, and (c) radiation spectrum.

4. Conclusion

In this paper, we have demonstrated that a periodic train of powerful ultrashort microwave pulses can be generated based on the passive mode-locking effect in an electron oscillator consisting of two coupled gyro-TWTs with interaction spaces in the form of multi-fold, helically corrugated waveguides. One of these gyro-TWTs should operate in the amplification regime, while the other – in the regime of saturable absorption. For the required absorption, the Kompfner dip regime can be used, that is, realized in a gyro-TWT for the value of the guiding magnetic field slightly exceeding the resonance one. For minimization of the absorber relaxation time, the grazing incidence of dispersion characteristics of the electron beam and the normal wave of a corrugated waveguide should be realized. At the same time, the intersection of these characteristics is more beneficial for maximal amplification of ultrashort electromagnetic pulses in the active unit of a mode-locked microwave oscillator. Depending on the power and range, ultrashort microwave pulses can be used for various applications, including location and NMR spectroscopy.

Acknowledgements

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5. References

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