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GENERATION OF ULTRA-POWERFUL MICROWAVE PULSES IN STRETCHER-AMPLIFIER-COMPRESSOR SYSTEMS

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Abstract. We theoretically investigate the possibility of generating ultra-high-power ultrashort microwave pulses based on the Chirped-Pulse Amplification (CPA) method, which is widely used in laser physics. This method includes preliminary elongation of the initial pulse in a stretcher, sequential amplification of spectral components in a broadband amplifier, and compression in a line with negative dispersion (compressor). We consider the scheme in which waveguides with multi-fold helical corrugation are used as dispersing elements (stretcher and compressor), and a relativistic Cherenkov TWT or helical gyro-TWT is used as an amplifier. For the parameters of experimentally realized amplifiers in the 30 GHz range, we show that the peak pulse power in the stretcher-amplifier-compressor system significantly exceeds not only the saturation level of the amplifier, but also more than 4 times higher than the power of the used electron beam.

Key words: Ultrashort microwave pulses, compression of amplified chirped pulses, helical gyro-TWT, relativistic Cherenkov amplifier.

Introduction

At present, laser pulses with the record peak power are achieved with use of Chirped Pulse Amplification (CPA) method [1,2]. This method comprises three steps. At the first step, the initial short pulse passes through the "stretcher" - the dispersing line, which elongates the initial signal, reduces its peak power and makes its frequency chirped. At the second step, the spectral components of stretched pulse are sequentially amplified in one or more amplifiers. At the final stage, the original pulse shape is restored in the compressor - a line with negative (with respect to the stretcher) dispersion. Implementation of the CPA method in the microwave frequency range would make it possible to generate electromagnetic pulses of ultra-high (from multi-megawatt to multi-gigawatt) power, which is of interest for creating accelerators and electronic countermeasure systems, as well as for the plasma and solid state diagnostics.

Obviously, the CPA method of generating ultra-high-power microwave pulses is quite universal and a wide class of electronic amplifiers can be used for its implementation. In this paper, we consider the possibility of using a gyro-TWT with a helical corrugation of the waveguide [3,4] to obtain pulses of multi-megawatt power. With an appropriate choice of parameters, one of the normal modes of such a waveguide has a sufficiently large and practically constant group velocity in a wide (10-20%) frequency range, which makes it possible to ensure effective resonant interaction of the wave with a helical electron beam in this entire range. As a result, the considered gyro-TWT provides effective amplification of ultrashort electromagnetic pulses with a wide spectrum. To achieve a multi-gigawatt power level, it is proposed to use a relativistic Cherenkov TWT with an increased waveguide radius [5,6], which makes it possible to avoid the development of vacuum breakdown when a high power level is reached.

Efficient stretcher and compressor is an important part of the CPA method. Increasing the stretched pulse duration allows to increase in the amount of energy received in the amplifier, and the decrease in the peak power allows to avoid the development of undesirable nonlinear effects. At the same time high compressing efficiency increases the output peak power. Thereby we consider using waveguides with multi-fold helical corrugation, which have the ability to change their dispersive properties in a wide range, as dispersing elements. An additional advantage of the considered waveguides is the absence of the reflection band in the operating frequency range, which makes it possible to avoid parasitic effects such as generation in the amplifier and disruption of the master oscillator.

1. Model and basic equations

Let us consider the "stretcher - amplifier - compressor" system (Fig. 1), in which we propose to use waveguides with multi-fold helical corrugation of the walls as dispersing elements: $r(\varphi, z) = r_0 + \tilde{r}\cos(\bar{m}\varphi - \bar{h}z)$, where r_0 – is the average radius of the waveguide, $\bar{m}$ – number of corrugation folds, $\bar{h} = 2\pi/d$, $\tilde{r}$ и d – amplitude and period of corrugation. Under the Bragg resonance condition: $\bar{m} = m_A + m_B$, $\bar{h} \approx h_B$, such corrugation provides coupling of two counter rotating $TE_{m.n}$ modes of the unperturbed cylindrical waveguide [7], namely, near cut-off mode (*A*), and far from cut-off traveling mode (*B*).

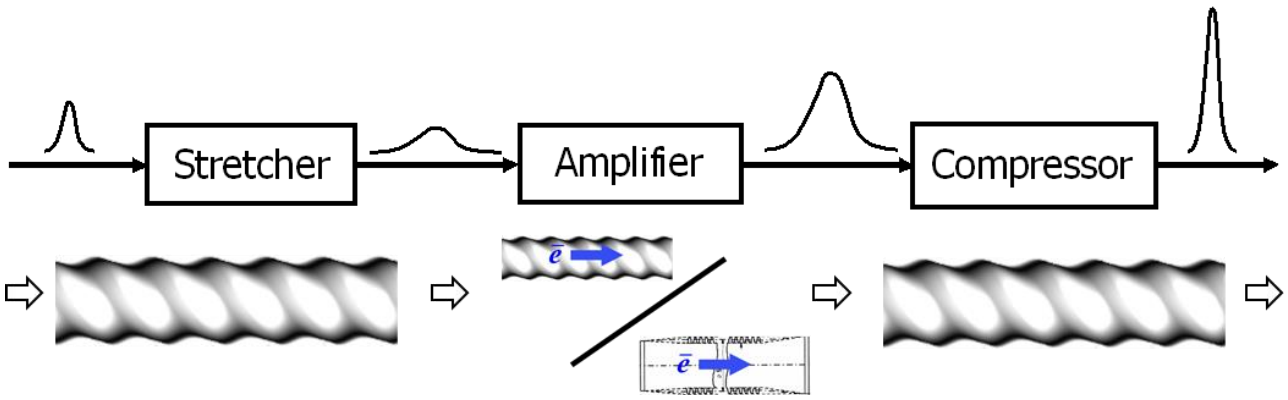

Fig.1. Block diagram of «stretcher – amplifier – compressor» system with helically corrugated waveguides as dispersive elements and different types of amplifiers.

Propagation of a pulse in the stretcher and the compressor can be described by the system of evolution equations [8]:

$$\frac{\partial^2 a}{\partial z^2} - 2i\frac{\kappa_A}{c}\frac{\partial a}{\partial t} = 2\sigma\kappa_A^2 b, \tag{1}$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{V_{gr}}\frac{\partial}{\partial t}\right)b - i(\bar{h} - h_0)b = i\frac{\kappa_A^2}{h_0}\sigma a. \tag{2}$$

Here $a = eA\sqrt{N_A}/mc^2\kappa_A$ and $b = eB\sqrt{N_B}/mc^2\kappa_B$ are normalized amplitudes of partial waves, $\sigma = \tilde{r}\left(\nu_B^2 - m_A m_B\right)/2r_0\sqrt{\left(\nu_A^2 - m_A^2\right)\left(\nu_B^2 - m_B^2\right)}$ is the wave coupling parameter on the corrugated surface of the waveguide,

$N_{A,B} = \left(\nu_{A,B}^2 - m_{A,B}^2\right) J_{m_{A,B}}^2\left(\nu_{A,B}\right)$ are the norms of the partial waves, J_m is Bessel function of order *m*, $\nu_{A,B} = \kappa_{A,B} r_0$ are the roots of equations $J'_{m_A}\left(\nu_A\right) = J'_{m_B}\left(\nu_B\right) = 0$, $V_{gr} = h_0 c/\kappa_A$ is the group velocity of traveling wave *B*, $\kappa_A = \omega_A/c$.

Preliminary selection of the helical waveguides parameters was carried out from the analysis of the normal wave *W* dispersion characteristics. Its dispersion equation can be derived from the system of equations (1) - (2) by writing the amplitudes of partial waves in the form $a,b \sim \exp\left(i\omega t - ihz\right)$:

$$\left(\omega - \omega_A - \frac{h^2 c^2}{2\omega_A}\right)\left(\omega - \omega_A - V_{gr}\left(h + \bar{h} + h_0\right)\right) = \sigma^2 \omega_A^2 . \quad (3)$$

To match the dispersion characteristics of the stretcher and compressor, we use a kinematic approach. The input pulse is represented as a set of "particles" with velocities equal to the group velocities of the spectral components $V_{gr}(\omega) = \left(dh/d\omega\right)^{-1}$ in the dispersive line. In this case the evolution of the plane wave $u(z,t) = U(z,t)\exp\left(i\omega t - ih\left(\omega\right)z\right)$ in a linear dispersive medium can be represented in the form:

$$u(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int u_0(t')\exp\left[i\omega\left(t - t'\right) - i\psi(\omega)\right]dt'd\omega \quad (4)$$

where $u_0(t) = u(z = 0,t)$ is the input signal, $\psi(\omega) = h_{str}(\omega)L_{str} + h_{com}(\omega)L_{com}$ is the total phase shift, L_{str} and L_{com} are stretcher and compressor lengths, respectively, and $h_{str}(\omega)$ and $h_{com}(\omega)$ are their dispersion characteristics determined by relation (3). Restoration of the initial pulse shape after passing through the "stretcher-compressor" system is equivalent to fulfilling the following condition: $\psi(\omega) = \tau_d \omega + \alpha$, where the delay time τ_d represents the time of pulse transmission through the system. Within the framework of the kinematic approach, the stretcher parameters were chosen in such a way that the “particles” scatter with the largest velocity, ensuring effective signal stretching. The compressor parameters are chosen to fulfill the condition for the linear phase shift $\psi(\omega)$ [8].

2. Numerical simulation of the system with helical gyro-TWT

Simulation of the "stretcher - amplifier - compressor" system with a helically corrugated gyro-TWT as an amplifier was carried out with use of evolutionary equations system (3). In the case of an amplifier it was supplemented with the corresponding equations of electron motion [8]. The calculations were performed for an initial pulse with a central frequency close to 30 GHz, a peak power of 3 kW, and a duration of 200 ps (a spectrum width of ~ 10%, which allows to avoid distortions at the edges of the amplification band). The amplifier parameters were chosen corresponding to the experimentally realized 30-GHz gyro-TWT [4] in which a three-fold helical corrugation couple the traveling $TE_{1,1}$ mode and near cut-off $TE_{2,1}$ mode of an unperturbed cylindrical waveguide. For the parameters of the electron beam: energy - 68 keV, current - 10 A, pitch factor 1.2, and for the value of the guiding magnetic field H_0 = 6.1 kOe during interaction at the second cyclotron harmonic, the tangency regime is achieved in a band of ~ 15% for the following corrugation parameters: r_0 = 3.56 mm, d = 7.36 mm, $\tilde{r}$ = 1.47 mm. For stretching and compressing purpose, we considered waveguides with a five-fold helical corrugation coupling the traveling $TE_{3,1}$ mode and near cut-off $TE_{2,2}$ mode and with an increased average radius, which makes it possible to reduce the total ohmic losses.

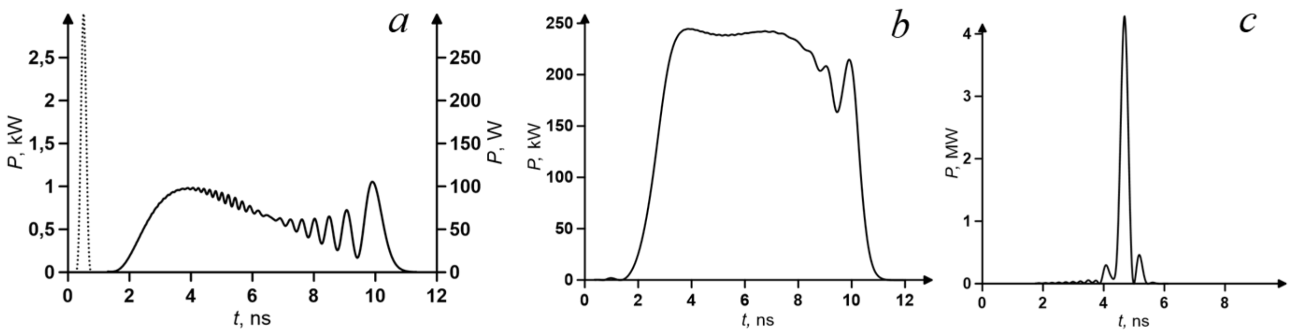

Fig. 2. Numerical simulation results for the system with helical gyro-TWT. Time dependence of the radiation power at the input to the system (dashed curve) and at the output of the corresponding sections: a) stretcher; b) amplifier; c) compressor.

Numerical simulation show that after passing through the 100 cm long stretcher with the following corrugation parameters: r_0 = 8.9 mm, d = 8.93 mm, $\tilde{r}$ = 2.02 mm, the initial pulse is elongated 23 times to 4.6 ns, and the peak power decreases 30 times (Fig. 2.a). In an amplifier section with the electron beam power of 700 kW, the peak pulse power increases to 230 kW, and its duration increases to 7.1 ns (Fig. 2.b). The additional elongation of the pulse and distortion of its shape is due to the nonlinear mode of operation in the amplifier, which turns out to be more optimal compared to the linear mode in which the signal shape is preserved. According to the simulation (Fig.2.c), after passing through a 100 cm long compressor with the following corrugation parameters: r_0 = 8.41 mm, d = 6.82 mm, $\tilde{r}$ = 4.05 mm, the original pulse shape is restored. In this case, the peak power of the output signal with a duration of ~ 260 ps is 4 MW. Thus, the conversion factor of this system - the ratio of the pulse peak power at the end of «stretcher – amplifier – compressor» system to the power of the used electron beam reaches 6.

3. Numerical simulation of the system with relativistic Cherenkov TWT

Numerical modeling of the "stretcher - amplifier - compressor" system with a relativistic Cherenkov TWT as an amplifier was carried out with a spectral approach that uses equation (5) to describe the stretching and compression of a pulse after passing through dispersing elements. Similarly to the system with a helical gyro-TWT, we consider five-fold helically corrugated waveguides as a dispersive elements. However, when using a relativistic amplifier, the choice of waveguides with an increased average radius is not only due to a decrease in ohmic losses, but also due to a decrease in the probability of breakdown development. This fact is especially important in a compressor, where the pulse peak power can reach several gigawatts.

Simulation of a relativistic Cherenkov TWT with a Slow Wave System (SWS) made – a cylindrical waveguide with periodic corrugation was carried out using a stationary 1D model [9], which describes the interaction of the operating $TM_{0,1}$ mode with an electron beam with the following parameters: electron energy - 500 keV, current - 4 A. The parameters of the SWS (the period of corrugation 2.30 mm, the maximum radius 8.97 mm, the minimum radius 6.45 mm) was similar to those described in [5]. The coupling impedance of 1.1 Ohm was achieved with a hollow electron beam with a radius of 5.2 mm. The simulation results showed the possibility of achieving an efficiency of more than 30% at an optimal SWS length of 74 mm for the operating frequency band of about 3 GHz.

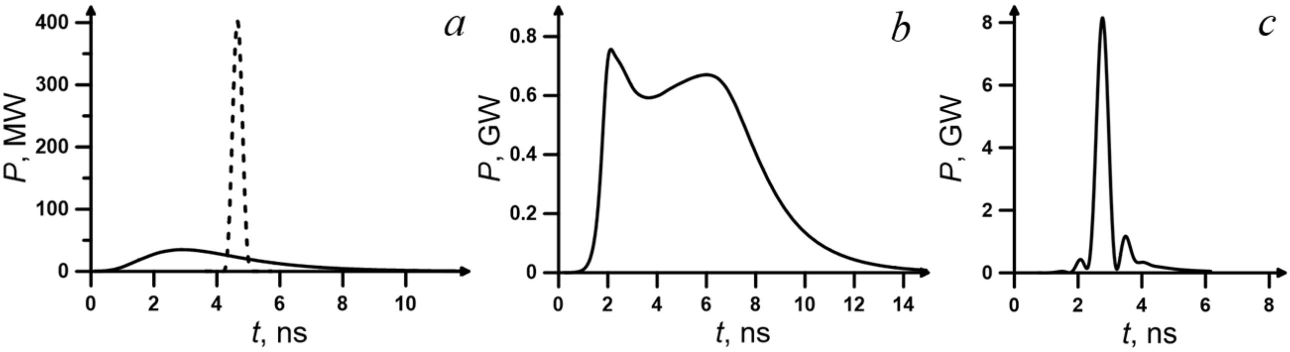

Fig. 3. Numerical simulation results for the system with relativistic Cherenkov TWT. Time dependence of the radiation power at the input to the system (dashed curve) and at the output of the corresponding sections: a) stretcher; b) amplifier; c) compressor.

For the initial signal at the input to the "stretcher - amplifier - compressor" system we considered a superradiance pulse at a frequency of 30 GHz, a duration of 360 ps, and a power of 400 MW [10,11]. Numerical simulation of this pulse propagation through the 100 cm long stretcher was performed for the following parameters of a helically corrugated waveguide: r_0=10.7 mm, d=9.2 mm, $\tilde{r}$ =2.5 mm. The calculation show that the initial pulse is stretched by about 10 times, and the peak power is reduced by 11 times (Fig. 3.a). In an amplifier with the electron beam power of 2 GW, the peak power of the stretched pulse increases up to 600 MW, and its duration increases to 6 ns (Fig. 3.b). Thus, direct amplification of the considered 400 MW superradiance pulse in this amplifier is impossible. According to the calculations (Fig. 3.c), after passing through the 100 cm long compressor with the parameters of a helically corrugated waveguide: r_0 = 9.4 mm, d = 8.8 mm, $\tilde{r}$ = 2.5 mm, the initial pulse shape is restored. In this case, the peak power of the output signal with a duration of ~ 460 ps is 8 GW. Thus, the conversion factor of this system is 4.

Conclusion

We have demonstrated the possibility of implementation of the CPA method in the microwave frequency range using multi-fold helically corrugated waveguides as a stretcher and compressor. It is shown that with use of the broadband helical gyro-

TWT as an amplifier, this method allows the generation of multi-megawatt ultrashort pulses. When using a relativistic Cherenkov amplifier, the method makes it possible to amplify short pulses to a level of the order of ten gigawatts. Note also that, in contrast to other methods of generating high-power ultrashort pulses, the "stretcher-amplifier-compressor" scheme looks more promising, since it makes it possible to achieve power levels significantly exceeding the power of the used electron beam.

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