UDC 621.375.9(045)

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THE TWO-STREAM MULTI-HARMONIC FEL AS A POWERFUL SOURCE OF FEMTO-SECOND WAVE PACKAGES

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A possibility to construct a powerful source of femto-second wave packages is analyzed. The method as well as design variant of the system for forming such packages (the multi-harmonic two-stream superheterodyne free electron laser - MTSFEL) are proposed. It is shown that very short packages (units– tens femto-second) can be obtained in the case, when the frequency of the input monochromatic (transforming) signal is much less than the optimal frequency for two-stream instability.

Introduction

It is well known that ultra-short solitary powerful electric pulses (including the femto-second wave packages) can propagate in a medium practically without any attenuation. At first sight, this makes the sources of such signals very promising for building various types of technological systems. These could be the laser systems for welding and cutting sheet materials. However, it should be mentioned that this idea, in spite of its external attractiveness, failed to find any worthy practical application till today. The point is that no suitable methods of forming directed narrow beams of such femto-second packages (which are necessary for practice) were known. This can be explained by the fact that the systems earlier realized experimentally were constructed on the basis of different types of arresters, which can not, in principle, form the required directed narrow beams.

It is also well known that femto-second laser pulses [1] also can propagate in the medium practically without attenuation.

Let us note that here we have to do with the so-called *radio-pulses*, whereas in the first case we talked about the *wave packages*.

Such femto-second signals in the form of narrow wave beams can penetrate deeply within a solid material with relatively small damping and with extremely high level of the peak power. Unfortunately, systems of this type did not find wide essential practical application either. The main problem there is low levels of the mean power attained (tens milliwatts [1]).

Method of compression of the electromagnetic wave packages

A new principle way for obtaining the femto-second wave packages has been proposed in work [2–4]. The authors call it *the method of compression of wave packages.*

In contrast to both discussed above, the method proposed allows to form narrow beams of the femto-second packages with very high mean power (hundreds kilowatts and more). The instantaneous (pulsed) power can achieve units terawatts and more. The essence of the method proposed is illustrated in fig. 1.

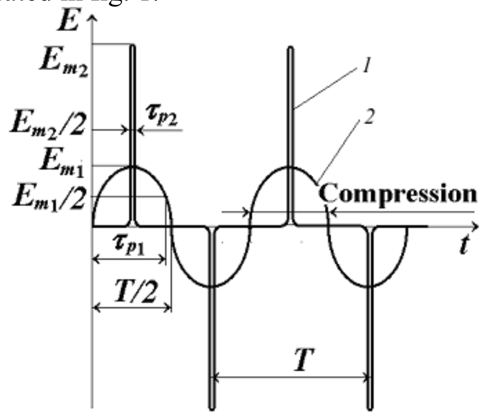

Fig. 1. The method of compression of femto-second wave packages:
1 – the sequence of compressed femto-second delta-like pulses; *2* – a harmonic signal represented in the form of a sequence of semi-sine pulses;
E – the wave electric intensity; E_{mj} – the maximal amplitudes of the initial wave (with the millimeter range, for example, j=1) and the output femto-second pulse (j=2), respectively, *t* – the time coordinate

It is quite clear, the initial sine-like signal *2* can be represented formally as a sequence (with the period T) of semi-sine pulses.

The main idea of the method proposed is to compress essentially these half-sine pulses into a sequence (with the same period T) of the output delta-like (femto-second, for instance) pulses *1*. The compression factor f_{com}, which characterizes this process, can be determined in the following form

$$f_{com} = \tau_{p1}/\tau_{p2} \approx T/2\tau_{p2} , \quad (1)$$

where all definitions are obviously illustrated in fig. 1.

One can make certain of that increasing the instantaneous pulse amplitudes occurs in the discussed case simultaneously with reducing the time duration τ_{p2} or, that is the same, increasing the compression factor f_{com} (fig. 1). For instance, the instantaneous pulsed power increases by 100 times in the case when the magnitude of the compression factor $f_{com} \cong 100$.

All this theoretically looks very promising for practice, but a 'little' question arises: how to accomplish such a possibility technologically? As shown in the works [2–5] rather an effective solution of the problem discussed can be found by the use of the multi-harmonic two-stream superheterodyne free electron lasers (MTSFELs).

Multi-harmonic two-stream superheterodyne free electron laser

The simplest design-scheme of the klystron-type MTSFEL-amplifier is provided in fig. 2.

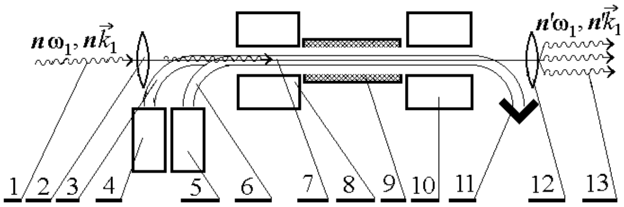

Fig. 2. Simplest variant of design scheme of the klystron-TSFEL-amplifier:
1 – the input wave signal; *2* – the optical input system; *3* – the first one-velocity relativistic electron beam; *4* – the first electron accelerator; *5* – the second electron accelerator; *6* – the second electron beam; *7* – the two-velocity (doubled) electron beam; *8* – the first multi-harmonic pumping system; *9* – the transit system; *10* – the second multi-harmonic pumping system; *11* – the electron collector; *12* – the output signal system; *13* – the output multi-harmonic signal in the form of a sequence of femto-second wave packages; $n'\omega_1$, $n'k_1$ are its frequency and wave vector, n is the number of n'th Fourier-harmonic)

The device works in the following manner. Weak input electromagnetic (transforming) signal *1* ($n\omega_1, n\vec{k}_1$) enters the input system *2* and it is then directed in the operation part of the MTSFEL. The signal *1* can be monochromatic as well as multi-harmonic. Moreover, in the first case it can be represented by the first only or one of higher harmonics.

Relativistic electron beams *3* and *6*, which have different initial energy, are formed by means of accelerators *4*, *5*.

Furthermore, both beams *3* and 6 are merged together into only two-velocity (i.e., two-energy) electron beam *7*.

The latter, in turn, is directed to the operational part of the first multi-harmonic pumping system *8*. Transformed signal wave 1 is amplified here owing to the superheterodyne amplification mechanism [2–5]. The main result of this mechanism operation is the modulation of two-stream electron beam *7* (with respect to its density) and excitation of a number of highest electronic harmonics.

Then, the electron waves (including all their harmonics) are amplified strongly in the transit section *9* owing to realization of the mechanism of two-stream instability [2–6]. This leads to that the initial electromagnetic signal *1* eventually transforms (at this stage of the process considered) into the electron-wave multi-harmonic form. Therein, the absorber of the transit system *9* absorbs the initial transformed electromagnetic signal *1* completely. This means that only strongly modulated (and multi-harmonic) electron beam 7 enters the input of second pumping system *10.* The generation of the output electromagnetic signal *13* takes place within the second pumping system *10*. This occurs owing to realization of the parametric-resonant interaction of the amplified multi-harmonic electron waves with the (multi-harmonic one also) field of the second pumping system *10*. It is here where the forming of the femto-second electromagnetic signal *13* takes place.

Essence of the problem and a way for its solution

A theoretical multi-harmonic model, described in the work [2], is used as a basis for the studies presented here.

Let's note that two types of nonlinear model arrangement have been studied earlier in the mentioned works [2–5]. The first is the model with monochromatic pumping and signal fields, in which the process of excitation of highest signal harmonics is not taken into account. The second is the explicitly expressed multi-harmonic model [2–4], in which the input monochromatic signal *1* transforms into the multi-harmonic output signal *13* (fig. 2). There the input transformed signal *1* is chosen monochromatic, whereas the pumping systems 8, 10 are multi-harmonic.

The main peculiarity of this model is that the frequency of the input transformed signal *1 coincides with the optimal frequency of two-stream instability*.

It has been shown there that the mechanism of compression discussed above could be realized in the MTSFEL.

However, it also was shown that the magnitude of compression factor (1) turned out to be rather small in this case ($f_{com} \sim 4{,}5$ times only). But, it is obvious that the system discussed could have a practical interest in the case only, when the compression factor f_{com} attains a few tens, at least. Thus, the main problem here is to increase essentially the compression factor f_{com}.

The main purpose of the work presented is looking for the ways of the formulated problem solution. For this we analyzed the main physical mechanisms, which caused the mentioned low levels of the compression factor f_{com}. A few ways for the solution of the formulated problem have been found as a result of this analysis. Including, it is proposed to choose the frequency of the initial signal *much less the optimal frequency of two-stream instability*. As it is shown in this work, this opens a possibility to obtain much higher magnitudes of the compression factor. Based on this idea and analysis accomplished, a project of possible experiment has been proposed.

The project of a femto-second MTSFEL-former

A preliminary physical and project analysis allows to formulate the main project parameters of a possible femto-second TSFEL-former (fig. 2). This device is proposed to be used as a basis of the system for welding and cutting sheet materials. Relevant calculated project parameters are shown in table. The form of the generated femto-second wave package is illustrated in fig. 3. Therein, 25 harmonics have been taken into account on relevant calculations.

As it is readily seen, the proposed device allows to prove that the compression effect can be realized experimentally on the existing modern technological basis.

On the other hand, the compression factor ($f_{com} \sim 12$), attained in the system considered, is not enough for most interesting practical applications. This means automatically that we should look for more perfect design solutions for femto-second TSFEL-former. These solutions should be characterized by the compression factor at least ~100 and more. Relevant analysis carried out allows to clear up that such class of the femto-second TSFEL-formers could be constructed practically. For instance, such "improved" femto-second TSFEL-former can be characterized by $f_{com} \sim 120$, efficiency ~30%, and the pulsed power ~$5 \cdot 10^{10}$ W.

Then, modernizing this system by use of electron beams with higher current (for instance, 2x10kA) and energy (for example, 5MeV), we can obtain a practical possibility for constructing relatively compact femto-second TSFEL-formers with the pulsed power at the level ~ $4 \cdot 10^{13}$ W and mean power ~ 50-100 kW or higher.

This looks very promising for modern systems of considered type.

Relevant calculated project parameters

Parameter	Magni-tudes
Accelerator block	
Pulsed current strength of the electron beam, A	250
Beam pulse duration, ns	100
Mean beam energy of the two-velocity electron beam, MeV	1.2
Difference of energy of the one-velocity beams, MeV	0.051
Energy thermal spread of the beam, %	2
Beam perveance μ, $A \cdot B^{(-3/2)}$ $AB^{(-3/2)}$	0.19
Beam diameter, mm	2.48
Plasma frequency of the beam, s^{-1}	$6 \cdot 10^{10}$
Electromagnetic signal	
Ratio of the signal and optimal frequencies	15
Signal wavelength, mm	4.9
Power of the input signal, W	1.67
Average (for the period) power of the output signal for the first harmonic, W	$5.76 \cdot 10^{4}$
Average (for the period) power of the output signal for all harmonics, W	$7.2 \cdot 10^{5}$
Pulsed power of the femto-second pulse, W	$1.73 \cdot 10^{7}$
Duration of the output femto-second wave package, fs	340
Other design characteristics	
Period of the undulation, cm	8.85
Induction of the undulator magnetic field (the first harmonic), Gs	600
Focusing magnetic field, Gs	443
Length of the first pumping section, m	1
Length of the transit section, m	0.5
Length of the second pumping section, m	1
Total length of the laser section, m	2.5

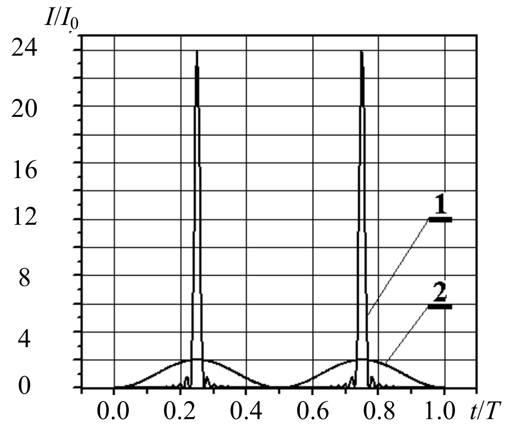

Fig. 3. Dependency of the normalized signal intensity I/I_0 on the normalized duration of the femto-second wave packages t/T:

1 – is the intensity of the output signal; *2* – is the intensity of the input signal; I_0 is the averaged intensity of the equivalent sin-like signal

It should specially be mentioned that today the nonlinear electrodynamics of the superpower periodical femto-second electromagnetic wave packages is, in itself, a new science. Now we have no satisfactory nonlinear theory for propagation of such signals in mediums.

Nor there are any experiments in this aria. The technology of forming such kind of signals today is not developed yet. Therefore, we can say that the project discussed, apart from the obvious purely practical benefits, will play the role of a powerful stimulus for further development of fundamental aspects of physics as well as the femto-second wave packages technology.

Conclusion

Thus, a new method of generation of femto-second electromagnetic packages is considered, and a new model of a source of such packages is proposed. The analysis accomplished showed that such sources can be constructed on the basis of multi-harmonic two-stream superheterodyne free electron laser (MTSFEL). Therein, it can be done at the current technological level.

Literature

1. *Ахманов С.А., Вислоух В.А., Чиркин А.С.* Физика фемто-секундных лазерных импульсов. – М.: Наука, 1988. – 346 с.

2. *Kulish V.V., Lysenko A.V., Savchenko V.I.* Two-stream free electron lasers. Part I // Intern. Journal on Infrared and Millimeter Waves. – Febr., 2003. – Vol. 24, N 2. – P. 129–172.

3. *Kulish V.V., Lysenko A.V., Savchenko V.I.* Two-stream free electron lasers. Part 2 // Intern. Journal on Infrared and Millimeter Waves. – Mar., 2003. – Vol. 24, N 3. – P .285–309.

4. *Kulish V.V., Lysenko A.V., Savchenko V.I.* Two-stream free electron lasers. Part 3 // Intern. Journal on Infrared and Millimeter Waves. – Apr., 2003. – Vol. 24, N 4. – P. 501–524.

5. *Kulish V.V.* Hierarchical methods. Vol. II. Undulative electrodynamic systems, Kluwer Academic Publishers. – Dordrecht/Boston/London, 2002. – 326 p.

6. *Kulish V.V.* Hierarchical methods. Vol. I. Hierarchy and hierarchical asymptotic methods in electrodynamics, Kluwer Academic Publishers. – Dordrecht/Boston/London, 2002. – 354 p.

The editors received the article on 23 March 2005.

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Двопотоковий мультигармонічний лазер на вільних електронах як потужне джерело фемто-секундних хвильових пакетів

Проведено аналіз можливості створення потужного джерела фемто-секундних хвильових пакетів. Запропоновано варіант системи для формування таких пакетів (мультигармонічний двопотоковий супергетеродинний лазер на вільних електронах – МДСЛВЕ). Показано, що дуже короткий імпульс (одиниці – десятки фемто-секунд) можна отримати у випадку, коли частота вхідного монохроматичного (того, що трансформується) сигналу набагато менша ніж оптимальна частота для двопотокової нестійкості.

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Двухпотоковый мультигармонический лазер на свободных электронах как мощный источник фемто-секундных волновых пакетов

Проведен анализ возможности создания мощного источника фемто-секундных волновых пакетов. Предложен вариант системы для формирования таких пакетов (мультигармонический двухпотоковый супергетеродинный лазер на свободных электронах – МДСЛСЭ). Показано, что очень короткий импульс (единицы – десятки фемто-секунд) может быть получен в случае, когда частота входного монохроматического (трансформируемого) сигнала намного меньше оптимальной частоты для двухпотоковой неустойчивости.