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Generation of nanosecond microwave pulses in corrugated transmission lines with ferrite

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Abstract. The results of the development of nanosecond high-frequency pulse generators based on corrugated coaxial transmission lines with ferrite saturated in the field of permanent magnets are presented. In terms of its dispersion properties, the line is similar to a line with lumped parameters and capacitive coupling between adjacent cells of the line. Using numerical simulation, two configurations of corrugated lines with maximal center frequencies of 1.5 and 3.6 GHz were developed and implemented. The peak power of the lines is 800 and 170 MW, respectively. The dependences of the power and frequency of excited oscillations on the voltage of the incident pulse were obtained. The dependences of the frequency of excited oscillations, its amplitude and pulse duration on the axial magnetic field were also obtained for 1.5 GHz CNLTL configuration.
Keywords: high power microwaves, nonlinear transmission lines, ferrite, permanent magnets.

1. Introduction

The development of methods and technologies for generating high power nanosecond microwave pulses has been going on for over 50 years [1]. Powerful microwave radiation pulses have peak power exceeding 100 MW and radiation frequency above 1 GHz up to 300 GHz. The pulse energy reaches 1 kJ. Traditional devices of high-power microwave electronics are devices that use the energy of electron beams (traveling wave tube, backward wave oscillator, vircator, relativistic magnetron, klystron, gyrotrons, etc.). A distinctive feature of vacuum devices is small partial spectrum width, which classifies them as narrowband.

The development of broadband generators based on vacuum devices seems possible when generating ultrashort pulses with the development of technology in the frequency range of the order of 1 GHz. Generators of powerful ultra-wideband pulses, usually, represent the excitation of an ultra-wideband antenna by short (on the order of several nanoseconds) monopolar or bipolar high-voltage pulses [2, 3]. The main difference of these systems from traditional devices in terms of use is the absence of vacuum systems and electron beams and, as a consequence, the absence of accompanying X-ray radiation, as well as problems associated with the limited resource of explosive emission cathodes.

Another method of generating ultra-wideband pulses is the use of gyromagnetic nonlinear transmission lines (GNLTLs) [4]. GNLTLs are transmission lines filled with saturated ferrite. When a high voltage pulse propagates along the line, powerful high-frequency oscillations with a power of hundreds of MW are excited in it, the duration of which can reach 10 ns. To date, the possibility of exciting oscillations in the frequency range from hundreds of MHz to several GHz has been demonstrated based on ferrite lines [5, 6]. The main difficulties in mastering generation frequencies above 10 GHz are the difficulties in creating high-voltage pulse sources with a front duration of hundreds of picoseconds, as well as issues of the electrical strength of lines of small transverse dimensions, typical for this frequency range.

An important step in the development of high-frequency pulse generation methods based on saturated ferrite lines was the creation of line configurations in which the ferrite is saturated in the field of permanent magnets located inside the line. In this case, the line is a coaxial transmission line with a corrugated inner conductor (CNLTL) [7]. The energy efficiency of CNLTL is a few percent and can be improved to 10% with optimal selection of the duration of the video pulse supplied to the line input.

2. Corrugated Nonlinear Transmission Lines

2.1. CNLTL

The traditional configuration of an NLTL with ferrite is a section of coaxial transmission line, between the conductors of which ferrite rings are located, saturated in the field of the solenoid. When a nanosecond voltage pulse with a subnanosecond front propagates in it, under certain conditions, high-frequency oscillations are excited in the line [4]. Other working regimes of the line with saturated ferrite are the front sharpening and energy compression regimes of the voltage pulse [8, 9]. Earlier, the authors of this paper proposed a configuration of NLTL with ferrite that does not use a solenoid. In it, ferrite is saturated in the field of rings of NdFeB permanent magnets, alternating with ferrite rings inside the line. The transmission line in this case is a coaxial line with a corrugation on the inner conductor (Fig. 1).

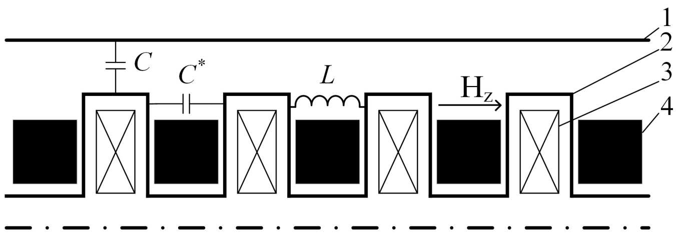

Fig. 1. A schematic image of a corrugated nonlinear transmission line.

2.2. Dispersion properties of CNLTL

This work is aimed at studying the issue of expanding the frequency range of generation in CNLTLs, as well as the possibility of retuning the oscillation frequency by an axial magnetic field. The problem of determining the generation frequency in a nonlinear transmission line is mainly associated with its dispersion properties. It is known that in an NLTL with a continuous ferrite filling, the dispersion properties of the line are determined by the precession of the ferrite magnetization vector excited by the pulsed magnetization reversal of the ferrite. In the case of a corrugated line, the inner conductor is a slowing structure that determines its dispersion properties.

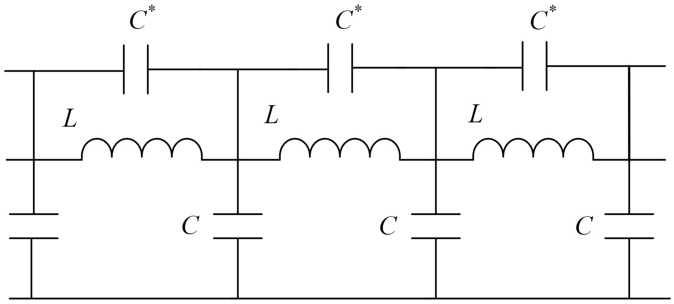

Fig. 2. Equivalent circuit of a CNLTL.

The dispersion characteristic of a corrugated line without taking into account the gyromagnetic properties can be found by solving an electrodynamic problem, similar to corrugated waveguides of relativistic devices [1]. The dispersion characteristic of the line can also be obtained using numerical electrodynamic modeling. For CNLTLs, a simpler method of finding is to use the equivalent circuit of the line (Fig. 2). The equivalent circuit of the CNLTL is a lumped line with capacitive coupling between adjacent cells of the line. This method allows us to write an analytical expression for the frequency dispersion of the line, which is given by the following expression:

$$\omega^2 = \frac{4\omega_0^2 \sin^2(\varphi/2)}{1+4\gamma_{coup}\sin^2(\varphi/2)}, \qquad (1)$$

here $\omega_0 = 1/(LC)^{1/2}$, $\gamma_{coup} = C^*/C$ – capacitive coupling coefficient, φ – phase shift per line cell. In the case where there is no capacitive coupling between adjacent cells of the line, its dispersion properties are given by the expression:

$$\omega^2 = 4\omega_0^2 \sin^2(\varphi/2). \qquad (2)$$

Fig. 3 shows the dispersion characteristics of a corrugated line using ferrite rings with dimensions of 32×20 mm^2 for different values of the capacitive coupling coefficient. Fig. 3 also shows the dispersion curve for the line with a capacitive coupling coefficient of γ = 0.235, obtained using numerical simulation in CST Studio [10]. This line will be further investigated in this paper. From the analysis of the curves, it becomes clear that an increase in the capacitive coupling coefficient leads to a decrease in the generation frequency of the line. To increase the generation frequency, it is necessary to reduce the transverse dimensions of the line and ferrite rings. Fig. 4 shows the dispersion curves for a corrugated line with ferrite rings of 10×6 mm^2 and γ = 0.03, obtained analytically and using numerical simulation. Increasing the capacitive coupling coefficient when using small rings is difficult, due to the design features of corrugated lines using magnets. In this line, a significant slowdown begins to manifest itself only for waves with an oscillation frequency above 2.9 GHz. In the line with 32×20 mm^2 rings for waves with a frequency above 1.3 GHz. Good agreement between the dispersion curves obtained analytically and in numerical modeling indicates that the equivalent circuit approximation of the line correctly describes the high-frequency properties of the lines in the case when the ferrite is magnetized to saturation in strong magnetic fields (~ 100 kA/m).

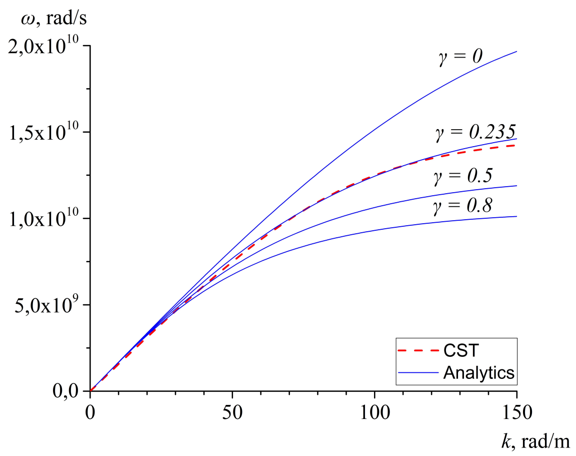

Fig. 3. Dispersion of CNLTLs using 32×20 mm^2 ferrite rings.

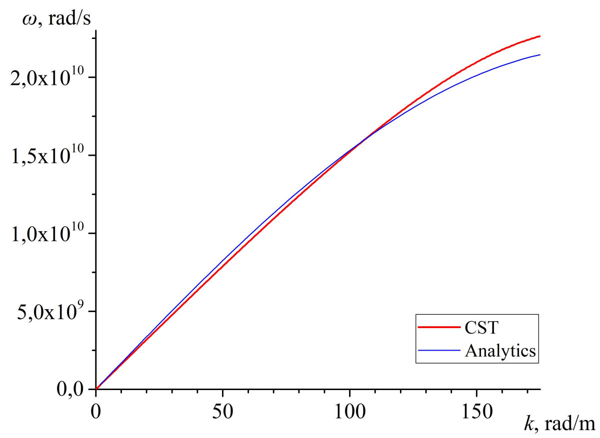

Fig. 4. Dispersion of CNLTLs using 10×6 mm^3 ferrite rings.

3. Configurations and simulation results

Numerical modeling plays an important role in the development of nanosecond RF pulse generators based on CNLTLs. The parameters of the corrugation of the inner conductor of the line should be optimized to achieve the required values f impedance, values of the magnetic field strength components, generation frequency and electric field strength to prevent line breakdown. The electromagnetic code KARAT [11] was used to model lines with saturated ferrite. In it, saturated ferrite is taken into account as a phenomenological medium described by a magnetization vector that obeys the Landau-Lifshitz equation. In the macrospin approximation for the magnetization vector, it has the form:

$$\frac{d\mathbf{M}}{dt} = \gamma[\mathbf{M} \times \mathbf{H}] + \frac{\alpha\gamma}{M_s}[\mathbf{M} \times [\mathbf{M} \times \mathbf{H}]], \tag{3}$$

here **M** – ferrite magnetization vector, **H** - magnetic field strength vector, M_s – saturation magnetization, γ – gyromagnetic ratio, α – phenomenological dumping constant.

Two CNLTL configurations were developed, designed to generate high-frequency pulses in two frequency ranges - above 1 GHz and above 3 GHz. Information on the line configurations is presented in Table 1. The main task was to minimize the line impedance to increase the oscillation power. When moving to a higher frequency range, it is necessary to increase the impedance due to the high electric field strength in the line of smaller transverse dimensions.

Table 1. CNLTLs parameters

	1 GHz CNLTL	3 GHz CNLTL
Ferrite size	32×20 mm^2	10×6 mm^2
Corrugation periods	100 periods	100 periods
Working voltage range	150–360 kV	60–190 kV
Axial magnetic field	30 kA/m	40 kA/m
Impedance	22 Ohms	28 Ohms
Frequency range	1.2–1.5 GHz	2.9–3.6 GHz
Coupling coefficient γ_{coup}	0.235	0

4. Experimental results

The experiments were carried out according to the scheme shown in Fig. 4. Two SINUS-type generators [12] were used to power the lines, forming voltage pulses with a duration of 13 ns for 1 GHz and 7 ns for the 3 GHz line at half-width on a matched load. The typical duration of the pulse front from the SINUS generator is at least 3 ns. To sharpen it, a section of the line with a continuous ferrite filling and a solenoid was used, which made it possible to reduce the voltage pulse rise time to values of 0.8–1.2 ns depending on the pulse voltage. The voltage pulses were recorded by D-dot sensors and a digital oscilloscope (6 GHz, 25 GS/s).

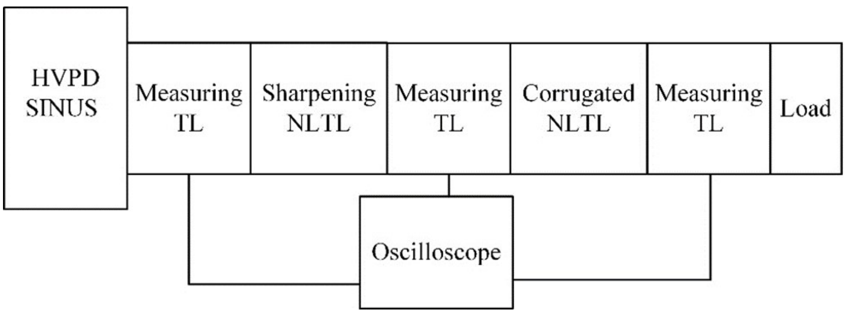

Fig. 4. Block-scheme of the experimental setup

4.1. 1 GHz CNLTL

Fig. 5 shows the waveform of the voltage pulse at the line output when a 360 kV pulse is fed to its input. The peak power of the obtained high-frequency oscillations is 800 MW, the pulse duration is 12 ns. With increasing voltage, the duration of the high-frequency pulse increased from 8.5 ns to 12 ns. Fig. 6 shows the dependence of the amplitude of the first oscillation of the high-frequency pulse on the voltage of the incident pulse. Fig. 7 shows the dependence of the central frequency of the high-frequency pulse on the magnitude of the incident voltage.

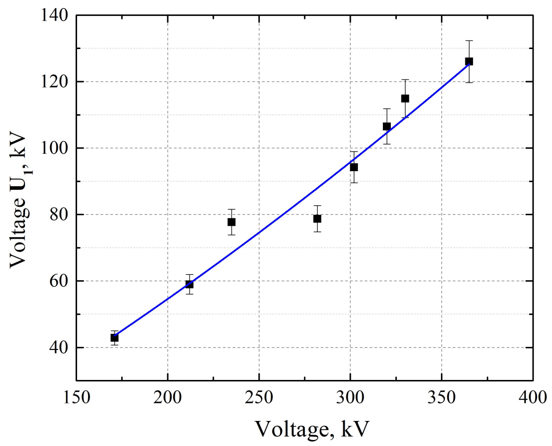

Fig.5. Dependance of the first oscillation amplitude on voltage of the initial pulse for 1 GHz CNLTL.

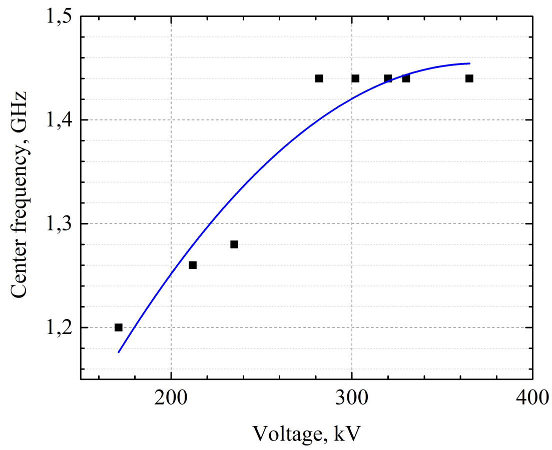

Fig. 6. Dependance of the center frequency on voltage of the initial pulse for 1 GHz CNLTL.

4.2. 3 GHz CNLTL

Fig. 7 shows the oscillogram of the voltage pulse at the line output when a 190 kV pulse is fed to its input. The peak power of the obtained high-frequency oscillations is 170 MW, the pulse duration is 4 ns. With increasing voltage, the duration of the high-frequency pulse was in the range from 3 to 4 ns. Fig. 8 shows the dependence of the amplitude of the first oscillation of the high-frequency pulse on the voltage of the falling pulse. Fig. 7 shows the dependence of the central frequency of the high-frequency pulse on the magnitude of the falling voltage.

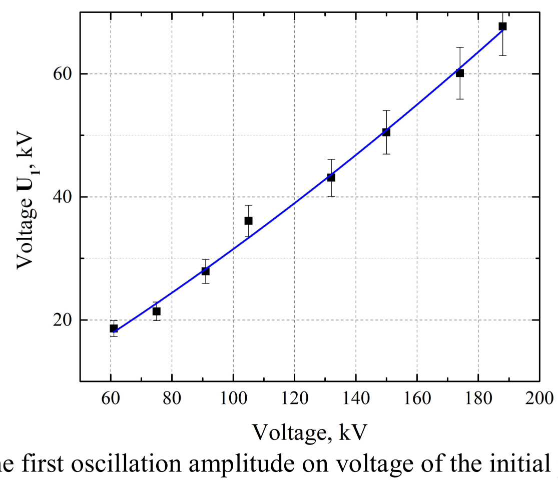

Fig. 7. Dependance of the first oscillation amplitude on voltage of the initial pulse for 3 GHz CNLTL.

4.3. 1 GHz CNLTL with various axial magnetic field

In addition, an experiment was conducted in which the 1 GHz CNLTL was placed inside a solenoid with a maximum magnetic field strength on the axis of 70 kA/m. For this experiment, the dependence of the central frequency of the high-frequency pulse on the axial field of the solenoid at a voltage of 350 kV was obtained. This dependence is shown in Fig. 9, where the negative magnetic field corresponds to a field directed opposite to the field of the permanent magnets. A decrease in frequency in a higher magnetic field is typical for lines with saturated ferrite. The dependences of the amplitude of the first oscillation and the duration of the high-frequency pulse on the axial field of the solenoid were also obtained (Fig. 10 and 11). The results of the experiment showed that the field in the ferrite created by the permanent magnets is optimal for obtaining the maximum energy efficiency of the generator. The duration of the high-frequency pulse decreases in a higher axial magnetic field.

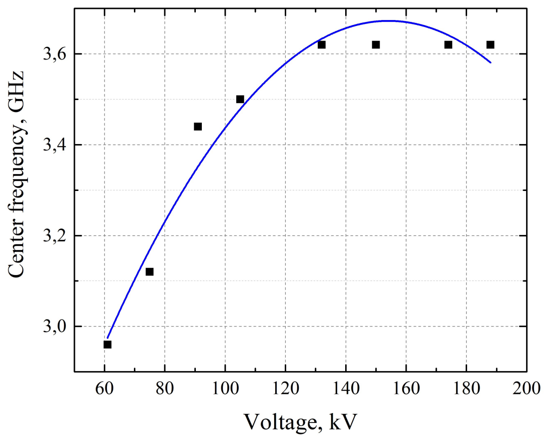

Fig. 8. Dependance of the center frequency on voltage of the initial pulse for 3 GHz CNLTL.

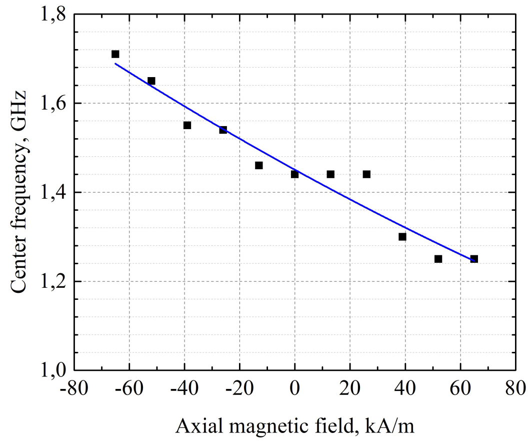

Fig. 9. Dependance of center frequency on axial magnetic field for 1 GHz CNLTL.

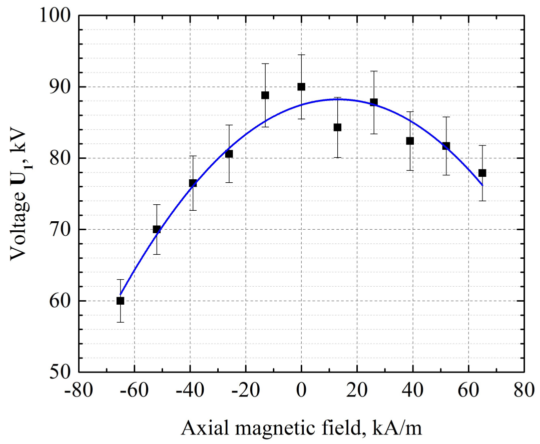

Fig. 10. Dependance of the first oscillation amplitude on axial magnetic field for 350 kV initial pulse for 1 GHz CNLTL.

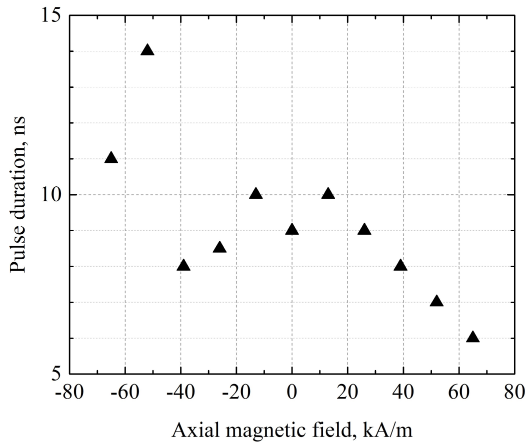

Fig. 11. Dependance of the pulse duration on axial magnetic field for 350 kV initial voltage pulse for 1 GHz CNLTL.

5. Conclusion

A method for generating nanosecond high-frequency pulses using corrugated nonlinear transmission lines with ferrite saturated in the field of permanent magnet rings is demonstrated. A feature of the line configuration is the corrugation of the inner conductor of the line, whose dispersion properties primarily determine the frequency of the excited oscillations of the line. The size of the ferrite rings and the coefficient of capacitive coupling between adjacent line cells have the greatest effect on the generation frequency. When the axial field inside the ferrite changes, the generation frequency changes by several hundred megahertz. In the experiment, two configurations were implemented, the central frequency of which is in the ranges of 1.2–1.5 GHz and

2.9–3.6 GHz, respectively. The peak power level is measured in hundreds of megawatts, which makes CNLTL-based sources promising alternatives to traditional vacuum microwave devices.

Acknowledgements

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