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Influence of voltage pulse polarity on excitation of high-frequency oscillations in a nonlinear transmission line with saturated ferrite

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Abstract. Experimentally and using numerical simulation the process of excitation of high-frequency oscillations in a nonlinear transmission line with saturated ferrite, depending on the polarity of the incident voltage pulse, was studied. As part of the work, an effect was discovered in which the voltage pulses generated at the output of the transmission line depend on the direction of rotation of the magnetization vector of the ferrite filling. The shape and characteristics of these pulses were studied and compared depending on the polarity of the incident voltage pulse.
Keywords: ferrite, saturated ferrite, nonlinear transmission lines, radiofrequency, high power microwaves.

1. Introduction

The problem of generating nanosecond pulses of high-frequency high-power oscillations has attracted a significant number of new researchers over the past few years. Today, this is largely due to the use of these pulses as means of electromagnetic countermeasures, as well as in electromagnetic compatibility problems. There are several approaches to generating high-frequency pulses. First of all, these are devices that use the energy of electron flows, such as traveling wave lamps, backward wave lamps, magnetrons, vircators, etc. [1]. An alternative approach in the decimeter wavelength range is the use of nonlinear transmission lines (NLTLs) with saturated ferrite. Advantageous differences between NLTL-based generators and devices with an electron beam are the absence of vacuum, they do not require large magnetic fields that is needed to transport the beam, and the absence of accompanying X-ray radiation during operation.

Over the past 20 years, generators of nanosecond high-frequency pulses have come a long way in development. To date, NLTL-based generators have demonstrated the ability to operate in the centimeter wavelength range and have already crept close to the millimeter range with a generation frequency up to 20 GHz [2–4]. In the decimeter wavelength range, generators based on NLTLs are close in their peak power to vacuum devices. The maximum peak power reported in the literature is 700 MW with energy efficiency of about 10% for converting video pulse energy into radio pulse energy [2]. In addition to the generation of high-frequency oscillations in the NLTL with saturated ferrite, the voltage pulse front sharpens with the possibility of controlling the time of pulse propagation by changing the external magnetic field. This effect makes it possible to create phased multichannel radiating systems based on NLTLs with the possibility of beam steering in open space. To date, the possibility of creating two and four-channel radiation sources in the frequency range from 1 to 8 GHz with the possibility of beam steering in the horizontal plane has already been demonstrated [5, 6].

Despite the fact that, from the point of view of technical implementation, NLTLs with ferrite have come a long way, the theory of the process of excitation of high-frequency oscillations in them is still not quite clear. This is primarily due to the impossibility of building an analytical model due to the complexity of the mathematical description of nonlinear processes in the transmission line. Today, the most appropriate way to study the physical processes occurring in a NLTL with ferrite is to use numerical simulations along with real experiments.

2. Theoretical background

Traditionally, NLTL with ferrite, used to generate high-frequency pulses, is a coaxial transmission line, between the conductors of which ferrite rings are located. Coaxial geometry is due to its increased electrical strength. Ferrite does not occupy the entire cross section of the line, and, usually, the remaining space is filled with oil with its dielectric constant $\varepsilon = 2.2$ to further increase the electrical strength of the gap. In rare cases, liquid dielectric is not used, SF_6 is used instead. However, a number of studies show that the use of a liquid dielectric increases the generation efficiency. The NLTL is located inside a solenoid, which creates a constant axial magnetic field, which brings the ferrite filling to saturation state.

During the passage of a current pulse in the line, under the action of the azimuthal magnetic field created by this current, the process of pulsed magnetization reversal of the ferrite filling occurs. In the macrospin approximation, the dynamics of the magnetization vector **M** can be described by the Landau-Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma\mu_0 \left[\mathbf{M}\times\mathbf{H}\right] - \frac{\alpha\gamma\mu_0}{M_S}\left[\mathbf{M}\times\left[\mathbf{M}\times\mathbf{H}\right]\right]. \tag{1}$$

Here, γ is the electron gyromagnetic ratio, α is a phenomenological constant that determines dumping of the precession, μ_0 is the magnetic constant, M_s is saturation magnetization, and **H** is the total magnetic field strength vector. As a result, a shock wave is first formed in the line. It is a voltage pulse with a rise time of hundreds of picoseconds. After that, when the shock wave propagates along the NLTL with saturated ferrite, damped high-frequency oscillations are observed behind it.

In the first approximation, the frequency of the excited oscillations is determined by the Larmor precession formula and does not depend on the angle by which the resulting vector of the magnetic field strength deviates [7]

$$f = 3.52 H_\Sigma 10^4 \text{ Hz}. \tag{2}$$

Here H_Σ is the value of the total magnetic field strength, which includes axial, azimuthal, demagnetizing and anisotropic magnetic fields.

Another approach to determining the frequency of oscillations excited in the NLTL can be an approach that considers voltage and current waves propagating in the transmission line with ferrite, taking into account equation (1), which describes the filling response to these waves. To describe the current and voltage waves in a transmission line, the simplest way is to use telegraphic equations, which are one-dimensional

$$\begin{aligned} \frac{\partial J(t,z)}{\partial z} &= -C_0\frac{\partial U(t,z)}{\partial t} \\ \frac{\partial U(t,z)}{\partial z} &= -\frac{\partial \Phi(t,z)}{\partial t} \end{aligned}. \tag{3}$$

Here $J(t, z)$, $U(t, z)$ – functions of current and voltage waves, $\Phi(t, z)$ – magnetic flux in the transmission line, which is the sum of linear and nonlinear fluxes, C_0 – capacitance per unit length of the transmission line. Linearization of (3) together with (1) gives the expression for the frequency of oscillations

$$f = \frac{\gamma\mu_0 H_\theta}{4\pi}\sqrt{1+\frac{\chi M_S}{\mu_0\sqrt{H_\theta^2+H_z^2}}}. \tag{4}$$

H_z, H_θ – axial and azimuthal magnetic field strength χ – ferrite filling factor of the transmission line.

Expression (4) describes well the trends in the frequency of excited oscillations in the NLTL with saturated ferrite and gives a close quantitative result. Indeed, in experiments with an increase in the axial bias field H_z, a smooth decrease in the oscillation frequency is observed, and in the case of an increase in the current flowing through the line, the oscillation frequency increases. It should be said, that there are optima in the ratio of the axial and azimuthal fields in terms of NLTL efficiency.

In all experiments with NLTLs, the process of excitation of oscillations did not depend in any way on the direction of the axial field H_z. The study of the operation of the NLTL in cases of different polarity of the voltage pulse, apparently, has not been carried out. The main reason for this may be the fact that generators used to accelerate electron beams are usually used as sources of high-voltage pulses and, as a result, they have a negative pulse polarity. This paper presents the results of studying of the dependence of the characteristics of excited oscillations in a NLTL with saturated ferrite on the polarity of the voltage pulse. The studies include both the results of numerical simulation and experimental studies.

3. Simulation

3.1. Simulation technique

Equations (3) are not suitable for describing an electromagnetic wave propagating in a NLTL with a partial ferrite filling, since the approximation of telegraph equations involves averaging of electromagnetic fields over the cross section of the transmission line. However, to model the process of excitation of oscillations in transmission lines with ferrite, it is necessary to take into account the transverse structure of electromagnetic fields. A more correct approach is the joint solution of the Landau-Lifshitz equation (1) with the Maxwell's equations. This possibility is implemented in the non-stationary code KARAT [8]. It has already successfully proved itself in the problems of modeling the processes occurring in NLTLs with saturated ferrite.

3.2. Simulation results

In numerical simulation, as an object for studying the effect of the voltage pulse polarity, one of the NLTL geometries was chosen, which has a high energy efficiency and was previously implemented in the experiment. Its outer and inner diameters are 57 and 28 mm, the dimensions of the ferrite rings are 45 and 28 mm, and the length of the NLTL is 800 mm. The free space of the transmission line is filled with vacuum oil having its dielectric constant $\varepsilon = 2.2$. The maximum operating voltage of the line with oil filling is 300 kV.

Fig.1 shows the simulation results. Waveforms of voltage pulses at the output of the NLTL with ferrite are presented for different amplitudes and polarities of the incident pulse. The incident pulse was a trapezoidal pulse with a FWHM of 7 ns and a rise time of 1 ns. The external magnetic field is 50 kA/m, which is optimal for this geometry.

The simulation results showed that the voltage pulse shapes at different pulse polarities are noticeably different. For the case of positive polarity, the frequency of excited oscillations turns out to be slightly higher. For a positive voltage pulse, the period of the first few oscillations is, on average, 0.2 ns shorter than that for a negative voltage. In this case, the shape of the pulse at the NLTL output is more similar to the case of excitation of soliton-like waves similar to the waves excited in NLTLs with nonlinear dielectrics [9].

4. Experiment

4.1. Experimental setup

To conduct an experimental study of this effect, an experimental scheme was developed, shown in Fig. 2. As a source of voltage pulses, a SINUS-200 generator was used, which is a coaxial forming line with a secondary winding of Tesla transformer placed inside it. The change in the polarity of the voltage pulses was achieved by charging the primary low-voltage capacitance to a voltage of a different sign. After the voltage pulse generator, there was a section of a nonlinear transmission line with ferrite without external magnetic field, which was used to sharpen the pulse front. The sharpening NLTL is used to reduce the size of the solenoid used to generate high frequency oscillations, since it is able to sharpen the front of the incident pulse by the amount necessary to excite high frequency oscillations. The amplitude of the voltage pulse could be varied in the range from 100 to 300 kV. The length of the gyromagnetic NLTL (GNLTL) was 800 mm and was located inside a 1000 mm long solenoid capable of creating a magnetic field of up to 100 kA/m. The measurements were carried out using D-dot sensors built into the sharpening transmission line and into special measuring lines, which provided sufficient time decoupling to register voltage pulses in a case of any reflections inside.

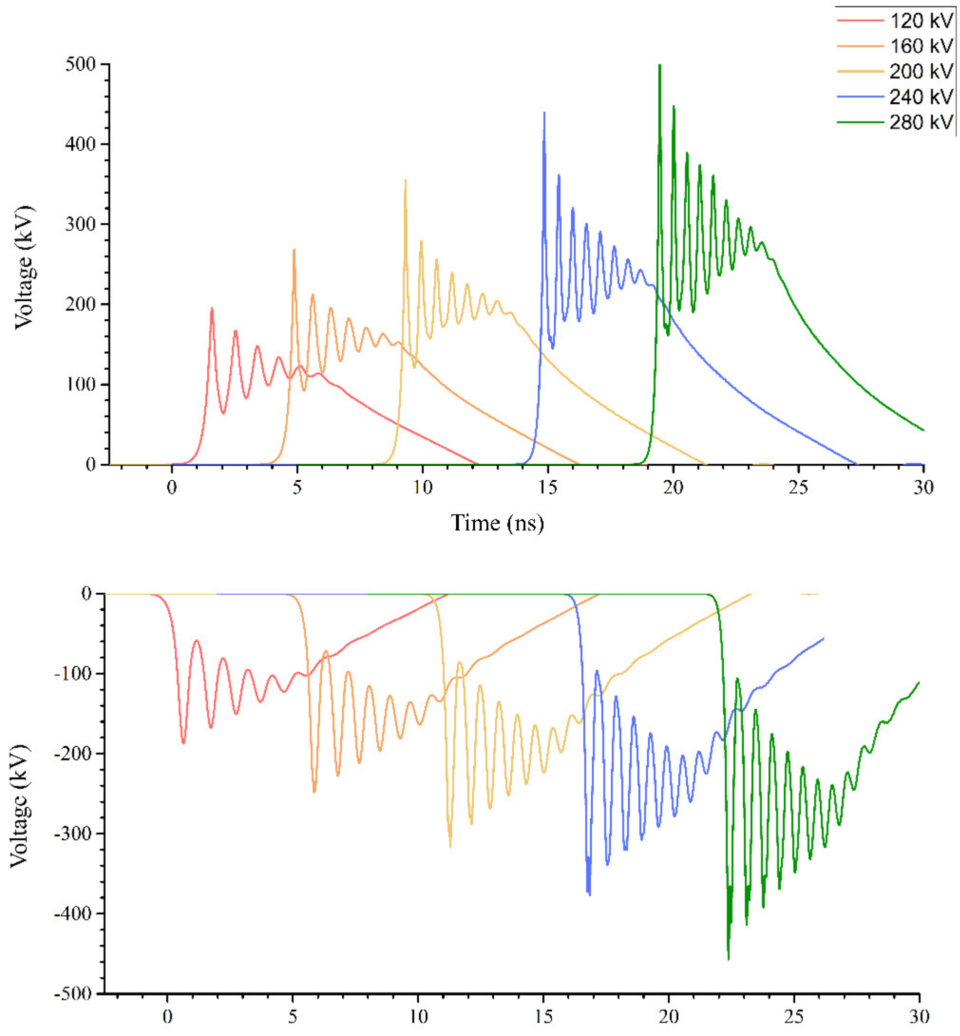

Fig.1. Typical simulation waveforms of the NLTL output voltage pulses for different input voltage and polarity.

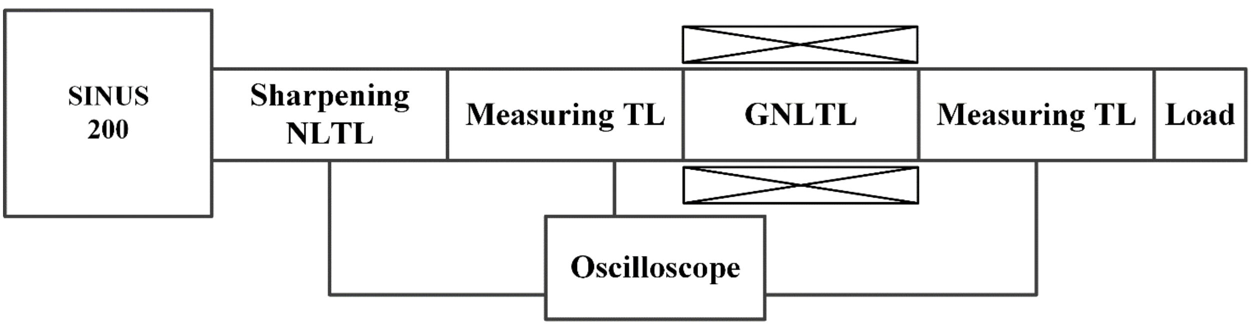

Fig.2. Block-scheme of the experiment.

4.2. Experimental results

In the course of the experiment, voltage oscillograms were measured at the NLTL's output at different polarities of the voltage pulse. Typical output voltage pulse waveforms of such measurements are shown in Fig.3 for the case of an incident voltage pulse of 240 kV. The incident pulse had a quasi-trapezoidal shape with rise time of 900 ps at a level of 0.1–0.9 after the sharpening section. Fig.4 shows the dependences of the center frequency of the output high-frequency on the magnitude of the axial bias field for different voltage polarities.

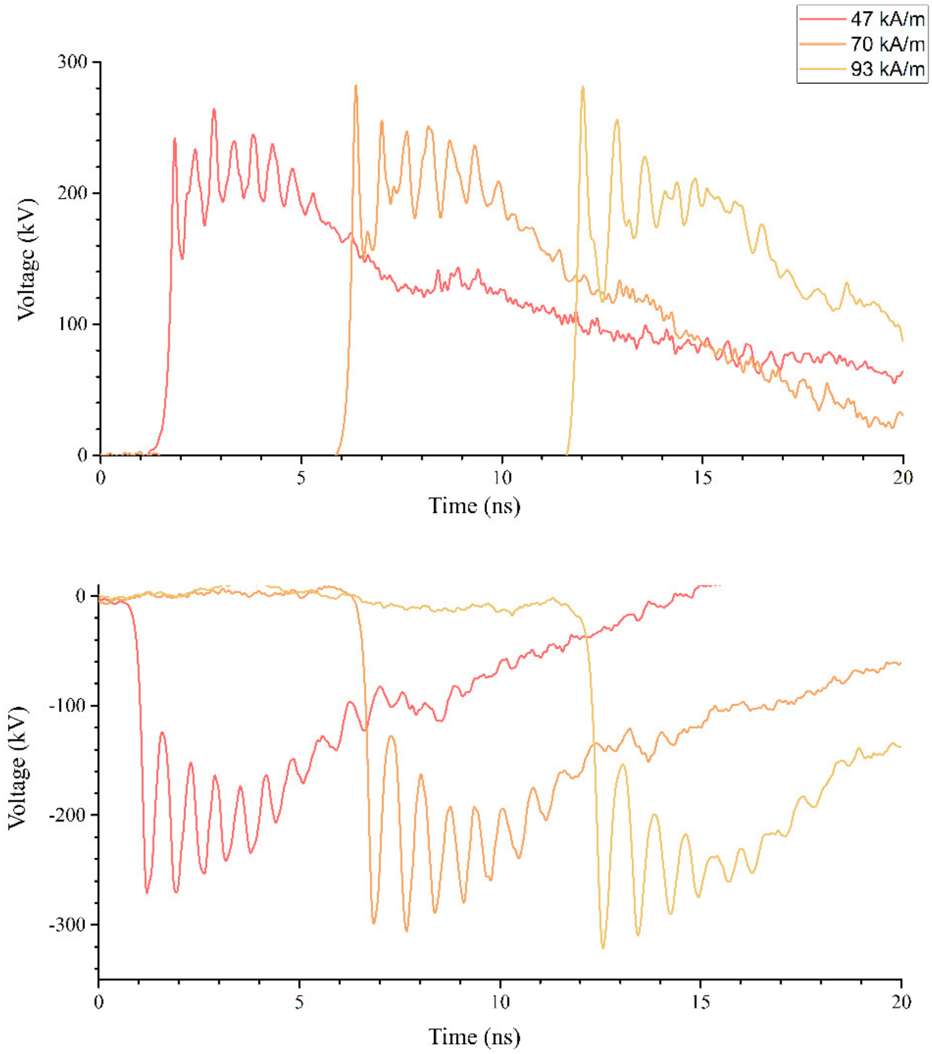

Fig.3. Experimental NLTL output voltage waveforms for different axial magnetic field. Input voltage ±240 kV.

4.3. Discussion

The results of the experiment, as well as simulation, showed a significant difference between the shapes of the pulses at the output of the NLTL for different polarity of the voltage pulse. In the experiment, the shape of the voltage peaks also strongly resembles the shape of the signal obtained by excitation of soliton waves in transmission lines with nonlinear dielectrics. In this case, the frequency of the central oscillation frequency is noticeably higher in the case of positive polarity than in the case of negative polarity for a wide range of voltages and the magnitude of the axial bias field. It should also be noted that when a positive voltage is applied to the output of the line, the efficiency of the NLTL decreases as well. A similar effect was also observed in other experimental works [10], when the ferrite rings were located near the outer conductor of the coaxial line with a large oil gap to the inner conductor. In this case, after the front, a soliton-like peak was also observed, behind which there were practically no high-frequency oscillations.

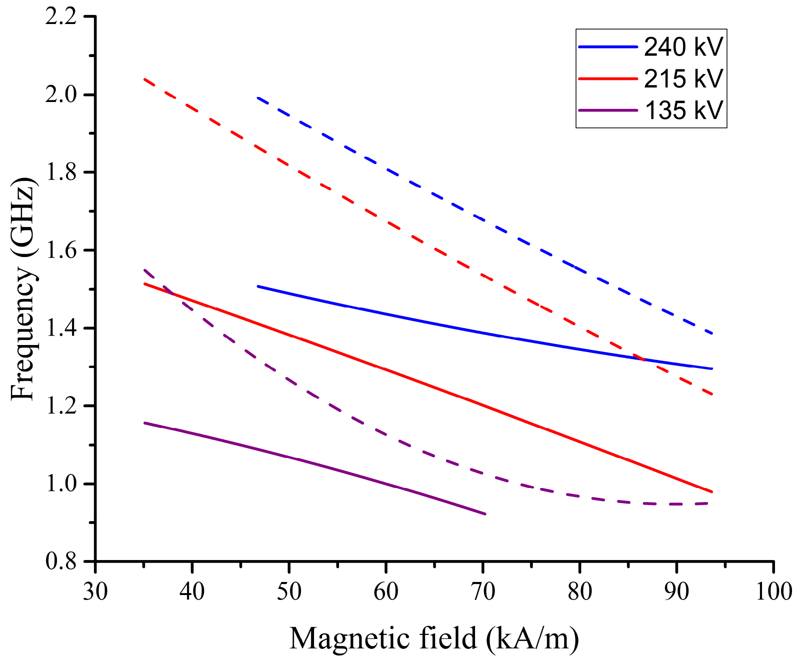

Fig.4. Dependence of the central oscillation frequency on the axial magnetic field for different voltage polarities. Solid – negative polarity, dashed – positive polarity.

5. Conclusion

In contrast to changing the direction of the bias field, changing the direction of the vector of the azimuthal magnetic field in an NLTL with saturated ferrite results to a noticeable change in the shape of the voltage pulse at its output. The effect of the formation of soliton peaks behind the pulse front and a significant change in the frequency of excited oscillations in the case of different polarity of the voltage pulse is difficult to describe in the approximation of TEM waves and, apparently, requires an analysis of the transverse structure of the field in the NLTL.

Acknowledgements

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6. References

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