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Systems and technologies based on nonlinear transmission lines with ferrite (Review)

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Nonlinear transmission lines with ferrite have been actively developed and studied for about two decades. At the same time, the first works on this topic date back to the middle of the last century. Nonlinear transmission lines with ferrite find their application in various problems of electrophysics, with the greatest application being found in the problems of pulse sharpening, as delay lines and generators of high-power pulses of microwave radiation. The main scientific and technical results of the development of technologies of nonlinear transmission lines with ferrite are presented in chronological order, starting from lines for sharpening the fronts of voltage pulses, ending with multichannel microwave sources based on them.

Keywords: high power microwaves, ferromagnetic materials, pulsed power, electromagnetic shock waves.

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Introduction

The active study of physical processes in nonlinear transmission lines (NTL) and the development of devices based on them dates back decades. The main interest is related to the fact that NTLs are completely solid-state devices and can be used to solve various problems of radiophysics and electrophysics. Two types of devices are referred as NTLs: transmission lines with distributed parameters filled with nonlinear dielectrics or magnets whose properties depend on electromagnetic fields in the line [1–3]; lines with concentrated parameters with elements in the form of nonlinear capacitances or inductors [4–7], the values of which depend on voltage or current, and also may include semiconductor diodes as nonlinear elements of the NTL [8,9].

Today, sharpening of the leading edges of high-voltage pulses and the generation of high-frequency pulses of high power are the most common applications of nonlinear transmission lines. The development of high-power microwave electronics (high power microwaves) dates back to more than fifty years. However, in the last few decades, the pace of development of microwave devices has slowed down a little, powerful microwave electronics devices are being actively upgraded and their parameters are continuously improving. To date, their power characteristics reach the level of units of GW [10]. High-power microwave electronic devices in the international literature include devices with power values exceeding 100 MW, covering the centimeter and millimeter wavelength ranges. These devices have a number of practical applications related to electromagnetic compatibility tasks, in electromagnetic countermeasures, in radars, in space technologies for the transmission of energy and motion of aircrafts, for plasma heating, acceleration of charged particles, biophysical research, etc., etc. [10].

Special mention should go to vacuum electronic generators with pulse energy of the order of 100 J among microwave generators of the gigawatt power level. A relativistic reverse wave lamp, a multi-wave Cherenkov generator, a diffraction radiation generator, a relativistic magnetron and klystron, a magnetically isolated linear oscillator (MILO), a free electron laser and a cyclotron resonance maser are such devices. Traveling wave lamp, a reverse wave lamp, and a vircator are generators with energy in tens of joules. All of these devices use electronic streams to generate pulses of microwave radiation. The energy efficiency of all these generators is in the range of 10−60%, however, these estimates do not take into account the total energy costs of generation, transportation of the electron beam, as well as radiation. Taking into account all energy costs, the energy efficiency of the final sources of microwave pulses according to today's estimates usually does not exceed 10% [11,12], reaching in exceptional cases 20−30% [13,14]. The efficiency is fractions or units of percent in a number of laboratory samples. The maximum power of microwave radiation in the centimeter and decimeter wavelength ranges, which is produced or can be produced in the near future in laboratory conditions, is on the order of a gigawatt in the case of a high pulse repetition rate (up to 200 Hz) and several GW in rarely repeated pulse mode.

Nonlinear transmission lines belong to a separate class. Their main differences over traditional devices with electron fluxes are the absence of requirements for high vacuum, which is required for the transport of the electron beam, the absence of concomitant deceleration X-ray radiation, a strong magnetic field is not required for the operation of generators, an increased lifespan of devices due to the absence of cathodes for the generation of electron fluxes.

NTLs using nonlinear dielectrics and nonlinear capacitances are based on the effect of generating soliton-like waves in the transmission line due to the effect in which the base of the voltage pulse moves at a speed lower than the vertex of this pulse, which allows it to catch up with its base, which leads to a reduction in the duration of the leading edge of this pulse. This is attributable to a decrease of the dielectric constant of the elements in the line with an increase of the voltage amplitude. Lines with dielectric nonlinearity, as a rule, are used as desktop generators of radio pulses with a frequency of units or tens of MHz with a peak power of units of Watts, there are laboratory samples with the power reaching a dozen of MW. NTLs based on semiconductor diodes [8,9] today are rather demonstration samples of the possibility of generating in they are microwave pulses and are promising for synchronous development together with semiconductor technologies. A significant reduction of residual resistance of diodes after switching is required to use diodes in NTLs to excite powerful oscillations. Today, according to their parameters, NTLs with nonlinear capacitances and semiconductor diodes cannot belong to high-power microwave electronics devices. Thus, most technologies using nonlinear capacitances and semiconductor diodes are rather just demonstration laboratory samples.

A good result of the generation of powerful microwave pulses was shown by a generator based on the periodic arrangement of gas arresters in the rupture of the inner conductor of the coaxial transmission line [15]. The transmission line with dimensions 100×59 mm consisted of 2–12 gas-discharge gaps, which were under pressure from 1 to 20 atm. The transmission line had an impedance of approximately 32 Ω. The operating voltage was 50–250 kV. The possibility of generating nanosecond radio pulses with a central frequency of 0.8–1.15 GHz with a peak power of several hundred MW was demonstrated in this work. Unfortunately, this concept has not been further developed due to the complexity of the line design and the low knowledge of the nanosecond pulse breakdown under similar conditions

NTLs with ferrite have the strongest potential for the tasks of generating high-power microwave radiation today. In addition, record values of the exacerbation of the leading edge of a high-voltage pulse to tens of picoseconds with a rate of voltage rise in units of MV/ns were obtained on the basis of NTL with ferrite. As for the generation of radio pulses in ferrite-filled NTLs, their parameters today are close to the parameters of relativistic devices of high-power microwave electronics in the range of decimeter wavelengths. Peak power generators reach 700 MW [3]. The possibility of generating radio pulses in the frequency range from hundreds of MHz to 20 GHz [16] has been shown to date. At the same time, such generators can significantly reduce the output power values without changing the generation frequency, and also make it easy to change the central frequency of generation by up to 100% of the minimum frequency by changing the external magnetic field necessary to saturate the ferrite filling of the transmission line. It should also be noted that the development of NTL technologies with ferrite contributes to the improvement of the parameters of devices using an electron beam to generate powerful microwave radiation. Since the operation of relativistic devices requires the formation of voltage pulses with short fronts (in units of nanoseconds or hundreds of picoseconds) with the ability to control the time of their propagation, the use of ferrite NTLs with them allows solving these problems. To date, a number of technical solutions based on ferrite NTLs have already been developed, which can be used in other systems or as sources of powerful microwave pulses, in some cases comparable in parameters with relativistic devices, and also find application in applied studies.

A review of technologies created on the basis of nonlinear transmission lines with ferrite filling is provided in this paper. The review includes three parts: theoretical foundations of nonlinear transmission lines with ferrite, exacerbation of the front of a high-voltage pulse in a ferrite NTL, generators and sources of microwave pulses based on NTL with saturated ferrite.

1. Theoretical foundations of nonlinear transmission lines with ferrite

A non-linear transmission line with ferrite is a segment of a transmission line, usually not exceeding 1 m, between the conductors of which ferrite is located. As a rule, ferrite does not fill the entire cross-section of the line. Lines with ferrite operate at high voltages (starting from tens of kV) and, as a result, coaxial geometries of transmission lines are more common because they have increased electrical strength.

The first papers in which the propagation of electromagnetic waves in nonlinear lines was studied date back to the end of the 50s of the 20th century immediately following the creation of the first magnetic materials with nonlinear magnetic properties such as ferrites. The waves observed in these experiments were called shock electromagnetic waves (SEW) [17]. The name of the shock waves in this case is not related to the transfer and compression of the medium as such, it is primarily caused by the similarity of the mathematical description with the description of the generation of shock waves in gases. The change in the wave field at a certain moving interval is described by equations whose order is higher than that of the equations that describe the field outside this interval.

Soon, in the 60s, a theoretical model of the description of SEW [17–20] was formulated in a series of papers. It was found in the model that there are conditions for the formation of discontinuities of the field vectors when electromagnetic waves propagate in a medium without dispersion. Taking into account the dispersion and dissipative properties of the medium in the high frequency region leads to the elimination of gaps in the solutions for SEW, which means the establishment of a finite width (duration) of the shock front. Today, the shock front is understood in the literature as the leading edge of a high-voltage pulse, which received a finite duration as a result of propagation in a line with ferrite (or other nonlinearity) after the establishment of transients.

During the formation of a SEW, high-frequency oscillations are not observed behind its front. This is attributable to the fact that it is necessary to have a dispersion associated with reversible processes to excite oscillations during the propagation of the SEW leading edge in the transmission line. The dispersion associated with the irreversible dissipative process of — remagnetization is accountable for the formation of the shock front. As a consequence, the presence of temporal or spatial dispersion is required to excite oscillations in the line. The addition of a non-galvanic coupling between different sections of the transmission line may be accountable for the presence of spatial dispersion in the NTL. The appearance of time dispersion in a line with ferrite is associated with the effect of pulsed remagnetization of ferrite previously saturated with an external magnetic field.

Physically, pulsed magnetization of ferrite is the following process. Initially, unsaturated ferrite for its saturation is placed in an external magnetic field, collinear to the direction of wave propagation in the transmission line. Since the magnitude of the magnetic field required for pulsed magnetization reversal of ferrite is large, in this case it is possible to describe the magnet in the „macro-spin“ approximation, when it is permissible to introduce the magnetization vector as the sum of all magnetic moments averaged over the volume of the magnet [21]. The characteristic rise time of the magnetic field of the magnetizing ferrite is an important factor here. If this time is noticeably less than the characteristic relaxation time of a ferromagnet, then, since the modulus of the magnetization vector can no longer change due to saturation of the material, the magnetization vector **M** deviates by an angle θ from the total vector of magnetic field strength **H**. After that, it begins to move along the surface of the sphere around the direction of the resulting magnetic field intensity vector (Fig. 1).

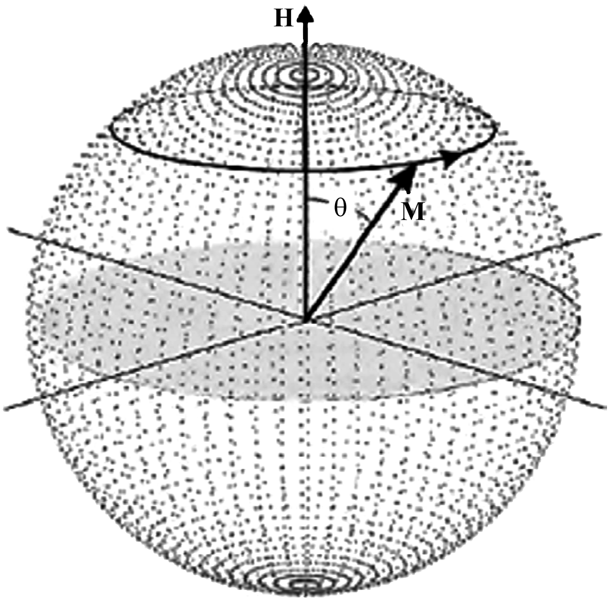

Figure 1. The trajectory of the magnetization vector **M** in case of the pulsed magnetization reversal.

Mathematically, the dynamics of the magnetization vector in this model is described by the Landau-Lifshitz equation [21,22]:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma\mu_0[\mathbf{M}\times\mathbf{H}] - \frac{\alpha\gamma\mu_0}{M_s}\big[\mathbf{M}\times[\mathbf{M}\times\mathbf{H}]\big]. \quad (1)$$

Here μ_0 is a magnetic constant, γ is a gyromagnetic ratio for electron, α is a phenomenological attenuation coefficient, M_s is a saturation magnetization. The first term describes gyromagnetic precession, the second term is accountable for magnetic losses in ferromagnets and is determined by the phenomenological attenuation coefficient. The presence of this equivalent of the friction force leads to the fact that the magnetization vector will eventually rush towards the direction of the resulting magnetic field. The solution of the Landau-Lifshitz equation in such conditions is a trajectory in the form of a spiral on the surface of a sphere. Thanks to this physics of the generators, in the modern literature, NTLs with saturated ferrite are called gyromagnetic NTLs (GNTLs).

2. Exacerbation of the high-voltage pulse front in NTL with ferrite

2.1. Development of technology for exacerbation of high-voltage pulses in transmission lines with ferrite

Historically, the study of ferrite transmission lines began with lines that used unsaturated ferrite. Such NTLs are broadly applied in pulse technology for the sharpening of the leading edge of high-voltage pulses along with peaking high-pressure dischargers [23–27]. The first work that showed the efficiency of NTL with ferrite for sharpening the leading edge of a high-voltage pulse was the work of Weiner 1981 [24]. The possibility of reduction of the rise time of a high-voltage pulse with an amplitude of up to 10 kV from 30 to 2 ns was shown using a ferrite line with a length of 120 cm without an external magnetic field and using an external field. Then, the possibility of sharpening of the voltage pulse leading edge to values in units of nanoseconds with a voltage rise rate of 100 kV/ns was demonstrated in a number of experimental and theoretical studies. Then, Seddon's paper [28] demonstrated the possibility of sharpening of the leading edge of a voltage pulse with an amplitude of 25 kV in the NTL with an impedance of 75 Ω from 20 to 2 ns. The line was a coaxial transmission line filled with ferrite located in the field of an external solenoid that consumes current up to 1.5 A. At the same time, the paper demonstrated the possibility of parallel operation of six sharpening NTL with the ability to control the signal propagation time up to 15 ns. The possibility of sharpening of the front to subnanosecond values was demonstrated, and front values of 100 ps [29] were also obtained in the nineties.

The development of this technology led to the fact that a team of authors from the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Sciences obtained subnanosecond values of fronts with a voltage rise rate of up to 500 kV/ns with a voltage pulse amplitude of up to 360 kV [30]. High-voltage pulses are sharpened without the use of preliminary magnetization of ferrite filling of the transmission line due to dissipative processes occurring during pulsed magnetization of ferrite. As a result, a pulse with a reduced front duration relative to the incident pulse is observed at the output of the NTL, and as a result of energy dissipation during magnetization reversal, the duration of the high-voltage pulse is reduced by tens of percent. It is necessary to use an external magnetic field to pre-saturate the magnetic material to increase the rate of rise of the voltage pulse in a line with ferrite. When the ferrite is pre-saturated, the propagation speed of the signal depends on its amplitude, thus, the tip of the high-voltage pulse propagates faster than its base, which leads to a decrease in the duration of the front at the line output. Dispersion and dissipation in a line with nonlinear filling prevent the front duration from decreasing below a certain value. At the same time, there is no significant reduction in the duration of the high-voltage pulse. The first studies on the sharpening of the front in lines with saturated ferrite were conducted by teams from the UK in the 90s. [31,32]. Experimentally, it was found that the use of initially magnetized ferrite filling can significantly reduce the duration of the front of the high-voltage pulse. As a result of these works, a record-breaking rate of front rise up to 1 MV/ns was achieved for that time.

2.2. Prospects for the development of technology for exacerbating high-voltage pulses in transmission lines with ferrite

The technology of sharpening of high-voltage pulses in NTL with ferrite today makes it possible to sharpen the fronts with a duration of tens of nanoseconds with an amplitude from ten to hundreds of kilovolts to subnanosecond values. Today, the values of the front with a duration of less than 100 ps at a voltage amplitude of 200 kV have been obtained. NTL without prior magnetization of ferrite can reduce the duration of the front from units of nanoseconds to subnanosecond values. The use of additional external magnetization of ferrite makes it possible to reduce the duration of the front in the same NTL configuration by an average of 2 times.

Today, the technology of sharpening the fronts of high-voltage pulses using spiral transmission lines with ferrite filling [33] seems promising. In similar transmission lines, ferrite is located inside a spiral inner conductor. The main advantage of this method of sharpening the front of a high-voltage pulse is the absence of the need for an external longitudinal magnetic field, since in this case the ferrite is saturated in the longitudinal magnetic field created inside the spiral conductor of the line. The electrical strength of the line increases as a result. The disadvantages of this approach include the difficulty in matching the spiral transmission line with ferrite with other elements of the high-voltage path. Today, the possibility of reducing the duration of the nanosecond pulse front with an amplitude of 150 kV to subnanosecond values of [33], as well as exacerbating the nanosecond pulse front with an amplitude of up to 400 kV [34] using spiral lines with ferrite has been demonstrated.

The sharpening of high-voltage pulses still attracts interest [35,36]. The technology of sharpening of the front in NTL with ferrite makes it possible to create high-voltage pulse energy compressors, which makes it possible to obtain record-breaking rates of voltage and power rise at load. Work on voltage pulse energy compressors is being actively carried out by the staff of the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences from Yekaterinburg. The first significant work on compressors is the work of [37], which presents a fully solid-state pulse generator consisting of an S-500 generator [38], a switch based on an SOS diode and a three-stage compression system on ferrite lines. Voltage pulses with an amplitude of 860 kV with a maximum voltage rise rate of 10 MV/ns and a front of 100 ps were obtained in this work. The peak power of the generator was 15 GW. The continuation of the work of [37] was the work of [39], which also presents a fully solid-state system with a peak power of 30 GW. The system consisted of a cascade of an S-500 generator and two compression lines with ferrite, in which the initial high-voltage pulse with a duration of 7 ns at a load of 40 Ω was compressed to 0.65 ns with an increase in voltage from 500 kV to 1.1 MV, and the peak pulse power increased from 6 to 30 GW. As a result, a voltage rise rate of 3 MV/ns was obtained, while the power growth rate was 100 GV/ns. The record amplitude of a high-voltage pulse using ferrite compressors was obtained in [40] and amounted to 1.62 MV, while the pulse power was 54 GW at a load of 48 Ω.

3. Generators and sources of microwave pulses based on NTL with saturated ferrite

3.1. Development of technology for generating high-frequency pulses with using NTL with ferrite

The first attempts to obtain high-frequency pulses using ferrite transmission lines date back to the middle of the last century. One of the first works is the work of Freidman 1960 g. [41]. At the same time, it was proposed to use a

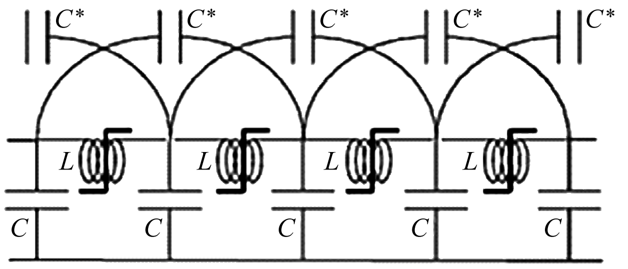

Figure 2. Line substitution scheme with spatial dispersion due to capacitive cross-links.

small ferrite sample as a coherent oscillator [i]n 1959 in the USA 42,43. To do this, the ferrite had to be in a strong magnetic field, which was created impulsively. The ferrite sample was located at the end of a rectangular waveguide. The generation of microwave pulses with a duration of the order of 1 ns at frequencies of 7−9 GHz was demonstrated in this experiment. The power of such a generator did not exceed 100 V. The development of the idea proposed in [42] was received in Pound's study [44]. However, no further development of the idea followed, apparently due to the smallness of the system and, as a consequence, the ferrite samples used, which did not allow increasing the power of the generator.

The development of methods for generating high-frequency pulses in NTL with ferrite after Pound's study continued after almost 40 years from the cycle of theoretical work of a group from Nizhny Novgorod based on the theory of SEW. Effective generation of nanosecond radio pulses by a shock front during its propagation in a line with spatial dispersion [6] was shown based on this theory. The line substitution scheme with spatial dispersion is shown in Fig. 2. Spatial dispersion in the transmission line is achieved by adding cross-capacitance connections of the line links and is determined by the parameter of the ratio of the capacity of the cross-link to the capacity of the link in the line C^*/C_0. The excitation of oscillations is observed during synchronization between the shock front propagating in the transmission line and the wave excited by it. This means that the velocity of the shock front should be equal to the phase velocity of the wave excited at a certain frequency $v_{\text{sh}} = v_{\text{ph}}(f)$, while effective generation requires that the group velocity of this wave at a given frequency be less than the velocity of the shock front $v_{\text{sh}} > v_g(f)$, which ensures an efficient outflow of energy from the shock front and leads to the formation of an extended oscillation wavetrain behind it. The possibility of obtaining a large number of oscillations in the wavetrain was demonstrated experimentally and in numerical modeling in the studies. The duration of the radio pulse and its frequency were limited by high-frequency losses in the NTL.

A number of theoretical papers followed this work [45–49] was aimed at increasing the efficiency of generating radio pulses, as well as expanding the frequency range of generators. The result of all these works was the creation of an experimental model of a radio pulse source by a group from the UK led by Seddon [7,50]. The developed generator operated at a voltage pulse amplitude of 30−50 kV with a pulse repetition frequency of up to 1.5 kHz and was a sequence of 40 *LC*-links with cross-capacitive coupling. The central oscillation frequency of the generator is in the range from 200 MHz to 2 GHz and is determined by the selection of line parameters, namely capacitances and inductances of the links. The frequency tuning interval of the line with specific parameters was ±20% in case of a change of the synchronism in the line. The velocity of the shock front and, as a consequence, synchronism with the excited wave in the NTL were controlled by changing the initial magnetization of the ferrite filling of the nonlinear inductors of the line. The maximum power of the generator was 20 MW. The pulse duration could vary from several oscillation periods to fifty, which made it possible to obtain a spectrum width from 2.5 to 40%. The paper also showed the possibility of phasing and adding power from four similar generators. The appearance of the generator and the multichannel system are shown in Fig. 3. Numerical modeling played an important role in the possibility of implementing the project. Later, another generator based on a cross-linked line was developed by a group from the USA [51]. This paper presents a generator consisting of 200 *LC* links, with a power of hundreds of

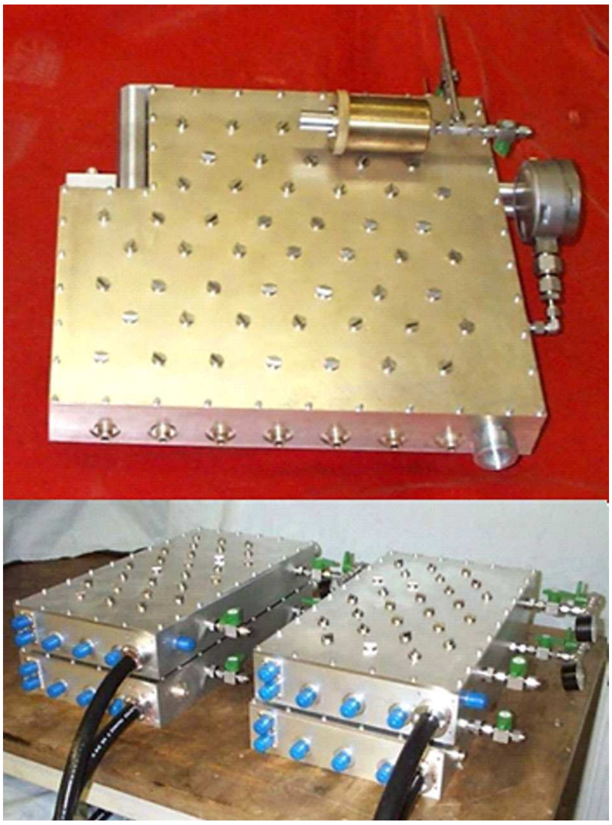

Figure 3. Appearance of the NTL with spatial dispersion at 1 GHz and a system of four lines with a controlled phase of work [7,46].

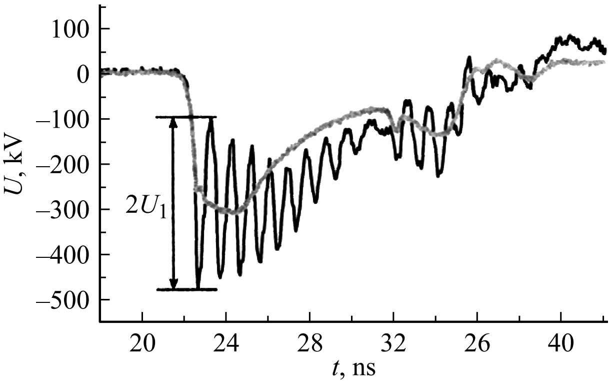

Figure 4. A typical voltage pulse waveform at the output of a NTL with saturated ferrite from the paper [52].

kilowatts and a central generation frequency of hundreds of MHz.

The next step in the development of high-frequency pulse generators based on NTL with saturated ferrite was the work of a team from High Current Electronics of the Siberian Branch of Russian Academy of Sciences [52]. Seddon's work [7] and the work of the team of the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Sciences [52] became the starting point in the development of ferrite NTL technologies and subsequently attracted new research groups to this topic. It demonstrates a method of excitation of high-frequency oscillations during the propagation of a high-voltage voltage pulse in a coaxial transmission line with ferrite filling, pre-saturated with a magnetic field created by an external solenoid. The transmission line was a line with a time variance. The time dispersion is due to the process of pulsed magnetization reversal of ferrite, which was described above. The central frequency of the excited oscillations was in the range from 600 MHz to 1.1GHz with a spectrum width of 3 dB about 15%. The length of the line was 1 m. Figure 4 shows a typical voltage pulse waveform at the output of a NTL with saturated ferrite from this work. As in all similar works, it is a video pulse modulated by high-frequency vibrations, the frequency of which increases slightly towards the end of the pulse. Frequency was tuned by changing the magnetization field of ferrite, with the optimal field value being in the range of 20−40 kA/m. It was shown in the study that the generation frequency in the line decreases by several hundred MHz with an increase in the magnetization field of ferrite Hz. This effect is used in GNTL based generators for tuning the generation frequency. At the same time, the generation frequency increases with a constant field H_z with the growth of the current flowing along the line, i.e., with the growth of the azimuthal field H_θ. The peak power of the generator reached 700 MW with a maximum energy efficiency of converting the energy of a video pulse into a radio pulse of about 10%. The logical continuation of this work was the creation of a microwave radiation source based on GNTL [53]. The appearance of the source is shown in Fig. 5. The source consisted of SINUS-200 high-voltage generator, a GNTL, a bandpass filter for separating the low-frequency and high-frequency components of the voltage pulse, a mode converter and a horn antenna. The GNTL was filled with vacuum oil to increase its electrical strength. Vacuum oil was chosen because it has significantly lower high-frequency losses compared to transformer oil. A microwave pulse with a duration of 5 ns was generated in the nonlinear transmission line, after which it was emitted and measured. The effective potential of the source was ∼ 560 kV with a central frequency of 1.2 GHz with a spectrum width of 0.4 GHz at the level of 10 dB. The source could operate with a pulse repetition rate of up to 200 Hz. Analyzing the spectrum of the emitted pulse and guided by modern classifications, the emitted pulse can be attributed to the class of broadband pulses.

The work [3] was an important step in understanding and identifying ways to improve the technology of lines with ferrite, demonstrating the limits of possible optimal solutions. A model based on telegraphic equations and the Landau-Lifshitz equation (1) was developed in this study without taking into account attenuation, and its solution in the form of a traveling electromagnetic wave was considered. The results obtained using the model are in good agreement with the trends observed in the experiments

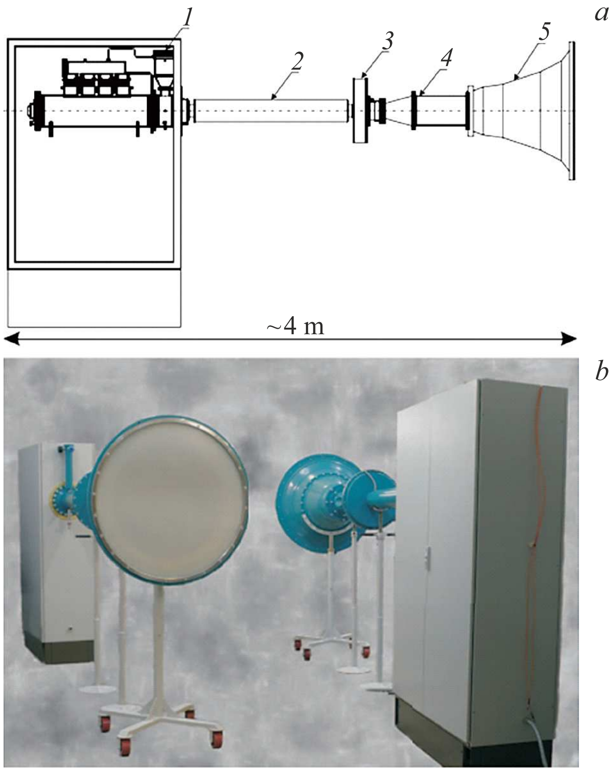

Figure 5. Appearance of the source of microwave pulses based on NTL with saturated ferrite from the work [53]: *a* — source circuit: SINUS-200 high-voltage generator (*1*), GNTL (*2*), bandpass filter (*3*), mod converter (*4*) and horn antenna (*5*); *b* — source photo.

in studies [52,53], as well as in the studies of other groups of researchers. In a simple model, a linear increase in the central oscillation frequency was shown with an increase in the current flowing along the line, the optimum dependence of the amplitude of the excited oscillations on the external magnetic field was shown. An important conclusion from the model is also that the maximum value of the high-frequency power averaged over the period does not exceed 25% of the power of the incident pulse.

Almost at the same time, generators based on GNTL attracted the attention of researchers from the UK and the USA. In 2011 scientists from the UK together with Rukin from the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences created a mock-up of a fully solid-state generator, including a generator of nanosecond voltage pulses on SOS diodes, forming video pulses with a duration of up to 10 ns with a voltage of up to 100 kV [54]. The maximum peak power of the developed microwave generator was 90 MW at an operating voltage of 80 kV. The central frequency of the high-frequency pulses was in the range from 750 MHz to 1 GHz. The pulse repetition rate could reach 2 kHz.

A series of papers from a group of researchers from Texas, USA was published in 2010 - 2013[55–58]. Their first work investigated the possibility of replacing the solenoid used to saturate ferrite with an assembly of permanent magnets [55]. The approach described in the article has proven itself poorly, showing low generation power and a very short high-frequency pulse with a duration of less than 2 ns. There were no new publications using permanent magnets from this group after that. Then the group from Texas followed the path of compact lines with wave resistance 50 Ω, operating from voltage pulses with an amplitude of tens of kV [56]. The generator's GNTL in diameter did not exceed 10 mm, and its length was approximately 50 cm. The maximum peak power obtained in the experiments was about 9 MW with a voltage pulse amplitude of 50 kV. Microwave pulses with a central frequency in the range from 2.7 to 5GHz with a maximum pulse duration not exceeding 3 ns were obtained in experiments [56]. It should be noted that high generation frequencies (2 GHz or more) are associated with small transverse dimensions of the nonlinear transmission line. In another work, the team considered various types of ferrites used to generate high-frequency pulses in order to increase the efficiency of generators [57]. Magnetically soft ferrites are usually used in GNTL, garnet ferrites are much less common, since they have a high initial magnetic permeability, low coercive force, high internal resistance and low losses on magnetization reversal. The effect of the ferromagnetic resonance band on the generation in NTL with ferrite was shown in the paper. The best results were shown by ferrites specially designed for the generation of high-frequency oscillations. It can be concluded based on this work that additional attention should be paid to the development of magnetic materials for improving their parameters to develop generators based on NTL with ferrite. Separately, a generator developed by the same group should be singled out, which is a strip nonlinear transmission line with a wave resistance of 50 Ω using YiG ferrites [58]. The generator has a central frequency of 1 GHz with a pulse duration of up to 5 ns, the spectrum width is 40%, the peak microwave power is in the range of 2−13,MW. There were no further new publications on strip geometry.

Another group from the USA implemented a generator with spatial dispersion in a coaxial transmission line [59,60]. The result was a generator in which ferrite is saturated with the field of an external solenoid. The ferrite was located inside the corrugated inner conductor of the coaxial transmission line, thus the NTL was 60 *LC*-links with wave resistance 50 Ω with capacitive coupling between adjacent links of the line. The possibility of generating radio pulses with a duration from 4 to 17 ns depending on the central frequency of oscillations in the pulse was demonstrated. A higher frequency corresponded to a longer pulse of high-frequency oscillations. The central frequency was varied by the magnetization field in the range from 0.95 to 1.45GHz. The peak power was more than 100 MW, and the maximum energy of the microwave pulse was 170 mJ.

The Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences has been actively developing methods for generating high-frequency pulses in the centimeter wavelength range in the recent years [16,61]. The maximum generation frequency of 20 GHz was achieved during the studies. The system described in [61] allows a sequential increase in the number of pulses in the output modulated pulse, thereby increasing its central frequency. This method allows obtaining a modulation depth of up to 70%. At the same time, a record-breaking short rise front of a voltage pulse of 45 ns was obtained at a voltage pulse amplitude of 850 kV in the work of [61]. Ferrites with a rectangular hysteresis loop were used in In [16] which significantly increased the efficiency of generation in GNTL. It has also been shown that it is possible to excite high-frequency oscillations in a ferrite NTL without an external magnetization field using rings with a rectangular loop.

Recently [62] a group from the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Sciences has developed a generator with a periodic arrangement of ferrite rings and rings of permanent neodymium magnets inside a coaxial transmission line. This technical solution allows avoiding the use of a solenoid used to saturate ferrite, moreover, the geometry of the line is a line with a corrugated inner conductor having a spatial dispersion similar to [59]. Permanent magnets were located inside a corrugated conductor. The result of the work was a demonstration of the possibility of excitation of high-frequency pulses with a central frequency of 1.3GHz and a peak power of 110 MW without the use of a solenoid. The energy characteristics of traditional GNTL and corrugated NTL with ferrite were compared. It was shown that the first prototype has a slightly higher efficiency than a similar GNTL with the same number of ferrite rings of the same transverse size, the peak power of which was 100

MW. The weight of permanent magnets used in the study does not exceed 1 kg, which significantly reduces both the dimensions and the final weight of the generator.

3.2. Development of technology of multichannel sources of microwave pulses with using NTL with ferrite

The generated microwave power from a single line cannot be directly increased to improve the effective potential of GNTL-based radiating systems. The solution is to use multi-channel systems based on lines with saturated ferrite. It is also convenient here that GNTL allow changing the propagation time of a high-voltage pulse through them by changing the external field of magnetization, which makes them effective lines with a controlled propagation time delay. Changing the time of propagation of high-voltage pulses in the GNTL is perfectly used for phasing several generators in multichannel systems.

A team from the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Science created a two-channel source of microwave radiation with the possibility of electronic control of beam scanning in 2015 [63]. Two-channel system is shown in Fig. 6. The GNTL could generate high-frequency pulses with peak power from 50 to 700MW at a central frequency of 0.5−1.7GHz in a single-channel mode. The pulse repetition rate was 100 Hz. Phasing was provided due to the presence of an additional GNTL section with a length of 30 cm to form the front of a high-voltage pulse of 0.5 ns and provide the necessary time delay between channels. A spiral antenna was used in each channel in the source, since it is the most convenient for the coaxial geometry of the generator and provides almost circular polarization of the emitted pulse. The radiated peak power was 350 MW, which corresponds to an effective potential of 350 kV. The possibility of scanning the beam in the horizontal plane on ±15° was demonstrated in two-channel mode.

Scientists from the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Science and the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences developed a four-channel system similar to the two-channel in 2017 [64]. Its appearance is shown in Fig. 7. The system is capable of operating with a pulse repetition rate up to 1 kHz. The central pulse frequency was 2.1GHz with a pulse duration of 3 ns. The maximum effective potential of 360 kV was achieved with the ability to scan the beam in the horizontal plane at ±17°. The emitted pulse had circular polarization.

Figure 6. The appearance of a two-channel microwave radiation source with the possibility of electronic control of beam scanning from work [63].

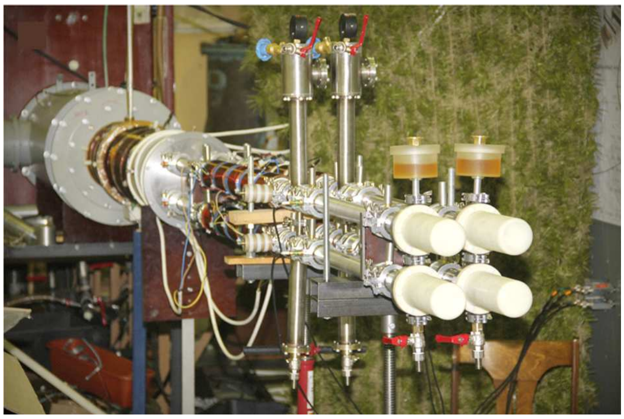

Figure 7. A four-channel system based on NTL with ferrite from the work [64].

Multichannel systems have also been developed abroad. So, researchers from the USA [65] presented a four-channel system operating at significantly lower capacities of about 5 MW (this corresponds to an electric field strength of 8 kV/m at a distance of 10 m) at frequencies of 2−4 GHz with pulse repetition frequency up to 1 kHz. The pulse duration did not exceed 2 ns. The beam was scanned in the horizontal plane at ±17°.

Recently, a team from the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences has created four-channel systems with a central frequency of radiated pulses of 4 and 8 GHz [66,67]. Electric field strengths were generated in systems by adding power from 4 channels in an open space of 250,kV/m for a system of 4,GHz and 1.5 kV/cm for an 8 GHz system at a distance of 3 m.

NTLs with ferrite for channel phasing can also be used with relativistic devices. A team from the Institute of High Current Electronics of the Siberian Branch of Russian Academy of Science and the Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences developed a two-channel nanosecond relativistic microwave generator, which implemented the possibility of controlling the phase difference in channels for coherent addition of electromagnetic fields using the exacerbation and delay section based on NTL with saturated ferrite [68]. The subnanosecond front of the voltage pulse ensured a mutual phase deviation between the channels in units of percent of the oscillation period for two superradiant lamps of the reverse wave of the 10 GHz range.

3.3. Prospects for the development of technologies for the generation and emission of high-frequency pulses with the use of NTL with ferrite

Today, generators and sources of nanosecond microwave pulses operating in the frequency range from hundreds of megahertz to 20 GHz have been developed and tested on the basis of NTL with ferrite. The maximum peak power of one generator can reach 700 MW with a pulse duration not exceeding 10 ns. At the same time, the pulse energy decreases with an increase in the generation frequency, both due to a decrease of the peak generation power due to a decrease in the transverse dimensions of the transmission lines, and due to a decrease of the pulse duration associated with a decrease of the time of transient processes in ferrite at higher frequencies. The generators being developed, operating at a frequency of up to 8 GHz, are capable of operating in pulse-periodic mode with a pulse repetition frequency of up to 1 kHz. The resulting generation of pulses with a frequency above 8 GHz is rather scientific in nature, since such systems can only operate in a single pulse mode due to the poor electrical strength of the system. Today, the most promising technology is the generation of high-frequency pulses in corrugated coaxial NTL with permanent magnets [62] due to the absence of a solenoid, which significantly simplifies the design and increases the total efficiency of the generator. Moreover, the development of corrugated line technologies may allow increasing the duration of the generated high-frequency pulses in a line with spatial dispersion.

While the first attempts for the creation of generators based on NTL with ferrite were mainly experimentally, today methods have been developed for numerical modeling of processes occurring in NTL using the finite difference method [69–71]. The use of numerical modeling makes it possible to optimize the design of nonlinear transmission lines, as well as to explore new physical effects that improve the parameters of devices.

As for multichannel systems, today both in Russia and in the world systems with parallel operation of four NTLs with ferrite have been created. The main limitation on the number of simultaneously operating channels here is the difficulty associated with the fact that with an increase in the number of channels, the voltage pulse source and its switch must increase the current flowing through them, which leads to a significant increase in the duration of the voltage pulse front and increased requirements for stored energy. Four-channel systems with a wave resistance of one channel in 50 Ω are optimal from the point of view of the availability of modern pulse technology. An increase in the number of channels of systems is not seen without simultaneously improving the characteristics of voltage sources and high-voltage switches. It should be noted that today NTLs with ferrite are also used in the development of multichannel systems of relativistic generators to sharpen the voltage pulse front and channel phasing.

Conclusion

Today, ferrite NTLs are reliable, cheap, fully solid-state systems for the tasks of pulsed technology and powerful microwave electronics. Microwave generators based on NTL have approached relativistic generators in their parameters in the decimeter wavelength range over the past 15 years of active development in this field. Many engineering tasks have been solved over the years: increasing of the electrical strength of the line, increasing of the pulse repetition rate, creation of multi-channel systems. The possibility of excitation of oscillations in the NTL at frequencies 10–20 GHz [16] in laboratory models has already been demonstrated. In this case, the peak power of the generators decreases proportionally to the square of the radiated wavelength.

Short duration of the high-frequency pulse is a specific feature of systems based on NTL with ferrite which results in the low pulse energy, liquid dielectrics are usually used for insulation in their design, which require increased pressure in the line. The development of the approach of coaxial NTLs with spatial dispersion seems promising, which may allow increasing the duration of the high-frequency pulse, as indicated by experimental results. The development of this approach is closely related to the transition from external solenoids, in the field of which ferrite is saturated, to the use of compact permanent magnets inside the line structure, which will lead to a significant reduction in the mass and size parameters of the sources.

The possibility of sharpening of the front and simultaneous control of the travel time of a high-voltage pulse along the NTL made it possible to create multi-channel sources of microwave radiation based on both NTL with saturated ferrite and on the basis of relativistic generators. This makes it possible to significantly increase the effective potential of radiation systems.

It should be separately noted that it seems relevant to develop and create technologies for producing new magnetic materials designed directly to excite high-frequency oscillations in transmission lines for improving the parameters of microwave generators based on NTL with ferrite.

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Conflict of interest

The authors declare that they have no conflict of interest.

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