Nonlinear gyromagnetic transmission line design optimization for increasing radiopulse generation efficiency

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Abstract. Using numerical simulation an optimization of gyromagnetic nonlinear transmission line design was carried out. The goal of simulation was to increase efficiency of video pulse into radiofrequency pulse transformation. Several factors significantly influencing the efficiency of generators were found. Experimental validation of some obtained results is also discussed.

1. Introduction
Nonlinear transmission lines (NLTLs) are known to be a part of high power microwave (HPM) for more than a decade [1]. The difference between an NLTL and traditional HPM devices is that the NLTL does not use an electron beam to generate powerful high-frequency radiation. The peak power of devices based on an NLTL is comparable to vacuum devices and reaches values exceeding 500 MW in the decimeter wavelength range [2]. NLTL with such peak power of high-frequency oscillations is a coaxial transmission line, between the conductors of which there is ferrite [2]. This type of transmission lines is called a gyromagnetic NLTL (GNLTL). Ferrite filling of the line is in saturated state by the axial field of an external solenoid. When a high-voltage pulse passes through the transmission line, high-frequency oscillations with a central frequency of several GHz are excited in it. The length of the radio pulse at the line output does not exceed 10 ns. Usually, the length of a GNLTL does not exceed one meter, since the ferrite used for generation has noticeable high-frequency losses. Thus, it is not possible to increase the peak power of the radiopulse by increasing the line length.

Thus, the problem of increasing the efficiency of transformation of the video pulse energy into high-frequency oscillations should be solved by means of optimization of the line design. The efficiency of generation of high-frequency oscillations in a GNLTL can be significantly influenced by the following parameters: the amplitude of the voltage pulse, the magnitude of the external magnetizing field, the characteristic impedance of the transmission line and the filling factor of the transmission line with ferrite. Effective excitation of oscillations occurs when the value of the magnetic field saturating the ferrite is lying in the range from 20 to 80 kA/m [3,4]. With an increase in the voltage amplitude of the incident pulse, the generation efficiency also increases. However, for the amplitude of the incident voltage pulse, there is an upper limit associated with the electrical breakdown of the line, and depends on the geometry of particular transmission line. The influence of the location of the ferrite between the line conductors, as well as the variation of the filling factor on the efficiency, were studied experimentally [5]. In the work, it was found that the maximum efficiency is observed when the ferrite is located near the inner conductor. Also, when the ferrite line filling factor is higher than 0.7, the
amplitude of the oscillations at the output is noticeably lower than in the case when it is equal to 0.4-0.5.

It should be noted that the experimental optimization of generators based on a GNLTL is very difficult. For this task, the use of theoretical models is best suited [6,7]. The existing theoretical models give rather a qualitative description of the process, since they are rather approximate. Therefore, it is necessary to build more accurate models using numerical simulations. The first works on numerical modeling was made more than 30 years ago [8]. It described the ferrite transmission line as an LC-line with non-linear inductance. There are also numerical models in which GNLTLs are considered in the telegraph equations formalism [9]. The use of telegraph equations gives good results when describing pulse sharpening process of a high-voltage pulse in a line with ferrite, but is not suitable for optimizing the line in terms of exciting high-frequency oscillations in it. For optimization problems, it is best to solve a complete electrodynamic problem. This requires a joint solution of the Maxwell equations and the Landau-Lifshitz equation [10]. This approach gives the most accurate results in modeling the process of excitation of high-frequency oscillations in a GNLTL.

2. Numerical simulation

2.1. Formulation of the problem

Within this work, several factors were considered that affect the efficiency of excitation of high-frequency oscillations in a GNLTL using numerical simulation. Numerical modeling was carried out using the fully electromagnetic, non-stationary KARAT code [11]. KARAT code allows solving Maxwell’s equations together with the Landau-Lifshitz equation both in two-dimensional cylindrical coordinate system and in three-dimensional case [12]. All simulation presented here were obtained in the two-dimensional RZ version of KARAT code.

2.2. Influence of wave impedance of the transmission line on the efficiency of oscillation excitation

As it was noted earlier, effective excitation of oscillations in a transmission line with saturated ferrite is observed at longitudinal magnetization field of 20-70 kA/m. In this case, the azimuthal magnetic field created by a current pulse passing through the transmission line should be comparable to the ferrite bias field. Since the early results of numerical simulations indicate a noticeable presence of higher types of waves upon excitation of oscillations in a line with ferrite [13], therefore, the transverse dimensions of the coaxial line in which the ferrite is located can significantly affect the efficiency of the process of oscillations excitation. A change in the transverse dimensions of the transmission line, obviously, leads to a change in the magnitude of the azimuthal magnetic field, which also noticeably affects operation of the line. It is of interest to search for the optimal value of the wave impedance of the transmission line for the most efficient excitation of high-frequency oscillations. Within this work, the characteristic impedance will be called the characteristic impedance of a coaxial transmission line without ferrite, associated exclusively with its transverse dimensions.

In the numerical simulation, a ferrite filling with transverse dimensions of 45x28 mm and a length of 800 mm was considered. The diameter of the inner conductor of the line was 28 mm, the diameter of the outer conductor was changed in the range of 50-100 mm in order to change the characteristic impedance of the line. The simulation was carried out for various values of the bias field in the range from 20 to 60 kA/m. The voltage pulse amplitude was 300 kV. The simulation results are shown in figure 1. They represent the dependence of the peak power of high-frequency oscillations value depending on the impedance of the line at different values of the biasing field. From figure 1 it is seen that the optimal value of the wave impedance of the transmission line lies in the range from 27 to 40 Ohms. The low efficiency in the case of low impedance is most likely due to the very large azimuthal component of the magnetic field in the line compared to the biasing field. When the value of the characteristic impedance is above 40 Ohms, the azimuthal component of the magnetic field becomes too small to effectively excite the precession of the magnetization vector in the ferrite. It can also be seen from the results that in the range of wave impedances, in which the maximum efficiency is
observed, the peak power of high-frequency oscillations changes little depending on the biasing field. This fact suggests that, since the tuning of the oscillation frequency in the line is possible due to a change in the biasing field, in the range of wave impedances from 27 to 40 Ohms, the oscillation frequency can be tuned with a minimum change in peak power of the radio pulse.

2.3. Influence of the ferrite filling factor on the efficiency of excitation of high-frequency oscillations

Within the framework of numerical modeling, the influence of the ferrite filling factor on the efficiency of excitation of high-frequency oscillations in a GNLTL was considered. The filling factor is understood as the following value $\eta = (D_f - d_f)/(D - d)$, where $D_f$ and $d_f$ are the outer and inner diameters of the ferrite, $D$ and $d$ are the outer and inner diameters of the conductors of the coaxial transmission line. The simulation was carried out for a coaxial transmission line with conductor diameters of 57 and 28 mm. The amplitude of the incident pulse is 300 kV, the biasing field is 40 kA/m. The simulation results are presented in figure 2, which shows the dependence of the maximum amplitude of high-frequency oscillations on the ferrite filling factor. With a decrease in the filling factor, a significant decrease in the amplitude of high-frequency oscillations was observed. This can be explained by the fact that the oscillating magnetic flux created by the precession of the magnetization vector is proportional to the cross-sectional area of the ferrite. As a consequence, a small oscillating magnetic flux excites oscillations of smaller amplitude. A rapid decrease in efficiency with an increase in the filling factor was also observed experimentally [5]. This decrease in amplitude can be caused by a violation of synchronism between the shock wave front and the high-frequency wave due to a significant change in the shock front velocity in a line with a larger filling factor.
2.4. Influence of the gap between the inner conductor and the ferrite on the efficiency of excitation of high-frequency oscillations

In the course of numerical experiments with different GNLTL geometries, a design feature of a nonlinear transmission line was discovered, which significantly affects the efficiency of oscillation excitation. As a rule, GNLTL is a coaxial transmission line with ferrite rings placed on the inner conductor. A small 1 or 2 mm oil gap remains between the ferrite and the inner conductor, which increases the electric strength of the line gap. The simulation results for various transverse dimensions showed that the absence of the oil gap between the ferrite and the inner conductor of the transmission line significantly increases the amplitude of the high-frequency pulse. Figure 3 shows oscillograms obtained in a numerical experiment for different diameters of the inner conductor of the transmission line. The transverse size of the ferrite was 45x28 mm, the diameter of the inner conductor was 57 mm, the rest of the volume not occupied by the ferrite was filled with a dielectric with its dielectric permittivity $\varepsilon = 2.2$ (vacuum oil). The amplitude of the incident voltage pulse is 300 kV at a biasing field of 50 kA/m. The figure shows a significant increase in the maximum amplitude of high-frequency oscillations. The ratio of the maximum amplitudes for lines with an inner conductor 25 and 28 mm in diameter is 1.3 times, which corresponds to 1.7 times increase in the peak power.

The simulation results for other transverse dimensions of ferrite showed that with a decrease in the transverse dimensions of the transmission line and, therefore, the ferrite filling, the effect of a 1 mm gap between the inner conductor and the ferrite becomes even more significant. For example, for a transmission line with conductor diameters of 44 and 18 (or 20) mm with a ferrite of 32 by 20 mm, the ratio of the maximum amplitudes is already 1.7 times. In the case of large transverse dimensions, the effect of the gap becomes less significant.

It has also been found that if the ferrite is located in the middle of the gap between the outer and inner conductors with significant gaps between conductors and ferrite, no high-frequency oscillations are observed in the transmission line. Thus, it can be assumed that the process of exciting high-frequency oscillations in a transmission line with a saturated ferrite is a complex wave process that cannot be described in terms of TEM waves and requires a detailed study.
3. Experiment
Within the work, an experimental study of the influence of the gap between the inner conductor and the ferrite on the efficiency of excitation of high-frequency oscillations was also carried out. An experiment was carried out with the same transmission lines and for the same parameters for which the numerical experiment was carried out in paragraph 2.4. Experimental oscillograms for different diameters of the inner conductor are shown in figure 4. The experimental results show an increase in the maximum amplitude of high-frequency oscillations by 2.1 times, which corresponds to an increase in the peak power by 4.5 times. For a more detailed explanation of this effect, apparently, it is necessary to develop a theoretical model of the process of excitation of oscillations in a line with ferrite, taking into account higher types of waves (not only TEM).

4. Conclusion
A study of the influence of various design features of the GNLTL in order to increase the peak power of the generators was carried out. The results were obtained using numerical simulations. The work
discovered the following features that should be taken into account when designing generators based on GNLTLs:

- For a nonlinear transmission line with saturated ferrite, there is a range of characteristic impedances of the coaxial transmission line, in which the most effective excitation of high-frequency oscillations is observed. For the line geometry considered in this paper, this interval lies in the range from 27 to 40 ohms. Within this range, it is possible to tune the oscillation frequency by external bias field with a small change in the peak power.
- The maximum amplitude of high-frequency oscillations is observed in the line with the filling factor $\eta = (D_f-d_f)/(D-d)$ in the range 0.3 - 0.7.
- It has been found that the gap between the inner conductor and the ferrite has a significant effect on the high-frequency oscillation excitation efficiency in the transmission line. In the case when ferrite is tightly put on the inner conductor of the coaxial line, the amplitude of high-frequency oscillations increases significantly. Moreover, if the ferrite is located in the middle of the gap between the conductors and is separated from them by oil, high-frequency oscillations are not observed.

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