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Dependence of the oscillations frequency in a nonlinear transmission line with saturated ferrite on magnetic fields and line dimensions

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Abstract. In the course of experiments on the excitation of high-frequency oscillations in the nonlinear transmission lines (NLTL) with saturated ferrite, it was shown that the frequency of the excited oscillations in the line depends on the strength of the magnetic fields in which the process of pulsed magnetization reversal of the ferrite filling occurs. It was found that an increase in the frequency of the excited oscillations corresponds to an increase in the azimuthal component of the magnetic field strength, while the frequency decreases with an increase in the strength of the longitudinal magnetic field saturating ferrite. However, to date, it is not possible to determine all the factors that affect the frequencies of excited oscillations in a NLTL, since today there is no analytical model for describing this process that considers non-TEM modes, and experimental study is too expensive. The solution to this problem can be the use of numerical simulation to conduct a numerical experiment on the process of excitation of oscillations in the NLTL. This work is devoted to the determination of the main factors affecting the frequency of excited oscillations in the NLTL with saturated ferrite. The influence of the magnetic field strengths, the coefficient of ferrite transverse filling, and the transverse dimensions of the line on the frequency and efficiency of the excited oscillations was studied.
Keywords: nonlinear transmission line, saturated ferrite, magnetic field.

1. Introduction

Recently, there has been growing interest in solid-state generators of powerful microwave pulses based on nonlinear transmission lines (NLTLs) with saturated ferrite. This is due to the fact that, in contrast to devices using an electron beam, NLTL-based generators are solid-state and, as a result, do not require vacuum and protection from accompanying X-rays. Such devices can achieve sub-gigawatt peak power levels. As a consequence, ferrite based NLTLs can be a good alternative for devices with electron beams in the frequency range of several GHz and pulse durations up to 10 ns.

In generators based on the NLTL, the process of excitation of high-frequency oscillations takes place due to the pulsed magnetization reversal of the ferrite, which is initially in a state of saturation in a longitudinal stationary magnetic field H_z. Within the framework of the macrospin model, this process can be described as follows: the azimuthal magnetic field H_φ of a high-voltage pulse applied to the line input excites a damped gyromagnetic precession of the ferrite magnetization vector, as the result damping high-frequency current oscillations are observed in the line output associated with gyromagnetic precession in ferrite. Today, for this reason, lines with saturated ferrite are called gyromagnetic NLTLs (GNLTLs).

The magnetization vector dynamics of the saturated ferrite filling of the transmission line $\boldsymbol{M}$ is described by the phenomenological Landau-Lifshitz equation [1]:

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

Here γ is the gyromagnetic ratio for an electron, α is the phenomenological damping constant, $\mathbf{H}$ is the magnetic field strength vector (including the external saturating field and the azimuthal field of the high-voltage pulse), M_s is the saturation magnetization of the ferromagnetic material (M_s is the constant of motion, hence the modulus of the magnetization vector $\mathbf{M}$ does not change with time).

Until now, an urgent task is to determine the frequency of excited oscillations in a specific GNLTL geometry. The main dependences of the frequency of excited oscillations on the components of the magnetic field strength were established empirically. With an increase in the longitudinal bias field H_z, the oscillation frequency decreases, and with an increase in the azimuthal field H_φ of the incident current pulse, the frequency increases. This effect allows for frequency tuning in a real generator.

To describe the physical mechanisms of excitation and propagation of high-frequency oscillations in a NLTL, an analytical model was constructed based on the joint solution of the telegraph equations and the Landau-Lifshitz equation [2, 3]. Neglecting precession damping (the second term on the right side of the Landau-Lifshitz equation (1)) an expression for the oscillation frequency in the absence of an external stationary longitudinal magnetic field can be written as [8]:

$$f_c = \frac{\gamma\mu_0}{2\pi} H_\varphi \tag{2}$$

Here μ_0 is the magnetic constant and H_θ is the azimuthal component of magnetic field. Taking into account the external stationary longitudinal field and the ferrite filling factor of the line, following expression for the frequency can be written [4]:

$$f_c = \frac{\gamma\mu_0 H_\varphi}{4\pi}\sqrt{1+\frac{\chi M_s}{\mu_0\sqrt{H_\varphi^2+H_z^2}}} \tag{3}$$

Here H_z is the longitudinal bias field, χ is the ferrite filling factor of a transmission line.

The constructed model gives a good qualitative idea of the process of oscillations excitation in a GNLTL, however, the lack of consideration of non-TEM waves can lead to restrictions on the use of the formulas (2) and (3).

Based on the experimental works [5–8], the frequency and efficiency (the ratio of the amplitude of the incident video pulse to the amplitude of the first oscillation) of oscillations noticeably depend on the transverse dimensions of the transmission lines.

Of great practical importance is the problem of determining the dependence of the frequency and efficiency of excited oscillations on the ferrite filling factor in transmission lines of different transverse sizes and different filling factor, as well as the dependence of the frequency on the azimuthal magnetic field of the incident pulse. In a real experiment, the solution of such a problem will require huge resource costs, and thus its experimental solution is complicated. However, such a problem can be solved using modern numerical simulation methods.

This paper presents a two-dimensional numerical simulation of the process of excitation of high-frequency oscillations in a nonlinear transmission line with a saturated ferrite using non-stationary KARAT code [9, 10], which allows for the FDTD method of jointly integrating the Maxwell's equations and the Landau-Lifshitz equation (1).

2. Modeling technique

Numerical simulation of nonlinear transmission lines with saturated ferrite is described in [9] in detail. In the non-stationary fully electromagnetic KARAT code, a saturated ferrite is dealt with as a phenomenological medium described by the Landau-Lifshitz equation (1), which describes the dynamics of the magnetization vector **M**. The time-varying ferrite magnetization vector generates eddy currents. Eddy current, in turn, is contained in the right side of Maxwell's equation:

$$\nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial\mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{J}_c \tag{4}$$

In the numerical simulation of a non-stationary problem, the Landau-Lifshitz equation must be solved at each time step synchronously with the Maxwell equations. The KARAT code implements the solution of the Landau-Lifshitz equation by the prediction and correction method, which provides the second order of accuracy.

3. Simulation

To identify the dependence of the frequency and efficiency of oscillations on the dimensions of the coax, 3 transmission lines of the same impedance 28 ohms with diameters of 20×10 mm^2, 40×20 mm^2, 80×40 mm^2 were selected. Such transverse sizes of coaxes and the impedance are typical for real experiments.

To study the dependence of the frequency and efficiency of oscillations on the ferrite filling, the ferrite filling factor was varied from 0.15 up to 1 with a step of 0.08 in each of the three coaxes.

The length of the ferrite filling remained constant and amounted to 1 m, which is the optimal value for real generators, since in a line longer than 1 m, the amplitude of high-frequency oscillations saturates and then attenuates with a further increase in the length of the GNLTL. The external longitudinal magnetic field was chosen equal to H_z = 48 kA/m, such field value is typical for a real experiment and is the closest to optimal for efficient generation of high-frequency pulses. A voltage pulse with a duration of 8 ns and a rise time of 3.2 ns was applied to the input of the line. Its waveform is presented in Fig.1.

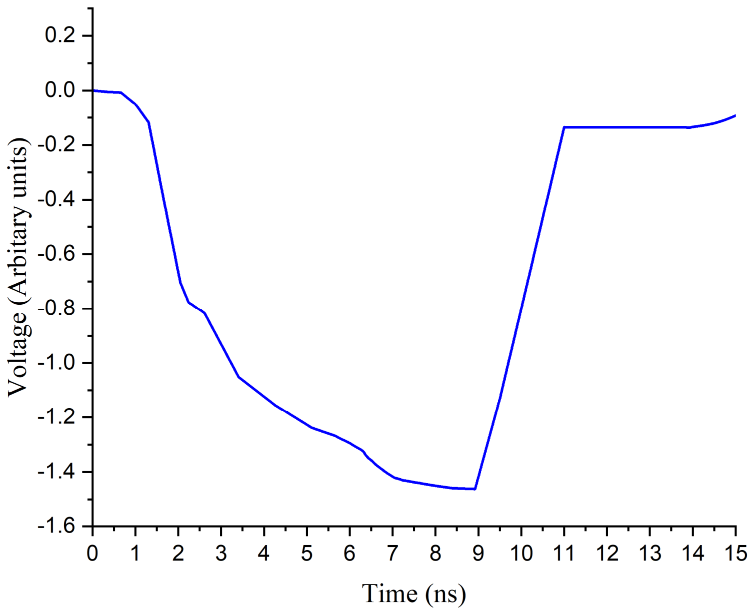

Fig.1. Waveform of an input pulse used in the simulation.

The azimuthal magnetic field H_φ, created by the current in the transmission line, in the TEM wave approximation is determined by the expression:

$$H_\varphi = \frac{J(r,z,t)}{2\pi r}.$$

To determine the dependence of the frequency of excited oscillations on the ferrite filling factor and the transverse dimensions of the transmission line, it is necessary to remain the values of the magnetic field components unchanged. Since the value of H_z is chosen constant, it is necessary to keep the azimuthal magnetic field averaged over the thickness of the ferrite filling unchanged in each case of ferrite filling. The expression for the average azimuthal component of the magnetic field strength is given by:

$$\overline{H}_{\varphi} = \frac{1}{(r_2 - r_1)} \int_{r_1}^{r_2} \frac{J}{2\pi r} = \frac{J \ln(\frac{r_2}{r_1})}{r_2 - r_1}.$$

Here J is current in the line, r_2 and r_1 are ferrite ring radii. Since the wave impedance of the coaxial line is determined through the inner and outer radii of the coaxial transmission line and the dielectric constant of the medium (a typical NLTL filling is transformer oil ε = 2.2) as

$$\rho = \frac{60}{\sqrt{\varepsilon}} \ln(\frac{R_2}{R_1}).$$

Here R_2 and R_1 are outer and inner radii of the transmission line. Then, the current is given by

$$J = \frac{U}{\rho},$$

$$\overline{H}_{\varphi} = \frac{\sqrt{\varepsilon} U \ln(\frac{r_2}{r_1})}{60(r_2 - r_1) \ln(\frac{R_2}{R_1})}.$$

It is possible to keep the average value of the azimuthal magnetic field for all coaxes at different values of the ferrite filling factor by changing the amplitude of the voltage pulse incident on the GNLTL. The value of the averaged azimuthal magnetic field in all numerical experiments was conserved and amounted to H_{φ} = 40 kA/m. The frequency of the radio pulse oscillations was determined through the central frequency (the frequency of the maximum spectral amplitude) obtained as a result of signal processing by the discrete fast Fourier transform algorithm.

4. Simulation results

For the three selected transverse sizes of the coaxial transmission lines, as a result of numerical simulation, the following dependences of the frequency on the ferrite fill factor were obtained (Fig.2):

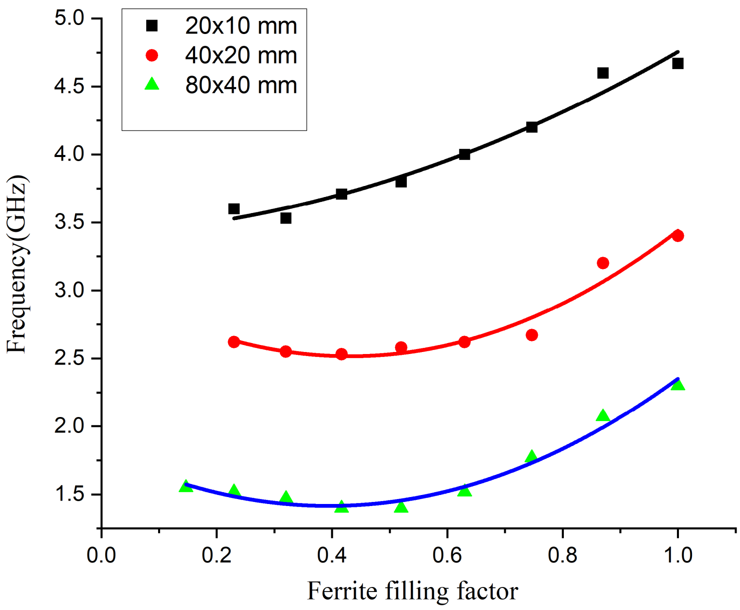

Fig.2. Dependencies of the frequency of microwave oscillations on the ferrite filling factor in different coaxial transmission lines (80×40, 40×20, 20×10 mm^2).

The dependences of the efficiency on the ferrite filling were also obtained (Fig.3):

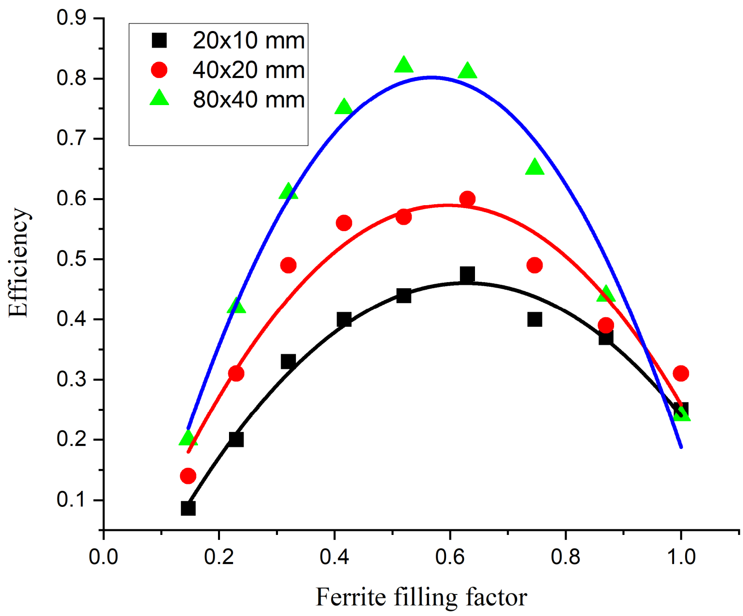

Fig.3. Dependencies of the generation efficiency of microwave oscillations on the ferrite filling factor in different coaxial transmission lines (80×40, 40×20, 20×10 mm^2).

The trends are similar to those observed in the experiments [5–8], and apparently reflect the general pattern for any transverse dimensions of the coaxial GNLTL. However, at fixed magnetic fields, with the same transverse geometric characteristics of the ferrite filling, the frequency of the excited oscillations in transmission lines with different transverse dimension is different. Within the framework of the theory based on the linearization of the telegraph equations and the Landau-Lifshitz equation in the TEM-wave approximation, the frequency of the excited oscillations should depend on the magnetic fields and the ferrite filling factor according to formula (3). It can be seen that, according to the theoretical analysis, at fixed fields and the same ferrite filling factor, the frequency should be close, including for different coaxes. Moreover, from the curves of the dependence of the frequency on the ferrite filling factor, obtained as a result of numerical simulation, it is observed that the larger the transverse dimensions of the coaxial become, the stronger the dependence differs from the analytical one. Moreover, the difference from the analytical model can also be seen in the absolute values of the frequency at different values of the ferrite fill factor.

Expression (3) predicts an unlimited increase in frequency with an increase in the azimuthal field. Within the framework of a numerical experiment, the dependence $f(H_\varphi)$ in a wide range of the magnitude of the azimuthal magnetic field of the incident pulse is of interest in order to reveal the limits of applicability of analytical constructions.

The numerical experiment demonstrates saturation and frequency decay at fields of the order of 1000 kA/m.

It should be noted that in a real experiment, this dependence is almost impossible to verify, such high values of the azimuthal magnetic field can only be obtained at very high incident pulse voltages (of the order of 1000 kV), which will inevitably lead to an electrical breakdown of the line.

The results of numerical simulation are in good agreement with the experimental data presented in [5–7].

The dependence of the oscillation frequency on the ferrite filling factor can be associated with a change in the structure of the field of the excited wave. The change in the structure of the electric field of the wave, as the ferrite filling increases, can be tracked by the amplitude of the first oscillations of the azimuthal and longitudinal components of the fields. As the ferrite filling increases, the wave structure undergoes modifications. With a small ferrite filling, only the radial component of the electric field strength oscillates significantly. With an increase in the ferrite filling factor, oscillations of the azimuthal and longitudinal components of the field start to appear. The longitudinal component of the electric field prevails over the azimuthal component up to the value of the ferrite filling factor close to 0.5. At half the ferrite filling (which corresponds to the maximum modulation depth and minimum frequency), all field components are compared in amplitude. A further increase in the ferrite filling factor leads to the fact that the azimuthal component of the electric field begins to dominate over the radial and longitudinal components (Fig.5).

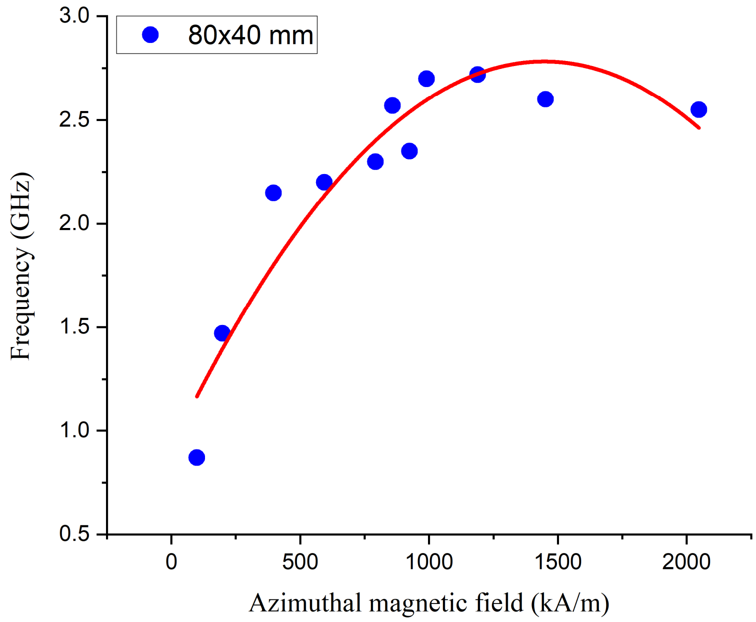

Fig.4. Dependence of the frequency of microwave oscillations of a radio pulse on the azimuthal magnetic field in coaxial transmission lines (80×40 mm^2).

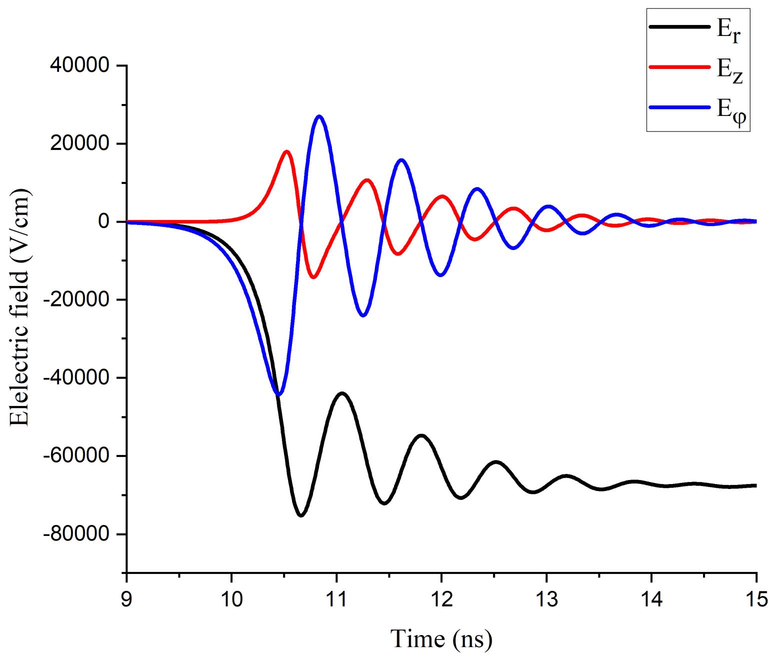

Fig.5. Electric field strength components of the wave at a filling factor of 0.6.

5. Recap

1. Using numerical simulation, a characteristic dependence of the oscillation efficiency on the ferrite filling factor was obtained with a maximum point lying near half of the ferrite filling, which is true for various transverse sizes of the coaxial transmission line and is indirectly confirmed experimentally.

2. The dependence of the frequency of excited oscillations on the ferrite filling factor χ was obtained. The oscillation frequency decreases with an increase in the ferrite filling factor up to a value close to 0.5, then the oscillation frequency begins to increase with an increase in χ.

3. The study of the dependence of the oscillation frequency on the azimuthal field leads to the conclusion that there is a maximum frequency value, more than which, by increasing the azimuthal magnetic field, it will not be possible to obtain.

4. The dependences of the oscillation frequency and efficiency on the transverse dimensions of the coaxial line are determined. As the transverse size of the coaxial increases, the maximum efficiency that can be achieved in the process of excitation of high-frequency oscillations in a nonlinear transmission line with saturated ferrite increases, the maximum frequency decreases. This fact, which is also observed in real experiments, cannot be explained within the framework of currently existing analytical constructions and requires further study.

6. Conclusion

In the course of the work, a numerical simulation of the process of generating high-power high-frequency oscillations based on a nonlinear transmission line with saturated ferrite was carried out in order to find the dependence of the frequency and efficiency of oscillations on the transverse dimensions of the nonlinear transmission line and on the azimuthal magnetic field. The simulation was carried out by means of solving the Maxwell's equations and the phenomenological Landau-Lifshitz equation by the FDTD method implemented in the KARAT code. As a result of the simulation, the dependences of the frequency and efficiency on the ferrite filling factor in three coaxes with different transverse dimensions, as well as the dependence of the oscillation frequency on the azimuthal magnetic field, were obtained. In the three coaxes for which the simulation was carried out, it is possible to identify two characteristic regions by the value of the ferrite filling factor, in the region with an increase in the ferrite filling, the efficiency increases, but the oscillation frequency decreases, in the region there is a reverse trend, an increase leads to a decrease in efficiency and an increase in frequency.

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