IMPROVING RF GENERATION CONDITIONS IN A FERRITE-FILLED TRANSMISSION LINE

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The paper considers transformation of the short unipolar pulse of electric current in a coaxial transmission line filled with a ferromagnetic into a shock wave, with later generation of quasi-monochromatic radio frequency oscillations. The frequencies and amplitudes of the oscillations are determined by dispersive and non-linear properties of the transmission line, governed by the geometry and size of the line proper, and layered structure and intrinsic dispersion of the ferromagnetic material. The numerical experiments done for a variety of geometrical and material parameters of the line have allowed suggesting technical solutions as to increase in the efficiency of the dc-to-rf power conversion.

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INTRODUCTION

The physical effects leading to direct conversion of short carrier-free electric pulses into radio frequency oscillations have been the subject of intense studies for quite a long time. In particular, a pulse of electric current traveling through a transmission line (TL) filled with a non-saturated ferrite demonstrates sharpening of its front edge and formation of a shock-like waveform, should the current magnitude be high enough to reveal non-linear response of the ferrite medium [1, 2]. When the ferrite gets magnetized close to saturation, under the influence of both the external DC magnetic field along the TL axis and the current-induced field oriented in a transverse direction, quasi-periodic oscillations may appear at frequencies falling into the RF or microwave range [2 - 5]. The effect opens prospects for creating a new branch of the high power electronics, operating without intense particle beams or vacuum devices. However, the underlying physics remains until now only poorly understood, despite the considerable efforts of many researchers. The most popular idea concerning the reason for the appearance of the oscillations has for some time been the precession motion of the magnetization vector about the direction of the external magnetic 'bias' [2, 6], however this cannot explain, *e.g.*, either the dependence of the oscillation frequency upon the line's cross-section diameter or even the value itself.

The present work is devoted to the analysis of the physical essence of the observed phenomenon on the basis of existing theoretical models in order to explain the above effect and to find ways to increase the efficiency of excitation of oscillations.

1. EXPERIMENTAL RESULTS

Experiments on exciting the oscillations in a coaxial line partially filled with a saturated NiZn ferromagnetic of grade 200VNP were carried out using the high-voltage impulse facility presented in [5]. The experimental system (Fig. 1) consisted of the input and output homogeneous coaxial transmission lines TL1 and TL2 and coaxial nonlinear transmission line (NLTL) containing a cylindrical ferrite insert. The coaxial NLTL waveguide had the length of 200…800 mm, different outer and inner diameters (D_3 = 10…52 mm, D_1 = 4…20 mm), and diameters of the ferrite layer (D_2 = 7…32 mm и D_2/D_1 = 1.6). The amplitude of the NLTL input voltage pulse U_0 was within 40...200 kV.

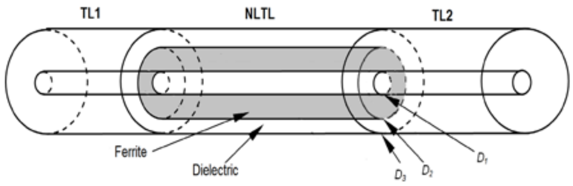

Fig. 1. Scheme of coaxial structure with NLTL

Fig. 2 shows typical input and output pulses of the NLTL with $D_3/D_2/D_1$ = 52 mm/32 mm/20 mm with the bias magnetic field H_0 = 30 kA/m and U_0 = 200 kV. The characteristics of the obtained RF oscillations were determined according to the data of the first periods of oscillations: the frequency $f = 1/(t_3-t_1)$, and the relative amplitude $a = 100\%(U_1-U_2)/(U_1+U_2)$. Typical oscillation characteristics registered in our experiments with large-dimension NLTL (52/32/20 mm) [5] were f = 1.3 GHz, and a = 53% (see Fig. 2), while with small-dimension NLTL (10 mm/7 mm/4 mm) were $f \sim 4$ GHz, and a = 7%. To the data of our experiments, we can add the results obtained by other authors. In the experiments [2] with the NLTL of very small diameter (D_3 = 3 mm), the oscillations were observed in the frequency range of ~6 GHz.

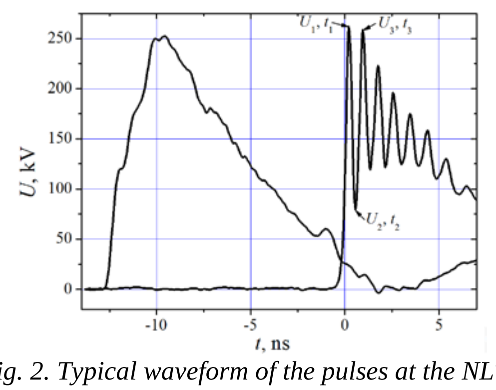

Fig. 2. Typical waveform of the pulses at the NLTL input (left) and output (right).
$D_3/D_2/D_1$ = 52/32/20 mm, L= 800 mm

The paper [3] reported about a larger diameter NLTL (D_3 = 80 mm), where the frequency of oscillations were registered in the range of 0.8…2 GHz, and $a \approx 50\%$. Finally, in the experiment [7], where a 500 kV pulse was used to excite a very large-diameter NLTL

(D_3 = 275 mm and D_2 = 200 mm), it was possible to obtain oscillations with $f \approx 0.3$ GHz and $a \approx 80\%$.

Summarizing, we can underline definite tendency observed in the experiments that use the coaxial NLTLs with magnetically saturated cylindrical NiZn ferrite layer – the increase in the transverse dimensions of the waveguide leads to the decrease in the oscillation frequency and increase in their relative amplitude.

2. NUMERICAL EXPERIMENT

Excitation of RF oscillations in a coaxial ferrite filled NLTL by a current pulse was simulated with the help of the technique based on solution of Maxwell's equations together with phenomenological Landau-Lifshitz-Gilbert equation of state of the ferromagnetic medium [8]. The calculations used the FDTD method [9].

The dielectric permittivities of the insulating dielectric and ferrite were, respectively, of 2.25 and 16. The ferrite layer diameter ratio D_2/D_1 was of 1.6. The saturation magnetic field M_S and the relaxation coefficient in the Landau-Lifshitzt equation were assumed to be 300 kA/m and 0.1, respectively.

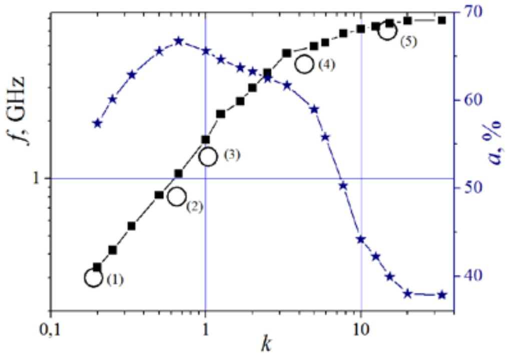

Fig. 3. Calculated oscillation frequency (square) and relative amplitude (star) as a function of the scaling factor. Experimental data (circles) from papers: 1 – [7]; 2 – [3]; 3 – [5]; 4 – [4]; 5 – [2]. k = 1 relates to D_3 = 52 mm

The relationship between the parameters of the oscillations and the transverse dimensions of the NLTL is shown in Fig. 3 as a function of the oscillation frequency and relative amplitude of the scale factor k, which takes into account the proportional change in the waveguide transverse dimensions $D'_i=D_i/k$, and the input pulse voltage $U'=U/k$. In this case, the azimuthal magnetic field of the current wave H_φ magnetizing the ferrite remains unchanged. It is taken into account that the factor value $k = 1$ corresponds to D_3 = 52 mm.

The simulation results (see Fig. 3) confirm the trend revealed in the experiment: with increasing the transverse dimensions, the oscillation frequency decreases, and their amplitude increases. It is also seen that when the transverse dimensions decrease (rising k), the oscillation frequency reaches a certain high level and then almost does not change.

3. ANALYSIS OF THE RESULTS

A number of authors [2, 4, 6, 10] consider the magnetic moment precession excited by TEM current wave in NLTL filled with saturated ferrite as a source of HF oscillations, and the oscillation frequency equal to the precession frequency. However, experiments and numerical calculations indicate that the oscillation frequency has a direct relationship with the transverse dimensions of the coaxial NLTL.

In our interpretation, the mechanism of excitation of RF oscillations in a coaxial NLTL filled with ferrite looks as follows. An unipolar electromagnetic pulse, which presents a TEM wave, propagates along the coaxial NLTL, in which a parametric relationship $\mu(H)$ exists, and forms a shock wave. The effects at the shock wave leading edge are determined by the balance of a number of conditions: (1) the nonlinearity of $\mu(H_\varphi)$, (2) the energy dissipation of the HF components due to losses in the waveguide, and (3) the dispersion properties of the ferrite medium. The first condition leads to the shock wave rise time decrease, while the second and third lead, on the contrary, to the rise time increase.

In the process the current wave propagation down the nonuniform coaxial NLTL, a more complex wave structure – quasi-TEM wave, which has a non-zero longitudinal component of the electric field E_Z, is formed. In this case, the LF components of the quasi-TEM wave coincide in properties with the TEM wave. However, for HF components with the frequencies in the region of the critical frequency of corresponding lower waveguide TE or TM modes of inhomogeneous NLTL the dispersion properties are noticeably manifested. As it follows from the calculation, the experimentally observed frequency of the oscillations is close to the critical frequency of the TM_{01} mode $f_{CR} \approx c(\varepsilon^*\mu^*)^{1/2}/(D_3\text{-}D_1)$, where ε^* and μ^* are the NLTL effective dielectric permittivity and magnetic permeability taking into account the ferrite filling factor of an inhomogeneous line. It is important to note that as the shock wave propagates through the NLTL and front edge contracts, its energy transfers from the LF to the HF components, providing an increase in the amplitude of the excited oscillations.

It should be noted that the calculations of the oscillation frequency carried out using a one-dimensional model of NLTL [2] does not take into account the features of wave propagation in nonuniform waveguide structure. Therefore, the analysis of such a system is correct only when using the complete system of Maxwell equations that takes into account the dispersion of the waveguide modes.

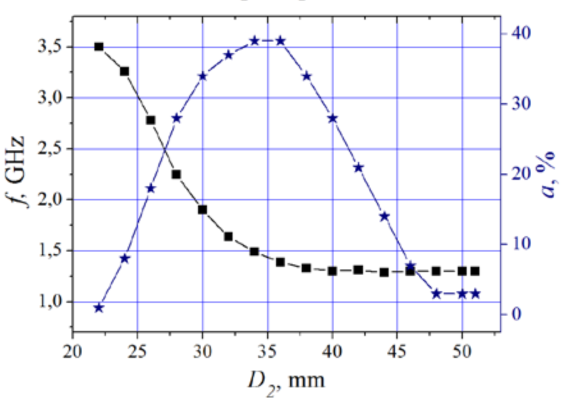

Fig. 4. Calculated oscillation frequency (square) and relative amplitude (star) as a function of the ferrite outer diameter (D_3 = 52 mm)

Fig. 4 presents the results of calculating the frequency and relative amplitude of the oscillations as a function of the outer diameter of the ferrite D_2 (for fixed geometrical parameters of the line, D_3/D_1 = 52/20 mm). As the NLTL filling factor with ferrite increases, the dependence $f(D_2)$ demonstrates a tendency to move to a certain $f_{CR\ MIN}$. This behavior can be explained by the gradual increase of the waveguide filling factor and, accordingly, increase of ε^* and μ, so that the corresponding f_{CR}, proportional to $(\varepsilon^* \mu^*)^{-1/2}$, shows monotonous decrease. The graph of the dependence of the oscillation relative amplitude on the waveguide ferrite filling factor (see Fig. 4) demonstrates a maximum at D_2/D_3 = 40…50%. An analogous dependence of $a(D_2)$ was observed in a number of our experiments with NLTL [5, 11].

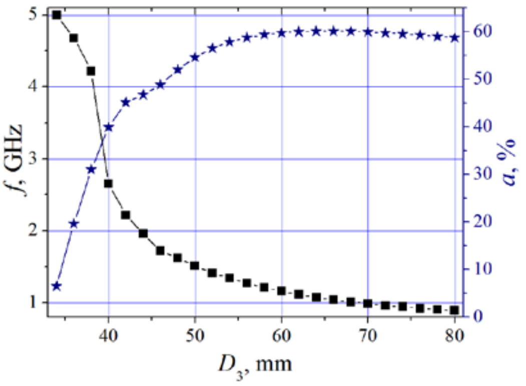

Fig. 5. Calculated oscillation frequency (square) and relative amplitude (star) as a function of the coax outer diameter (D_2 = 32 mm)

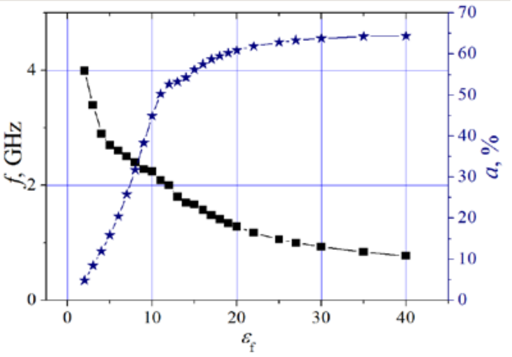

Fig. 6. Calculated oscillation frequency (square) and relative amplitude (star) as a function of the ferrite dielectric permittivity (D_3 = 52 mm, D_2 = 32 mm)

The interpretation of the results presented above also confirms the calculated dependence of the oscillation frequency on the coaxial outer dimension $f(D_3)$. Fig. 5 demonstrates the oscillation frequency monotonic decrease and tendency to a definite value with increasing D_3. Obviously, this trend is associated with an increase in the difference in diameters $D_3 - D_2$, which leads to a decrease in f_{CR} (TM_{01}). If the line external diameter D_3 is reduced, approaching the ferrite outer diameter D_2, then at $D_3 = D_2$, a line completely filled with ferrite is realized. The line with the new parameters D_3/D_1 = 32 mm/20 mm smaller than of the original ones D_3/D_1 = 52 mm/20 mm demonstrates, respectively, higher oscillation frequency (see Fig. 3). It worth noting that the frequency value observed at $D_3 = D_2$ is maximum for the line with D_3/D_1 = 52 mm/20 mm (see Fig.5), and is minimum for the line with D_3/D_1=32/20 mm.

4. IMPROVING THE OSCILLATION EXCITATION EFFICIENCY

Thus, the simulation has shown that the efficiency of formation of oscillations can be varied by means of choosing the characteristics the coaxial waveguide and ferrite. For example, this can be achieved by increasing the ferrite permittivity in comparison with the dielectric permittivity ε_f, as well as by increasing the ferrite magnetic saturation moment M_s. Fig. 6 shows the results of calculations for the NLTL with a variable ε_f and fixed M_s = 300 kA/m. Fig. 7 shows the NLTL output signal with hypothetical ferrite, for which ε_f = 50, and Ms = 1000 kA/m. In this case, the relative amplitude of the oscillations reaches 90%.

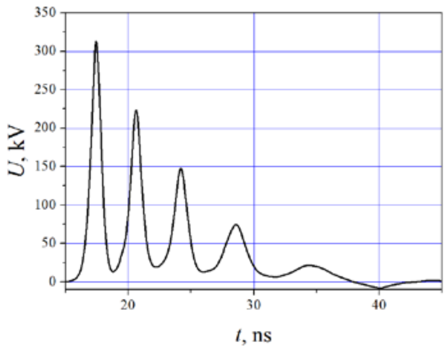

Рис. 7. The output signal waveform for NLTL with ferrite characteristics: M_s = 1000 kA/m, and ε = 50; U_0 = 200 kV

Obviously, this method is difficult to be implemented in practice, since it requires ferrites with abnormally high ε_f and M_s (usually $M_s \approx$ 300 kA/m). Thus, several other variants of NLTL, realizing more practical and efficient ways for exciting the HF oscillation are considered below.

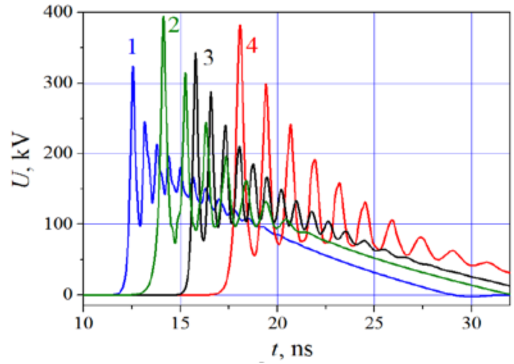

Fig. 8. The output signals of NLTL with different design: 1 – basic design; 2 – variant A; 3 – variant B; 4 – variant C. U_0 = 200 kV

Calculations were performed for NLTL with dimensions $D_3/D_2/D_1$ = 52/32/20 mm and L = 800 mm at U_0 = 200 kV:

Variant A – a ferrite layer was placed in a dielectric sleeve with diameters of 32/38 mm and ε = 30 (Fig. 8, curve 2).

Variant B – a homogeneous ferrite layer was replaced by a layered structure, where 10 mm thick ferrite disks were interchanged with 3 mm thick disks of a dielectric with ε = 30. The decrease in the ferrite volume was compensated by an increase in the structure length from 800 mm to 1400 mm (see Fig. 8, curve 3).

Variant C – both methods were used simultaneously (see Fig. 8, curve 4).

The results of the calculations are tabulated. All three methods increase the efficiency of the formation of oscillations, and the most effective is the third combined method. It should be noted that when using these methods, an increase in the amplitude of the oscillations is accompanied by a decrease in their frequency.

NLTL	*a*, %	*f*, GHz
Original design	54	1.62
Variant A (dielectric tube)	68	0.88
Variant B (layered structure)	63	1.27
Variant C (dielectric tube and layered structure)	74	0.75

CONCLUSIONS

In this paper we present an alternative treatment of the phenomenon of excitation of HF oscillations in a nonlinear transmission line. The oscillation frequency and amplitude are determined by the dispersion and nonlinear characteristics of the coaxial waveguide system, which in turn depend on its dimensions and geometry, as well as the dispersion properties of the ferrite and the layered structure of the line filling. The optimum filling factor of the NLTL by ferrite (from the point of view of obtaining the maximum oscillation amplitude) is of 40…50%. It is shown that the amplitude of the oscillations can be increased by increasing the difference between the permittivity of the ferrite and the insulating dielectric, and also by means of special inserts in the NLTL of a dielectric with high dielectric permittivity.

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ОПТИМИЗАЦИЯ УСЛОВИЙ ВОЗБУЖДЕНИЯ ОСЦИЛЛЯЦИЙ В КОАКСИАЛЬНОЙ ЛИНИИ С НАМАГНИЧЕННЫМ ФЕРРИТОМ

С.Ю. Карелин, В.Б. Красовицкий, И.И. Магда, В.С. Мухин

Рассматривается трансформация короткого униполярного токового импульса в коаксиальной линии, заполненной ферромагнетиком, в электромагнитную ударную волну с последующей генерацией квазимонохроматических осцилляций радиочастотного диапазона. Частота и амплитуда возбуждаемых осцилляций определяются дисперсионными и нелинейными характеристиками передающей линии, которые зависят от ее размеров и геометрии, а также собственных дисперсионных свойств феррита и слоистой структуры заполнения линии. Численные эксперименты, выполненные для различных значений геометрических и материальных параметров системы, позволяют предложить технические решения для увеличения эффективности преобразования импульсов «постоянного» тока в радиочастотные колебания.

ОПТИМІЗАЦІЯ УМОВ ЗБУДЖЕННЯ ОСЦИЛЯЦІЙ В КОАКСИАЛЬНІЙ ЛІНІЇ З НАМАГНІЧЕНИМ ФЕРИТОМ

С.Ю. Карелін, В.Б. Красовицький, І.І. Магда, В.С. Мухін

Розглянуто трансформацію короткого уніполярного імпульсу струму в коаксиальній лінії, що заповнена феромагнетиком, в електромагнітну ударну хвилю з подальшою генерацією квазімонохроматичних коливань у радіочастотному діапазоні. Частота та амплітуда збуджуваних коливань визначаються дисперсійними та нелінійними властивостями лінії передачі, що залежать від її розмірів і геометрії, а також власних дисперсійних властивостей ферита і шаруватої структури заповнення лінії. Числові експерименти, що проведені для різних значень геометричних та матеріальних параметрів системи, дозволяють пропонувати технічні рішення щодо підвищення ефективності перетворення імпульсів «постійного» струму в радіочастотні коливання.