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РАДІОФІЗИЧНІ ЯВИЩА В ТВЕРДОМУ ТІЛІ І ПЛАЗМІ

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S. Y. KARELIN, V. G. KORENEV, V. B. KRASOVITSKY,
A. N. LEBEDENKO, I. I. MAGDA, V. S. MUKHIN,
V. G. SINITSIN, and N. V. VOLOVENKO

Institute for Plasma Electronics and New Acceleration Methods,
National Science Center "KIPT", National Academy of Sciences of Ukraine,
1, Akademichna St., Kharkiv, 61108, Ukraine
E-mail: magda@kipt.kharkov.ua

PULSED POWER TO MICROWAVES CONVERSION IN NONLINEAR TRANSMISSION LINES

Purpose: *Experimental results and numerical simulations are presented, concerning effects of microwave generation in coaxial transmission lines which are fed with unipolar, high voltage electric pulses. The work is aimed at clarifying the relative importance of several mechanisms that could be responsible for the appearance of microwave-frequency oscillations in the course of pulse propagation through the guiding structure.*

Design/methodology/approach: *Dispersive and filtering properties of coaxial waveguides that involve three structural sections are discussed. These latter follow one another along the axis of symmetry. Two identical sections at the input and output are filled with an isotropic liquid dielectric, while the middle part may, in addition, be either partially or fully filled with a non-conductive gyrotropic material. The inserted core represents a set of ferrite rings showing a nonlinear response to the initial high voltage, pulsed excitation. Throughout the series of measurements, the diameters of the inner conductor and of the ferrite core were kept constant. The outer conductor's diameter was varied to permit analysis of the effect of that size proper and of the degree to which the cross-section is filled with ferrite. The gyrotropic properties of the ferrimagnetic material were realized through application of a magnetic bias field from an external coil. The measurements were made for a variety of pulsed voltage magnitudes from the range of hundreds of kilovolts, and magnetic bias fields of tens kiloamperes per meter.*

Findings: *As observed in our experiments, as well as in papers by other writers, a unipolar pulse coming from the radially uniform front-end section, further on gives rise to quasi-monochromatic voltage oscillations. These appear as soon as the pulse has advanced a sufficient distance into the radially nonuniform portion of the guide. The oscillations may consist of a small number of quasi-periods, which suggests a large spectral line width. However, by properly selecting geometric parameters of the wave guiding line and the characteristics of the initial pulsed waveform it proves possible to obtain output frequencies of about units of gigahertz and pulse powers at subgigawatt levels.*

Conclusions: *The frequencies and amplitudes of the appearing oscillations, as well as their spectral widths, are governed by the complex of dispersive and non-linear properties of the guiding structure. The diameters of the inner and outer coaxial conductors in the line, diameter of the ferrimagnetic insert and its intrinsic linear dispersion determine the set of waveguide modes capable of propagating through the line. An oscillating part of the waveform may appear and get separated from the main body of the pulse if it has originated at a higher frequency than the cut-off value for a different mode than the initial TEM.*

Key words: *unipolar pulse, coaxial transmission line, microwave frequency oscillations, dispersion laws, waveguide modes*

1. Introduction

The effects of direct conversion of electric pulses of short duration into radio frequency oscillations, observed in transmission lines with nonlinear properties, have been studied quite intensely for more than a decade [1–4, 7, 8]. A critically essential feature of this technology is the employment of such transmission lines whose topology allows propagation of unipolar (roughly speaking, d.c.) voltage pulses. Falling into this category are planar strip lines and coaxial cables (along with lumped parameter, discrete cell circuits that will not be discussed here) [3, 6]. Quasi-periodic temporal variations in the values picked up by voltage sensors are observed, in particular, in coaxial cables whose cross-sections are partially filled with a magnetically saturated ferrimagnet. To start the oscillations, it is necessary to apply a high enough pulsed voltage, thus inducing a magnetic field vector transverse with respect to the magnetization vector at saturation [3, 4, 6]. As a result, the magnetization vector demonstrates precession about the direction of the external magnetic bias, which effect is often considered to be the one and only reason for the appearance of oscillations in voltage and current in the line (i.e., in the electric and magnetic field strengths). Meanwhile, by appealing to the magnetic precession alone one does not seem to be able to interpret some essential dependences shown by the oscillations [6, 7, 9], like frequency versus the outer conductor diameter, or size of the ferrite insert. This paper is yet another attempt at clarifying the physics that underlies appearance of quasi-periodic field strength variations in the course of propagation of unipolar pulses through a transmission line of nonuniform cross-section, showing a nonlinear response to an external excitation.

2. Experimental

The wave guiding structure used in our experiments involved two coaxial lines with linear response functions (lines TL_{in} and TL_{out} at the structure's front end and at the output, respectively), and the line NL (nonlinear) containing a ferrite core, placed in between. The latter represented a set of ferrite rings, fitted tightly on the central conductor and closely adjacent to one another along the longitudinal axis. The TL_{in} and TL_{out} lines were fully filled with a liquid dielectric (transformer oil with the dielectric constant $\varepsilon = 2.25$ and scalar magnetic permeability $\mu = 1$), whereas in the NL case, the filling medium occupied two layers. The outer one, $r_2 \le \rho \le R_2$ (see the notation in Table 1), contained the same isotropic dielectric as the TL_{in} and TL_{out} lines, while the space $r_1 \le \rho \le r_2$ accommodated the cylindrical ferromagnetic core (Ni–Zn ferrite of grade 200 VNP. The entire NLTL structure was placed in a d.c. magnetic field (up to 100 kA/m) provided by an external solenoid.

The diameters of the coax inner conductor and of the ferrite core nominally remained the same throughout the series of measurements, while the outer conductor's diameter, $2R_2$, was varied to permit analysis of the direct effect of that size proper and of the degree to which the cross-section was ferrite-loaded. Altogether, three different structures, designated NLTL1, NLTL2, and NLTL3, were considered, naturally described in a cylindrical frame of reference (z, ρ, φ), where z is the coordinate along the line's axis; ρ the radial, and φ the angular coordinate. Their geometrical parameters and values of the dimensionless filling ratio $K_1 = (r_2^2 - r_1^2)/(R_2^2 - R_1^2)$ are shown in Fig. 1 and listed in Table 1. Unlike many other studies, this series of experiments also included measurements for a fully filled coaxial cross-section, i.e. $K_1 = 1$.

The coaxial line was fed with voltage pulses of short duration (7 to 15 ns), arriving from a high voltage pulse generator which operated in a 30 kV to 320 kV range of amplitudes. The pulsed signals at the input and output of each NLTL were measured with capacitive (differentiating) sensors placed in the linear sections of the line closely before and after the nonlinear section. Such sensors responded to variations in the radial electric field component, E_ρ (actually, to its time derivative). The line impedances for the lowest order (TEM) linear mode were practically matched in all the three sections, since a similar impedance (about 38 Ohm) could be also expected for the nonlinear section when the magnetic bias field H_0 were at its maximum. At lower magnitudes of the bias field H_0, the matching was violated as operation conditions were different at those parts of the $B = B(H)$ curve ($\boldsymbol{B}$ being the magnetic induction). The oscillograms taken at the output from a NLTL were used to estimate the oscillation frequency, f, and the time delay Δt shown by the

Table 1. **Geometrical parameters of the coax lines and values of the dimensionless filling ratio K_1**

Coaxial line	R_1, mm	R_2, mm	r_1, mm	r_2, mm	L, mm	K_1
NLTL1	6	25.5	6	10	800	0.1
NLTL2	6	13	6	10	800	0.5
NLTL3	6	10	6	10	800	1.0

Note: R_1 – radius of inner conductor; R_2 – inner radius of outer conductor; r_1 – inner radius of ferrite core; r_2 – outer radius of ferrite core; L – total length of ferrite core

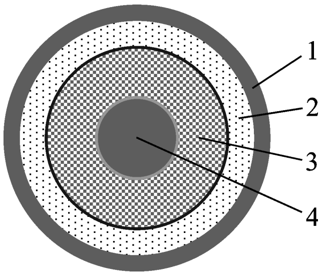

Fig. 1. Cross-sectional structure of the coaxial guide: 1 – outer conductor of inner radius R_2; 2 – isotropic dielectric; 3 – ferrite rings, outer radii r_2; 4 – inner conductor of radius r_1

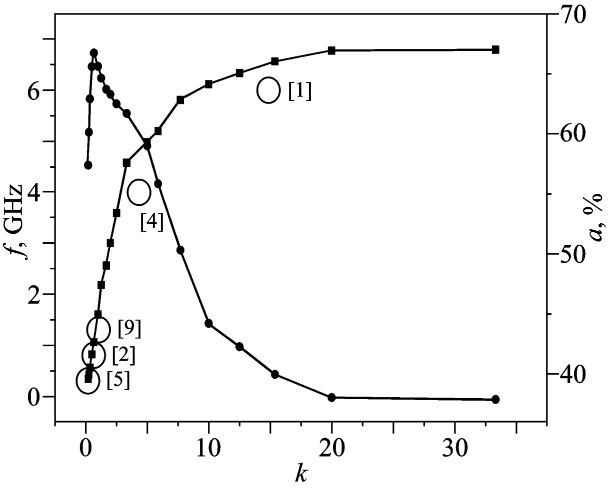

Fig. 2. Calculated and measured (referenced circles) oscillation frequencies, *f*, and relative amplitudes, *a*, for several values of the scaling factor, *k*

pulse's front edge. Both magnitudes were evaluated in dependence on the *z*-directed ("longitudinal") bias field $\boldsymbol{e}_z H_0$ and on the azimuthal magnetic field component, h_φ.

3. Results and discussion

As can be seen from the results of our measurements (as well as from the data presented in quite a number of other experimental papers, e.g. [2, 4, 6, 9], the oscillation frequencies observed in the NLTLs partially filled with a ferrimagnetic material clearly demonstrate dependences on sizes of the line's constituent parts. As it occurs in practice, the outer-to-inner diameter ratio of the standard ferrite rings is close to 1.6 or 1.7. Normally, the ferrite rings occupy about one half of the radial span between the central and the outer conductors, which allows introducing kind of a unification parameter for different guiding structures, ranging in the diameter $2R_2$ from 3 mm to 80 mm [1, 2, 4]. Such a scaling factor *k*, defined as $R_2' = R_2/k = R_1' = R_1/k$ can be applied to input voltage magnitudes $U' = U_0/k$ to effectively equate the azimuthal magnetic fields existing in the lines under comparison. Despite this practical identity of magnetic conditions, the frequency versus scaling factor *k* dependence (Fig. 2) shows a well pronounced tendency toward higher frequencies in lines of smaller diameter. Many experimental results relating to a variety of outer line diameters $2R_2$ and magnetic properties of the ferrites used, fit the formula $f \sim R_2^{-1}$, where *f* is the oscillation frequency observed. Thus, Dolan [1], in his pioneering experiments, operated with coaxial lines of very small diameters ($2R_2 \approx 3$ mm) and obtained oscillations at $f \approx 6$ GHz. Gubanov et al. [2] experimented with lines about 80 mm in diameter and observed oscillations at lower frequencies, specifically 0.8 GHz to 2 GHz. To interpret these results in respect to wave field propagation through a transmission line, we appeal to an analysis of the pulse's modal content and its transformation in different parts of the line.

Initially, a d.c. magnetic bias field from an external solenoid brings the ferrite core to a magnetic state close to saturation, the corresponding static magnetization vector being $\boldsymbol{M}_0 = \boldsymbol{e}_z M_s$, where M_s is a parameter of the material (in the case of 200 VNP, $M_s = 300$ kA/m). Next, the front line $\mathrm{TL_{in}}$ receives a unipolar voltage surge $U(t)$ from an external source, which gives rise to a set of TEM waves traveling toward the ferrite core. The frequency content of the set is determined by the pulsed waveform as fed-in from the source, while the spatial components in the TEM are only two, namely $E_\rho = \partial U/\partial\rho$ and $H_\varphi = J/2\pi\rho$, where $J = U/\zeta$ is the current through the line and ζ the line's impedance. Within a TEM mode, all the frequency components of a pulse travel at the same phase velocity. The incoming frequency spectrum extends from "almost d.c." to $1/t_r$, where t_r is the pulse's rise time. The highest frequency in the set determines the "sharpness" of the waveform edge. The lowest, of amplitude about $U_0/\left(2(R_2 - R_1)\right)$ carries the major part of the pulse's energy (U_0 is the peak voltage of the pulsed waveform).

Upon entering the ferrite-loaded part of the line the signal acquires, owing to diffraction at the dielectric–ferrite boundary, spatial field components E_z

and H_z, which the initial E_ρ and H_φ are coupled to through the Maxwell equations. With the appearance of E_z and H_z none of the modes capable of propagating through the coaxial line can be regarded as a pure TEM, not even those with $\partial/\partial\varphi = is = 0$. The modes with the angular dependence $\exp(is\varphi)$ and $|s| \ge 1$ may involve more (up to all six) spatial field components, posing as hybrid *EH* or *HE* modes. In addition, the frequency content of the pulse that travels through the layered (TL+ NL) portion of the structure is constantly being modified owing to the nonlinear response of the ferrite insert. This stage of pulse transformation is harder to describe analytically because the former linear solutions to the wave equation, i.e. eigenmodes are strongly coupled here. Contrary to that, the ferromagnetic core in a state close to magnetic saturation suggests a nearly linear magnetic response $\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{H})$ [5] ($\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M})$, where μ_0 is the magnetic permeability of vacuum and $\boldsymbol{M}$ the magnetization vector). The dynamics of variations in $\boldsymbol{M}$ is described in terms of the Landau–Lifschitz (L-L) equation. The frequency representation of that takes the form

$$\begin{aligned} &i\omega\boldsymbol{M}(\omega) = \\ &-\gamma\mu_0 \int d\omega' d\omega'' \left[\boldsymbol{M}(\omega') \times \boldsymbol{H}(\omega'')\right] \delta(\omega - \omega' - \omega'') - \\ &\left(\alpha\gamma\mu_0/M_s\right) \iiint d\omega' d\omega'' d\omega''' \times \\ &\left[\boldsymbol{M}(\omega') \times \left[\boldsymbol{M}(\omega'') \times \boldsymbol{H}(\omega''')\right]\right] \delta(\omega - \omega' - \omega'' - \omega''') \end{aligned} \tag{1}$$

(involving Gilbert's relaxation term), where $\boldsymbol{H}(\omega)$ and $\boldsymbol{M}(\omega)$ can be conveniently written as $\boldsymbol{H} = \boldsymbol{e}_z H_0 \delta(\omega) + \boldsymbol{h}(\omega)$ and $\boldsymbol{M}(\omega) = \boldsymbol{e}_z M_s \delta(\omega) + \boldsymbol{M}(\omega)$. The linear in $\boldsymbol{h}$ solutions to (1) are

$$\begin{aligned} &M_\rho^1 = (\mu_m - 1) h_\rho - i\mu_a h_\varphi \text{ and} \\ &M_\varphi^1 = (\mu_m - 1) h_\varphi + i\mu_a h_\rho, \end{aligned} \tag{2}$$

$$\begin{aligned} &\text{where } \mu_m = 1 - \omega_M \left[\omega_0 (1 + \alpha^2) + i\alpha\omega\right] \times \\ &\left[(\omega - i\alpha\omega_0)^2 - \omega_0^2\right]^{-1}, \text{ with } \omega_0 = \gamma\mu_0 H_0, \\ &\text{and } \mu_a = \omega_M \omega \left[(\omega - i\alpha\omega_0)^2 - \omega_0^2\right]^{-1}, \text{ with} \\ &\omega_M = \gamma\mu_0 M_s. \end{aligned} \tag{3}$$

Here $\gamma = 2.8 \cdot 10^{10}$ Hz/T is the gyromagnetic ratio, M_s the saturated level of magnetization in a field $\boldsymbol{H}_0 = \boldsymbol{e}_z H_0$, and α the relaxation constant in the L-L-G equation. (In our simulations α was varied, with the most frequently adopted magnitude $\alpha = 0.1$). As can be seen from (2), the magnetization vector $\boldsymbol{M}$ acquires spatial components oriented along the ρ- and φ- directions, varying with non-zero frequencies. The variations of M_ρ and M_φ with time represent the precession motion of $\boldsymbol{M}$ around the direction of $\boldsymbol{M}_0$. The frequency dependent functions μ_m and μ_a are, respectively, the diagonal and the off-diagonal terms of the magnetic permeability tensor. For an electromagnetic wave traveling through a guiding structure of importance is the combination of the tensor components which contributes into an effective refractivity index in the *z*-direction (along with the size of the guiding channel and the relevant boundary conditions). That combination may figure in the wave equation for a specific field component as

$$\begin{aligned} &\left(\omega^2/c^2\right) \varepsilon\mu_m \times \\ &\left[1 - (\mu_a/\mu_m)^2 - \rho^{-2}\left(1 + s^2\mu_m\left(1 - (\mu_a/\mu_m)^2\right)\right) - \beta_s^2\right], \end{aligned} \tag{4}$$

where β_s denotes the propagation constant along *z* for a mode with azimuthal index *s*. Upon setting $\beta_s = 0$ and equating (4) to zero we can use it as an imitation dispersion equation and investigate for the presence of cut-off frequencies. The estimates obtainable for our parameters of the line and the materials (see Table 1; also $H_0 = 30$ kA/m and $M_s = 300$ kA/m) offer cut-offs about 0.3 GHz to 1 GHz even for the modes with $s = 0$, like E_{01}. This is in agreement with the analysis in [10] of guiding properties of a dielectric layer placed on a metal substrate. Apparently this mode plays an important part in our case, too. Assuming that waveguide modes other than the TEM may be excited in structures like our NLTL, we have to conclude that the appearing frequencies are not determined by the outer conductor's diameter but rather by the size of the $R_2 - R_1$ gap and, probably, the size of $R_2 - r_1$. The higher oscillation frequencies pertinent to cables of smaller diameter are natural within that scheme. These considerations can be checked now against measurements.

Fig. 3 shows the oscillation frequencies f measured in transmission lines NLTL1, NLTL2, and NLTL3 in dependence on the quasi-static azimuthal magnetic field H_φ. The measured $f(H_\varphi)$ dependences obtained for the NLTL1, and NLTL2 with $H_0 = 30$ kA/m can be approximated to by linear graphs (curves 1 and 2 in the Figure). The insert to Fig. 3 shows the measured $f(H_\varphi)$ dependences obtained for NLTL2 with a variety of bias fields H_0, specifically $H_0 = 30, 45, 60,$ and 75 kA/m. These can be equally represented as nearly linear laws. The measurements at NLTL3 resulted in a single point to be presented, namely an asterisk at $H_\varphi = 17.5$ kA/m, with $H_0 = 40$ kA/m. As can be seen, equal frequency values are observed in waveguides of different diameters for different magnitudes of the azimuthal field H_φ.

Shown in Fig. 4 are results of measurements in NLTL1, NLTL2, and NLTL3 where nearly equal oscillation frequencies, close to 1.7 or 1.8 GHz, were obtained for greatly differing values of H_φ, namely $H_\varphi = 64$ kA/m (with $U_0 = 252$ kV and $H_0 = 30$ kA/m), $H_\varphi = 25$ kA/m ($U_0 = 77$ kV, $H_0 = 30$ kA/m), and $H_\varphi = 17.5$ kA/m ($U_0 = 25$ kV, $H_0 = 40$ kA/m). Note that a linear extrapolation toward $H_\varphi < 10$ kA/m of the $f(H_\varphi)$ dependences measured in the NLTL1 and NLTL2 (dotted lines 1 and 2 in Fig. 3) tends to a limiting frequency about $f = 0.5$ GHz. In the authors' view, this is evidence for the existence of a cut-off frequency lying below 1 GHz, and hence for the appearance in the line of higher-order modes than the "quasi-TEM".

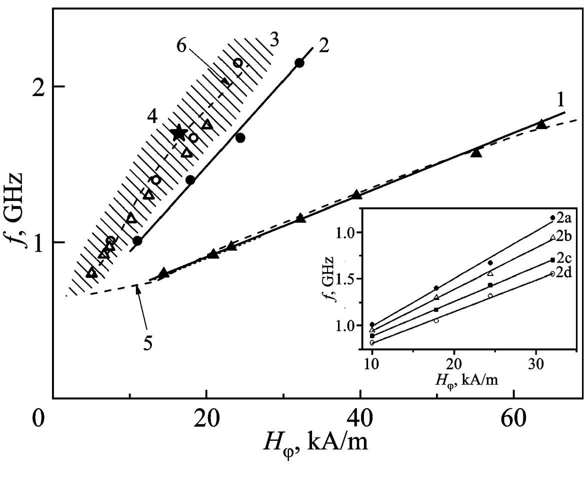

Fig. 3. Measured $f(H_\varphi)$ dependences with $H_0 = 30$ kA/m: triangles for NLTL1, (straight line); round points for NLTL2 and an asterisk for NLTL3. In the insert: NLTL2 with $H_0 = 30$, 45, 60, and 75 kA/m (from top to bottom)

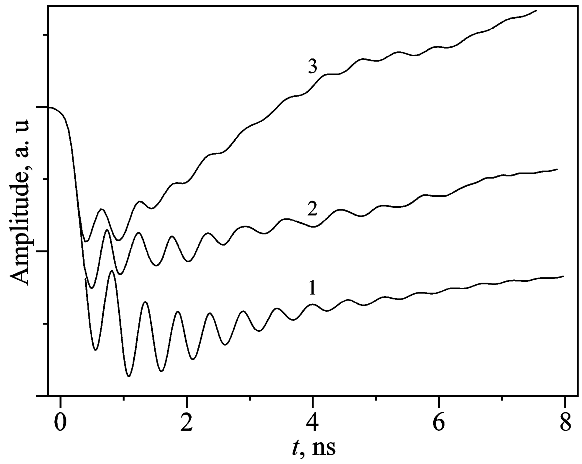

Fig. 4. Oscillation records at the output from NLTL1: curve 1 for $U_0 = 252$ kV and $H_0 = 30$ kA/m; curve 2 for $U_0 = 77$ kV and $H_0 = 30$ kA/m; curve 3 for $U_0 = 25$ kV, $H_0 = 40$ kA/m

4. Conclusions

The frequencies and amplitudes of the appearing oscillations are governed by a complex of dispersive and non-linear properties of the guiding structure. The diameters of the inner and outer coaxial conductors in the line, diameter of the ferromagnetic insert and its intrinsic linear dispersion properties determine the set of waveguide modes capable of propagating through the line. An oscillating part of the waveform may appear and get separated from the main body of the pulse if it has originated at a higher frequency than the cut-off one for a different mode than the initial TEM.

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С. Ю. Карелін, В. Г. Коренєв, В. Б. Красовицький,
О. М. Лебеденко, І. І. Магда, В. С. Мухін,
В. Г. Сініцин, М. В. Воловенко

Інститут плазмової електроніки
і нових методів прискорення,
Національний науковий центр "ХФТІ" НАН України,
вул. Академічна, 1, м. Харків, 61108, Україна

ПЕРЕТВОРЕННЯ ІМПУЛЬСНОЇ ЕНЕРГІЇ В МІКРОХВИЛІ В НЕЛІНІЙНИХ ЛІНІЯХ ПЕРЕДАЧІ

Предмет і мета роботи: Наведено експериментальні результати й дані числового моделювання стосовно ефектів збудження мікрохвиль в коаксіальних лініях передачі, в котрі подаються однополярні високовольтні електричні імпульси. Метою роботи є з'ясування відносної важливості кількох механізмів, що можуть відповідати за виникнення мікрохвилевих коливань під час проходження імпульсу крізь хвилеводну структуру.

Методи і методологія: Розглядаються дисперсійні та фільтрувальні властивості коаксіальних хвилеводів з трьома секціями, що є розташованими одна за одною вздовж осі симетрії структури. Дві ідентичні секції – на вході й на виході хвилевода – заповнені ізотропним рідким діелектриком, в той час як середня секція додатково заповнюється – або частково, або повністю – непровідним матеріалом з гіротропними властивостями. Вставлене ядро складається із набору феритових кілець, що характеризуються нелінійним відгуком на первинне високовольтне імпульсне збудження. У процессі вимірювань діаметри внутрішнього провідника та феритової вставки залишалися постійними. Діаметр зовнішнього провідника змінювався, аби проаналізувати вплив як власне цього розміру, так і ступеню заповнення перерізу феритом. Гіротропні властивості феромагнітного матеріалу реалізувалися завдяки накладанню поля магнітного зміщення від зовнішнього соленоїда. Вимірювання були проведені для різних значень імпульсної напруги в діапазоні сотень кіловольт при магнітних полях зміщення в десятки кілоампер на метр.

Результати: В наших експериментах, як і в роботах інших авторів, спостерігалося, що однополярний імпульс, що заходить в лінію із радіально однорідної передньої секції, далі призводить до виникнення квазімонохроматичних коливань напруги. Вони виникають, як тільки імпульс пройде достатню дистанцію в радіально неоднорідній частині хвилевода. Такі осциляції можуть включати невелику кількість квазіперіодів, тобто мати значну ширину відповідної спектральної лінії. Шляхом належного вибору геометричних параметрів хвилеводної структури та характеристик первинного імпульсу можливо одержувати на виході коливання з частотою у декілька гігагерц і субгігаватним рівнем імпульсної потужності.

Висновки: Частоти й амплітуди осциляцій, що виникають, а також їх спектральні ширини обумовлені комплексом дисперсійних і нелінійних властивостей хвилеводної структури. Набір хвилеводних мод, що можуть поширюватися в лінії, залежить від діаметрів внутрішнього й зовнішнього провідників коаксіальної лінії і діаметра феромагнітного включення з його власними дисперсійними властивостями. Осциляторна частина форми імпульсу може виникати й відокремлюватися від тіла імпульсу, якщо вона народжується на частоті, що є вищою за частоту відсічки для іншої моди, ніж первинна *TEM*.

Ключові слова: однополярний імпульс, коаксіальна лінія передачі, мікрохвилеві коливання, закони дисперсії, хвилеводні моди

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