QUASI-HARMONIC OSCILLATIONS IN A NONLINEAR TRANSMISSION LINE, RESULTING FROM CHERENKOV SYNCHRONISM

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Experimental data and results of numerical modeling are presented, concerning excitation of microwave oscillations by a wave of pulsed 'dc' current (eventually, a shock wave) traveling through a radially non-uniform coaxial guiding structure. Similar experiments with 'standard' structures that involve a nonlinear dielectric insert (ferrite) in the coax and another dielectric, characterized by a smaller dielectric constant, result in appearance of a short radio-frequency pulse, in the form of decaying sinusoidal voltage at the line's output. The decay is shown to be associated with a lack of velocity synchronism between the principal 'quasi-TEM' wave mode in the system and the slow E-mode excited by the electromagnetic shock. Numerical experiments within 3-D models have demonstrated possibilities for obtaining radio pulses of various lengths, involving oscillations of a stable frequency and nearly constant amplitude – provided that Cherenkov-type synchronism were satisfied, owing to slowing down of the faster 'quasi-TEM' mode. To cut its speed down two methods can be suggested, *(i)* using a dielectric material with a high value of the dielectric permittivity, and (*ii)* introducing a periodic slow-wave structure whose period would be smaller than the wavelength of the oscillations considered.

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INTRODUCTION

The recent decades have been marked by an ever increasing interest toward possibilities for directly converting the energy of a pulsed 'dc' (unidirectional) electric current into the energy of microwave oscillations. This kind of conversion can be effectuated when the pulsed current is fed into and travels through a guiding structure of dual connectivity, characterized by a nonlinear response function [1, 2]. For instance, a current pulse passing within a coaxial transmission line that involves a ferromagnetic kernel with non-linear properties (NLTL) can transform into an electromagnetic shock wave (EMSW) [3 - 5] which, in turn, may give rise to quasi-monochromatic UHF oscillations [5 - 10]. The effect has been noted to open new vistas for high power electronics [2, 6 - 9, 11]. However, many of the experiments with nonlinear coaxial structures, aimed at studying this kind of microwave generation, have also revealed substantial practical drawbacks. With the video pulse traveling along the NLTL, the amplitude of the UHF oscillations drops down rather rapidly, the number of peaks in the train being often limited to a figure less than ten, and the resultant frequency spectrum appearing rather wide, specifically 30% or more. As stressed in papers [10, 15], these drawbacks are specific for coaxial waveguides that contain layered material inclusions about the inner conductor. The stability of microwave generation in such structures is deteriorated because of absence of a velocity synchronism between the wave modes excited by the EMSW in the radially nonuniform coaxial guide.

Meanwhile, the ability to obtain long lasting radio pulses in a non-uniformly filled NLTL was reported back in 1990s (e.g., [1, 16]). The desired speed synchronism was reached in lumped-parameter NLTLs built around discrete LC-cells. The character of the frequency dispersion required for providing the synchronism of wave modes in the system could be adjusted by properly connecting the cells with properly selected parameters. The microwave pulse duration was determined by the quantity of cells involved. The intrinsic deficiency of that technology was the low attainable power level of the microwave oscillations, limited by the electric strength of the discrete components.

The present paper is aimed at combining the advantages offered by both of the approaches discussed, with application to a coaxial line in mind. We expect for realization of the considerable power levels allowable in guiding structures with continuous smooth boundaries, and for greater lengths of the radio pulses, owing to the velocity synchronism between the existing wave modes. The mode synchronism within a radially non-uniform coaxial guide can be implemented through slowing down one of the participant modes. Two approaches to organizing the slow-down are considered, namely

(i) introduction in the guiding line of a material with a high value of its dielectric constant, and

(ii) use of a spatially periodic structure whose period would be smaller than the expected radio wavelength. The quasi-monochromatic microwave oscillations generated in such transmission lines are analyzed numerically, within appropriate 3-D models.

1. OSCILLATIONS IN A NLTL IN THE ABSCENCE OF MODE SYNCHRONISM

The excitation of decaying microwave oscillations by a passing shock wave has been associated in quite a number of papers with the magnetization vector precession in the ferrimagnet ([5, 8, 11, 13], etc.). When suggesting interpretation to experimental results, the writers resort to a simplified description of magnetostatic waves in the guiding structure, based on a joint application of the Landau – Lifschitz equation [13] and the telegraphers' equation which is just a 1-D version of the Maxwell equation set, reduced to only two field components. Because of this simplification the analysis is lacking account of the structure's boundaries and proper conditions thereat, hence all dispersion-dependent effects are derived solely from dispersive properties of the gyromagnetic medium.

An alternative view on the nature of microwave oscillations in the NLPL was presented in paper [10], whose principal point was analysis of electromagnetic propagation through a guiding structure with a radially non-uniform filling within the bounded internal domain. The numerical simulations based on a 3-D model of the radially non-uniform coaxial guide included solution of *a full set of Maxwell equations*, with *proper conditions* at all metal or dielectric boundaries, plus the Landau-Lifschitz equation playing the part of a material relation and representing the dynamic behavior of the magnetization vector [14, 15]. (To simplify and speed up the computations, the writer [15] limited the analysis to the case of azimuthally uniform field distributions, $\partial/\partial\varphi=0$). A schematic of the coaxial guide's model with a ferrite insert about the inner conductor is given in Fig. 1.

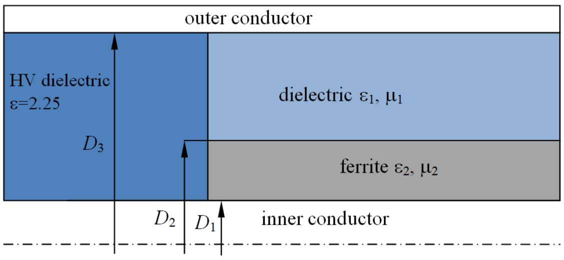


Fig. 1. Cross-section of a non-uniform coaxial waveguide: the dot-and-dash line represent the guide's central axis; the diameters are D_1=20 mm, D_2=32 mm, and D_3=52 mm. The permittivity ε_1 is a varied parameter (equal to 2.25 in [7, 10]); μ_1 = 1; ε_2 =16, μ_2 is a varied parameter (assuming values about 4 or 5 in a saturated ferrite)

The left-hand part of the structure is the input coaxial feedline, uniformly filled with a dielectric material. Another dielectric and the ferrite core occupy the right-hand part. The writers obtained data on the main parameters of the microwave signal at the output, such as amplitude, dominant frequency and spectral width, and analyzed their relation to the guide's geometry and volume parameters of the filling media (Fig. 2).

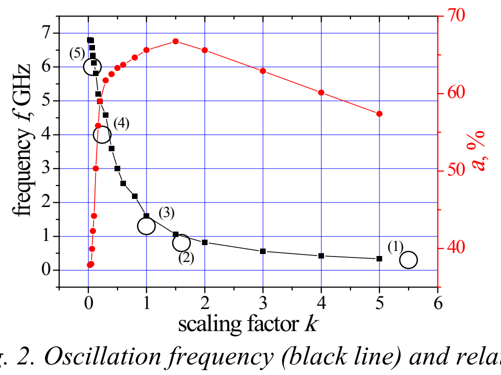


Fig. 2. Oscillation frequency (black line) and relative amplitude (red line) as functions of the scaling factor k (the case $D_3/D_2/D_1$=52/32/20 mm relates to k=1). White circles mark the results of referenced writers, 1 – [9]; 2 – [6]; 3 – [7]; 4 – [11]; 5 – [5]

The calculated parameters demonstrated a fair agreement with the measurements reported by a number of writers, like [5, 7, 11, 12], the discrepancy never exceeding 20%. Fig. 2 shows the oscillation frequencies and relative amplitudes $A=U/U_0$ (where U_0 is the voltage amplitude of the primary pulse) as functions of a scaling factor k. This latter suggests a proportional variation of the coax outer diameter on the one hand and pulsed voltage magnitude at the input on the other, $D'_i=D_i/k$ and $U'=U/k$. If this proportionality is held, the magnitude of the azimuthal magnetic field H_φ remains unchanged. (The H_φ field component is induced by the pulsed current in the line and acts to re-magnetize the initially magnetized ferrite core). As a result, the data measured in a variety of experiments can be rather easily compared (see the author identification in Fig. 2). The value k=1 corresponds to $D_3/D_2/D_1$=52 /32 /20 mm.

In paper [10] the 3-D simulation procedure was applied to three models of the coaxial guiding system of Fig. 1, characterized by the same general geometry and size but differing in the electromagnetic response functions of the layered inner media. Three types of radial non-uniformity in the filling of the line's right-hand part were considered, specifically case (*i*) where two layers of dielectric materials were characterized by unequal magnitudes ε_1, μ_1 and ε_2, μ_2 of constant, scalar electric and magnetic permittivities; case (*ii*) with two layers where parameters ε_1 and μ_1 of the outer layer were constant scalar values again, while in the inner layer ε_2 remained constant but the scalar magnetic permeability μ_2 was dependent on the azimuthally directed magnetic field induced by the pulsed current, $\mu_2=\mu_2(H_\varphi)$, and case (*iii*) where the outer layer contained a dielectric material with constant scalar magnitudes ε_1 and μ_1, while the inner one was a gyrotropic nonlinear medium with a constant ε_2 and a field-dependent permeability tensor $\boldsymbol{\mu}_2=\boldsymbol{\mu}_2(\boldsymbol{H})$. (So, the magnetic induction is $\boldsymbol{B}=\mu_0(\boldsymbol{H}+\boldsymbol{M})=\mu_0\boldsymbol{\mu}_2(\boldsymbol{H})\boldsymbol{H}$, where μ_0 is the permeability of a vacuum and the magnetization vector $\boldsymbol{M}$ is governed by the Landau-Lifschitz equation).

In all three cases the system produced decaying microwave oscillations, however different in intensity and spectral content. In case *(i)* the oscillations were only observable when the current pulse initially injected in the structure was characterized by a sufficiently short front edge (about 0.4 ns). Also, the oscillations were of low intensity (relative amplitude $A\approx0.2$). The frequency was governed by transverse dimensions of the guiding structure and electric parameters of the two dielectric layers. Case *(ii)* was characterized by sharpening of the front edge in the course of pulse propagation, *i.e.* reduction in the pulse's rise time because of non-linear magnetic response (field-dependent permeability μ_2). The microwave oscillations appeared when the pulsed waveform acquired a sufficiently sharp front edge. The estimated amplitude and frequency differed but slightly from the respective magnitudes of case *(i)*. Finally, the amplitude of the microwave oscillations excited was much higher when the medium was gyrotropic and nonlinear at a time (case *(iii)*). The oscillation frequency varied noticeably in dependence on the geometry and structure of the guide, physical parameters of its filling media, and magnitudes of the magnetic field components H_z and H_φ (axial and azimuthal, respectively). Both the experimental data and results of simulation provide definite evidence for the oscillation frequency dependence upon the cross-section size of the line and parameters of its non-uniform (layered) filling. Meanwhile, their relation to the magnetization vector dynamics $\boldsymbol{M}$ is not straightforward.

So, the excitation of radio frequency oscillations in the NLTL can be interpreted as follows. A current pulse passing through the NLTL transforms to an electromagnetic shock wave, i.e. a set of frequency components propagating as TEM modes and eventually giving rise to the lowest order dispersive mode ('quasi-*TEM*') and higher-order spatial harmonics/waveguide modes. The spatial harmonics of greater interest are those which are formed in the inner layer of the filling material. Depending on the layer parameters and size, these may behave as surface *E*-waves concentrated within the ferrite, closer to its boundary. The principal characteristics like frequency and propagation velocity are dependent on the transverse dimensions of the guide and its filling, as well as on the ε and μ in the inner layer. Meanwhile, the quasi-*TEM* mode exists in between the guide's conductive boundaries (taking after the 'pure' *TEM*), and its propagation velocity is determined by the effective magnitudes of ε and μ from the relevant part of the radially non-uniform guide. The appearance of intense microwave oscillations is associated with interaction of these concurrent wave modes, of which the quasi-*TEM* is the faster partner and the *E*-mode the slower one. Analysis of the simulated spatial distributions of the *E* and *H* wave fields and frequencies of the microwave oscillations excited allows us to suggest a E_{0n} mode (or a structurally similar hybrid *EH* wave) as the probable spatial harmonic-participant in the given waveguide geometry. The attenuation demonstrated by the microwave oscillations over the pulse duration is due to a lack of speed synchronism between the concurrent *TEM*- and *E*-modes. The synchronism condition can be written as a Cherenkov-type resonance condition at the circular frequency ω,

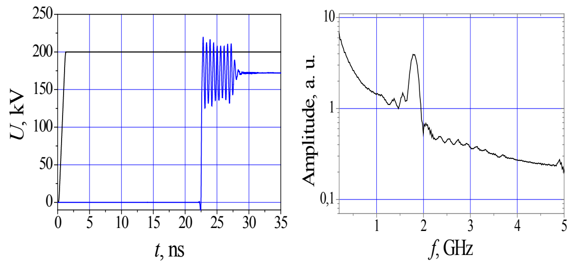
$$v_{phE}=\omega/k_z<v_{TEM}\,, \qquad (1)$$

where k_z is the longitudinal wavenumber of the spatial harmonic, while v_{phE} and v_{TEM} are, respectively, the harmonic's phase velocity and the propagation velocity of the quasi-*TEM* wave packet. (The group velocity of this latter is obviously close to phase velocities of many of its constituent frequency components, in view of the weak dispersion of the quasi-*TEM* mode). Note that under typical conditions of real, as well as numerical experiments the quasi-*TEM* mode always happened to be a faster wave in the ferrite layer than the *E*-mode, such that no stable pumping into the microwave oscillations was possible and the oscillations attenuated soon.

2. MICROWAVE OSCILLATIONS IN THE COAXIAL NLTL UNDER THE SYNCHRONOUS CONDITIONS

2.1. COAXIAL WAVEGUIDE WITH A UNIFORM DIELECTRIC IN THE OUTER LAYER (CHERENKOV-TYPE EFFECT)

To create quasi-continuous microwave oscillations in a radially non-uniform guiding structure, it is necessary to organize and support conditions for energy transfer from a pumping source (*e.g.*, a quasi-*TEM* wave mode) to a concurrent spatial harmonic in the outer layer. In a coax line of standard configuration (see Fig. 1) the speed synchronism condition (1) can be implemented through increasing the refractive index (*i.e.*, dielectric constant) of the material in the outer layer, achieving specifically $\varepsilon_1>\varepsilon_2\mu_2/\mu_1$. The group velocity of the shock wave traveling through the inner (ferromagnetic) layer in many cases can be estimated as $v_g\equiv v_s$=(0.12...0.14) *c*. This value corresponds to ε_2=16 and an effective magnetic permeability μ_2, controlled by the magnetic fields H_z and H_φ and ranging from 3 to 5. To ensure the required speed synchronism, we have taken a dielectric constant of the outer layer in the guide ε_1=80, thus reducing the phase velocity of the concurrent wave to v_{ph}=0.11 *c*, *i.e.* slightly below the group velocity of the shock wave. Other parameters of the numerical experiment were M_s=300 kA/m (saturated magnetization level of the ferrite); H_{z0}=30 kA/m (d.c. magnetic bias field), and α=0.1 (relaxation coefficient in the Landau-Lifschitz-Gilbert equation). The coaxial line at the system's input was fed with a voltage pulse of rectangular waveform, semi-infinite duration, 200 kV amplitude and front edge length of 2 ns. The resultant pulse at the output of the ferrite-filled middle section (800 mm in length) demonstrated a short front edge, about 0.4 ns, and kind of modulation in the form of a dozen or so nearly sinusoidal oscillations of roughly constant amplitude $U_{\sim}\approx$50 kV (Fig. 3,a). The frequency spectrum at the output (Fig. 3,b) was characterized by a pronounced peak at *f* = 1.8 GHz and a 190 MHz half-height width. Note the conspicuous absence in the spectrum of other bright frequency lines, which may suggest a possibility to use the synchronism condition for effectively selecting desired frequency components from the spectral content of the shock. At the same time, it shows the wave propagation conditions within the NLTL to be only slightly non-linear at the stage of saturated magnetization.



a *b*

Fig. 3. Pulsed waveform at the line output (a) and its spectrum (b), in the nonlinear line of length L=800 mm

In nonlinear sections of greater lengths the quantity of appearing oscillation quasi-periods increased proportionally, while their amplitudes and frequencies remained the same (Fig. 4). This confirms the ability of forming microwave pulses of any desired lengths. By increasing the dielectric constant ε_1 of the medium in the outer layer we could obtain oscillations of higher amplitude and duration, however of lower frequency (Fig. 5). By the end of the pulse train a short portion with a falling down amplitude can be observed. A similar effect was described in paper [16] and interpreted as being due to a strong local dispersion ($v_g<<v_{ph}$) in the vicinity of the resonance.

Meanwhile, as soon as the dielectric constant were taken at a level lower than $\varepsilon_1\approx$40, the condition (1) could not be satisfied and the stable-amplitude excitation stopped.

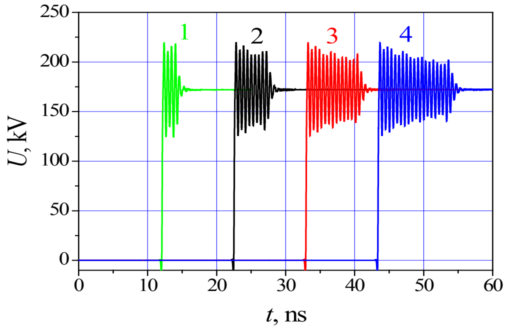


Fig. 4. Pulsed waveforms at the output of NLTLs of different lengths L: 1 – L=400 mm; 2 – L=800 mm; 3 – L=1200 mm, and 4 – L=1600 mm

This is evidence for reality of the Cherenkov-type mechanism for exciting the concurrent wave. Also, the oscillations in a system with a sufficiently low ε_1 appeared as a decaying sinusoidal waveform, accompanied by higher–order multiples of the fundamental frequency (*e.g.*, [7, 8]).

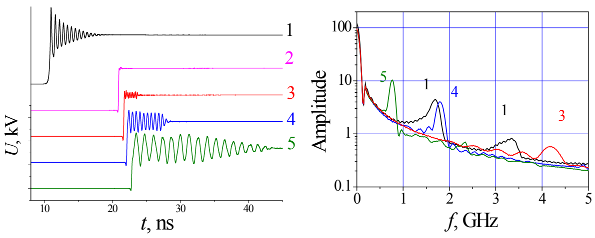


Fig. 5. Microwave pulsed waveforms and spectra as obtained in a NLTL of length L=800 mm, with different values of ε_1: 1 – ε_1=2.25; 2 – ε_1=-40; 3 – ε_1=60; 4 – ε_1=80;, 5 – ε_1=160

Some of specific features of the excitation process can be understood from the spatial structure of the wave fields in the guide. By way of example, consider the longitudinal profile of the H_φ component for the case of high ε_1 magnitudes (Fig. 6). As can be seen, the guiding structure supports a shock wave, composed of *TEM*-type partial modes. A *TEM*-mode, while being present in both material layers of the waveguide, is characterized by different velocities in each of them and, accordingly, different wavefront profiles. Within the inner layer that velocity is $v_{TEM}=v_s$, whereas in the outer one it is governed by the ε_1, μ_1 parameters of the dielectric. The wavefront existing in the outer layer may acquire the characteristic conical shape inclined at an angle α with respect to the normal to the layer-layer interface (see Fig. 6). Also, the wave undergoes multiple reflections between the inner metal surface of the outer conductor and the dielectric – ferrite interface separating materials with greatly different electric parameters (ε in particular). For a certain value of the incidence angle α that interface may become a reflecting boundary. The oscillation period obtainable from the geometry is

$$T = \frac{4\Delta R}{v_{TEM}\, tg\alpha}, \qquad (2)$$

where the apex angle α of the cone follows from $sin\alpha=v_{ph}/v_{TEM}$ and $\Delta R=(D_3-D_2)/2$; v_{ph} is the phase velocity in the dielectric layer, specifically $v_{ph}=c/(\varepsilon_1)^{1/2}$, and v_{TEM} the phase (and group) velocity of *TEM* modes in the ferrite, $v_{TEM}=c/(\varepsilon_2\mu_2)^{1/2}$. Finally, we have

$$T = \frac{4\Delta R\sqrt{v_{ph}^2 - v_{TEM}^2}}{v_{ph}v_{TEM}}. \qquad (3)$$

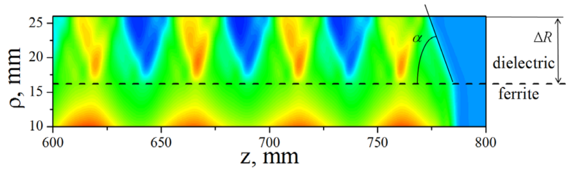


Fig. 6. The azimuthal magnetic field component's distribution along the z-axis of the nonuniform NLTL (ε_1=160)

Fig. 7 shows the spatial period of oscillations in dependence on the dielectric constant ε_1 (with the magnetic permeability in the ferrite taken as μ_2=3.5). The calculations after Eq. (3) are in good agreement with the results of a pertinent numerical experiment (see Fig. 5).

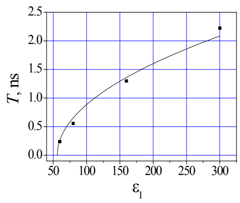


Fig. 7. Oscillation period in dependence on the dielectric constant ε_1 as calculated after Eq. (3) (solid line) and measured in the numerical experiment (dots)

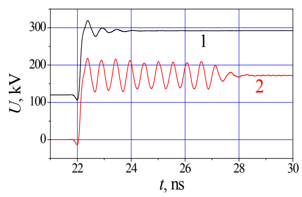


Fig. 8. Oscillations in a radially nonuniform coax trans-mission line employing water as a dielectric medium: curve 1 reflects effects of dispersion in ε_1; curve 2 presents a calculation without account of dispersion

2.2. COAXIAL LINE WITH A SLOW-WAVE STRUCTURE IN THE OUTER DIELECTRIC LAYER (SMITH-PURCELL EFFECT)

As discussed in the previous Section, the stable generation condition $v_{TEM}<v_{ph}$ can be reached by employing in the outer layer a dielectric material with an extremely high dielectric constant, $\varepsilon_1 >> \varepsilon_2$. Preferab-ly, the material should demonstrate a linear electric response and lack of dispersion in the vicinity of the expected oscillation frequency. Judging by the magnitude of ε alone, a suitable material for the outer filling layer could be distilled water with its value of ε = 78.4. Unfortunately, it happens to be a rather dispersive medium, and model calculations show the dispersive effects to practically suppress the anticipated microwave oscillations, see Fig. 8. (The estimates were obtained with the use of Debye's dispersion model for water [17], with the parameters ε_0 = 78.4, ε_∞= 3.1, and $t_0 = 8.27\cdot10^{12}$ s).

For a number of reasons, the use of dielectric materials with high values of ε in the high frequency range is somewhat inadmissible. Therefore, we simulated application of an alternative technique for slowing the concurrent wave down, namely introduction in the guide's outer region of a periodic structure. The model structure shown in Fig. 9 consisted of a set of identical metal disks placed around the inner ferromagnetic layer to form an array of narrow cylindrical cavities. The dielectric filling the outer layer (with the integrated periodic structure) was characterized by the same dielectric constant as the ferrite, i.e. $\varepsilon_1=\varepsilon_2=16$.

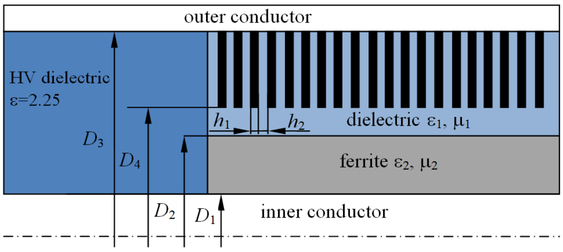
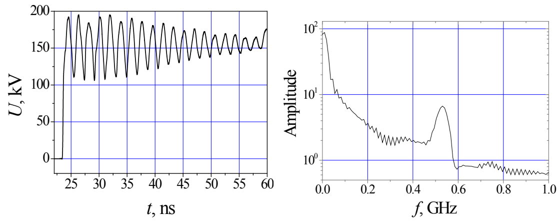


Fig. 9. A NLTL incorporating a periodic slow-down structure: D_1=20 mm, D_2=32 mm, D_3=102 mm, D_4=46 mm, and $h_1=h_2$=3 mm



a *b*

Fig. 10. Pulsed waveform (a) and its spectrum (b) at the output of a NLTL with the periodic structure of Fig. 9: Line length L=800 mm

The numerical results relative the periodic structure of Fig. 10 demonstrate the possibility of obtaining microwave oscillations of stable frequency and amplitude. (A small section of a descending amplitude, owing to localized dispersion effects [15], may be observable at the end of the pulse train). By means of varying the spatial period h_1+h_2 of the periodic structure, it proved possible to make adjustable the frequency of the oscillations excited. The calculated dispersion curve of a NLTL incorporating a periodic structure is given in Fig. 11. For the case of a structure of the dimensions given in Fig. 9, the highest frequency of the microwave oscillations is ~0.6 GHz. Taking into account the number of cavities per a spatial period of the oscillations (n=18), one may conclude that f_{MAX} corresponds to the operating mode $2\pi/n=\pi/9$ belonging to the low-order pass band of the slow wave structure selected.

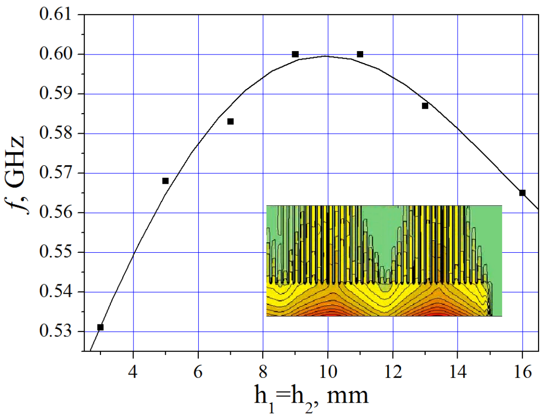


Fig. 11. Dispersion curve within the lowest order pass band of a radially nonuniform coaxial line with a cylindrically symmetric periodic structure (the small squares represent raw calculated results and the solid curve has been interpolated)

CONCLUSIONS

An efficient method of exciting microwave oscillations of stable amplitude in a coaxial nonlinear transmission line has been suggested, making essential use of properties of a speed-synchronous concurrent wave mode. The duration of the microwave pulse excited is limited only by the mechanical length of the transmission line. It has been shown that the underlying physics of the wave excitation is the Cherenkov effect or its variant forms. The driver (an electromagnetic shock wave) moves through the structure at a higher velocity than the speed of light in the ferrite medium. Apart from the use of dielectric materials with extremely high values of the dielectric constant, the slow-down effect can be effectively achieved by employing a spatially periodic structure.

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КВАЗИМОНОХРОМАТИЧЕСКИЕ КОЛЕБАНИЯ В НЕЛИНЕЙНОЙ ЛИНИИ ПЕРЕДАЧИ В УСЛОВИЯХ ЧЕРЕНКОВСКОГО СИНХРОНИЗМА

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Экспериментально и методом численного моделирования исследовано возбуждение СВЧ-осцилляций волной импульсного тока в радиально-неоднородном коаксиальном волноводе. В системах «стандартного» вида, включающих нелинейный диэлектрик (феррит) и диэлектрик с малой диэлектрической проницаемостью, на выходе формируется короткий радиоимпульс, имеющий форму затухающей синусоиды. Показано, что затухание обусловлено отсутствием скоростного синхронизма между основной квази-*ТЕМ* и медленной *Е*-модой, которые возбуждаются ударной волной. Численные эксперименты в 3-D модели нелинейной линии продемонстрировали возможность получения радиоимпульсов с однородными по амплитуде и стабильными по частоте колебаниями различной длительности при условии выполнения черенковского синхронизма за счет замедления быстрой квази-*ТЕМ*-волны. Рассмотрены два метода замедления: использование диэлектрика с большой диэлектрической проницаемостью и введение в систему периодической структуры с периодом, меньшим длины волны возбуждаемых осцилляций.

КВАЗІМОНОХРОМАТИЧНІ КОЛИВАННЯ В НЕЛІНІЙНІЙ ПЕРЕДАВАЛЬНІЙ ЛІНІЇ В УМОВАХ ЧЕРЕНКОВСЬКОГО СИНХРОНІЗМУ

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Експериментально, а також шляхом чисельного моделювання досліджено збудження НВЧ-осциляцій хвилею імпульсного струму в радіально-неоднорідному коаксіальному хвилеводі. У системах «стандартного» різновиду, що містять нелінійний діелектрик (ферит) та діелектрик з малим значенням діелектричної проникності, на виході формується короткий радіочастотний імпульс у формі синусоїди, що загасає. Показано, що таке згасання пов'язане з відсутністю швидкісного синхронізму між основною квазі-*ТЕМ* та повільною *Е*-модами, котрі збуджуються ударною хвилею. Чисельні експерименти в 3-D моделі нелінійної лінії продемонстрували можливість отримання радіоімпульсів із сталими за амплітудою та стабільними за частотою коливаннями різної тривалості – за умови виконання черенковського синхронізму внаслідок уповільнення більш швидкої квазі-*ТЕМ*-моди. Розглянуто два методи уповільнення, а саме використання діелектрика із великим значенням діелектричної сталої та введення в систему періодичної структури з меншим періодом порівняно із довжиною хвилі осциляцій, що збуджуються.