https://doi.org/10.46813/2022-139-082

VIDEO PULSE CONVERSION INTO A RADIO FREQUENCY PULSED WAVEFORM OF COMPLEX COMPOSITION

S.Y. Karelin, V.B. Krasovitsky, A.N. Lebedenko, I.I. Magda, V.S. Mukhin, V.G. Sinitsin, N.V. Volovenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: magda@kipt.kharkov.ua

The paper is a feasibility study for a nonlinear wave guiding structure, based on a coaxial line with a magnetized ferrite core inside, to form broadband pulsed signals with a controllable radio-frequency spectrum. A set of two serially connected coaxial guides of different diameters of order 10^1 mm is analyzed, where the ferromagnetic is subjected to an axial magnetizing field and the azimuthal field belonging to the initially incident video pulse. Possibilities have been demonstrated for a targeted alteration, over a broad band like $\Delta f/f$ =0.25…0.55, of the waveform and gigahertz-range frequency spectrum of the output signal. In case of employing a feeding high-voltage signal of relatively short duration it may become possible to implement the Peak Power Amplification operating mode.

PACS: 41.20 Gz; 41.20 Jb

INTRODUCTION

An impressive number of papers are known, e.g. [1-6], which present theoretical or experimental results on conversion of a high-voltage video pulse of short duration, like 5 to 20 ns, into a signal containing a quasi-monochromatic, damped radio frequency component. The conversion occurs in wave guiding structures with an essentially nonlinear electromagnetic (EM) response and, for the most part, of cylindrical coaxial geometry. In experiments with ferrite-filled coaxial lines the incoming $1/f$-type spectrum gets complemented by a 'detached' component f_{osc} which, depending on the structural and EM parameters of the guide, may lie in a range like (0.5…3.5) GHz, having a spectral width $\Delta f/f_{osc}$ ~ 0.2…0.3. The new frequencies in the spectrum are due to electromagnetic nonlinearity of the ferrite core, whereas formation of the quasi-monochro-matic oscillations at $f \approx f_{osc}$ is controlled by the dispersion law of the guiding structure (at first, that of the linear approximation). The latter combines the waveguide mode dispersion, characteristic of the structure's topology and size, and the dispersion inherent in the magnetized ferrite.

As was noted in paper [6], the period of the oscillations excited is roughly proportional to transverse dimensions of the nonlinear line (NLTL), which suggests a decisive role of wave guiding effects. As long as the initial video pulse has not noticeably changed its waveform, we can assume all the frequency components from its spectrum to travel at the same velocity $v_{phase}=v_{group}$. This is evidence for their compliance to a TEM-like linear dispersion law. To drop off from the primary wave packet, a 'detached' frequency component should convert to a different wave mode, hence acquire a different phase speed.

Then, it can be expected that by means of a targeted change in the magnetic state and geometry of the ferrite-containing line one might obtain possibilities for controlling the line's impedance and refractive index, and hence the waveform and spectral content of the radio pulse at the output.

1. PROBLEM FORMULATION

By applying a pulsed electric current to a set of serially connected NLTLs of different radial sizes, subjected to differing external magnetic bias fields, one might be able to create output signals of complex temporal behavior. That would be prescribed by dispersion properties of the guiding structure's sub-units and the total dispersion law. It seems quite reasonable to talk of a potential for controlling the characteristics of the complex high-frequency signal at the output by means of varying the magnetic state of every sub-unit of the NLTL, as well as through organizing a proper structural non-uniformity, both in the transverse and longitudinal direction.

We will present results concerning a relatively simple structure involving two serially connected NLTLs of different dimensions. The numerical analysis and experimental work have been aimed at studying transformation of a video pulse into a high-frequency signal of complex waveform and a much broader frequency spectrum than such achievable with a single NLTL.

The number of HF oscillations obtainable in the structure (and, hence, the duration of the resulting radio signal) is determined by the initial pulse duration τ_P and, in addition, may be dependent on some of the two parameters, either the decay time τ_D of oscillations, or travel time through the NLTL, τ_L. In the case of a video pulse of sufficiently large duration, like the rather standard τ_P = 10…20 ns, the inequality holds $\tau_P > \tau_D \approx \tau_L$. So, by using several NLTLs differing in the parameters τ_D or τ_L, one might obtain a complex pulsed waveform at the output, involving high frequency components that relate to each of the constituent NLTLs.

Of certain interest is the task of launching the so called peak power amplifier (PPA) regimen [7], where the NLTL is operated in such a way as to form solitary output video pulses of very short duration with, accordingly, a spectrum of maximum possible width. To that end, it is necessary that the pulse duration τ_P equaled about 2 or 3 temporal periods of the oscillations expected to be excited. Then the NLTL supports a virtually solitary pulse of peak magnitude reaching a 30 to 50 per cent greater height than the pulsed amplitude at the input. In order to further increase the peak power, several cascaded segments could be used, each involving coaxial lines and ferrite cores of two or three times smaller diameters than the preceding segment [8].

1.1. MODELING

We have conducted a series of numerical experiments corroborating the feasibility of the desired time- and frequency-domain transformations of a unipolar pulsed waveform. The experimentation proceeded from the earlier described NLTL model [6] where all structural and EM parameters were identical to their real-life counterparts. Thus, the coaxial line (in what follows, designated as NLTL1) consisted of electrodes of diameters D_1 = 20 mm and D_2 = 52 mm, and included ferrite rings with d_1 = 20 mm and d_2 = 32 mm (internal and external diameters, respectively). Both in the numerical and real-life experiments the ferromagnetic material of grade VNP-200 was used, known to have a relative dielectric permittivity ε = 16 and saturated magnetization $M_s \approx 340$ kA/m. The calculations performed in an adapted version of the FDTD software (see paper [9]) have shown that a unipolar electric current pulse of initial duration 1.2 ns (at a half-height level) can give rise to a signal similar to a PPA output [7], specifically, a high-peaked first half-period of voltage oscillations, followed by a several times lower second peak, with a depression in between (Fig. 1). A pulsed waveform like that could be shaped in a NLTL 350 mm in length.

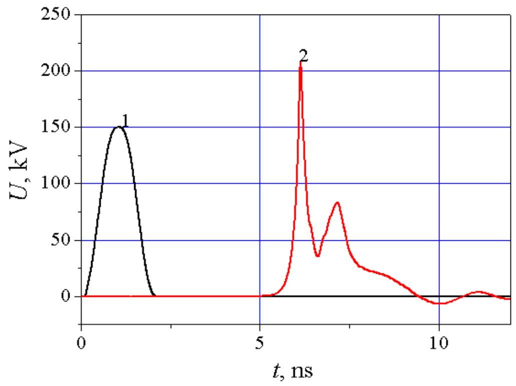

Fig. 1. Numerically simulated pulsed waveforms: 1 – incoming pulse; 2 – pulse at the NLTL1 output

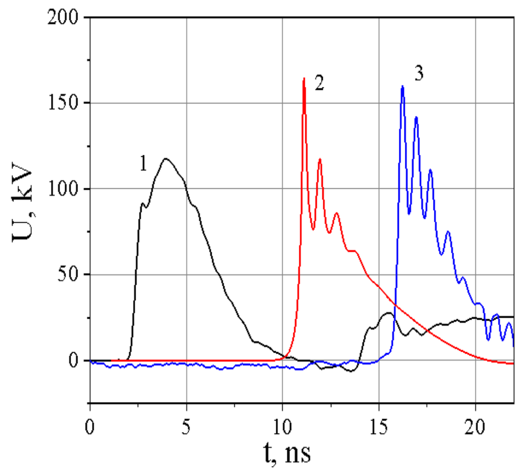

Fig. 2. Voltage pulse forms: 1 – real-life input; 2 – calculated at the NLTL1 output; 3 – measured at the NLTL1 output

Unfortunately, we were unable, for technical reasons, to have shaped a real-life initial pulse of a duration as short as 1.2 ns. Therefore, our further numerical work was performed with pulses of an initial duration about 4 ns (Fig. 2). The numerical and the real-life experiment with such a pulse both showed 3 to 5 oscillation periods, rather than a single peak at the line's output, with a modest depression between the first and the second peak. Still, the first peak happened to be 30 to 40 per cent higher than the incoming pulse. Once again, the calculation suggested an optimum length for the NLTL, like 300 to 500 mm, and an optimized value for the magnetizing field strength, H_0 = 5…20 kA/m (Fig. 3). Note the 'optimum' length of the NLTL to be higher for greater magnitudes of H_0.

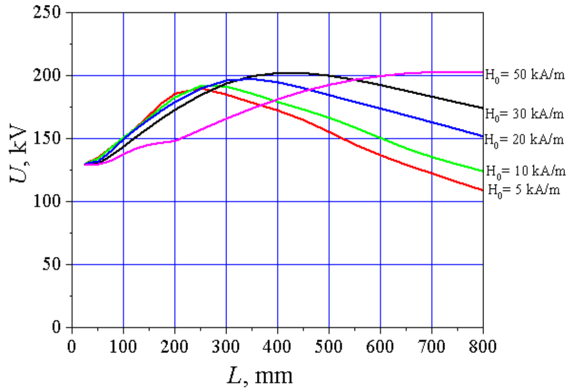

Fig. 3. Calculated maximum voltages at the NLTL1 output versus *line length, for a variety of magnetization field magnitudes H_0*

Improved conditions for transforming the incoming pulse into a signal that could be regarded as a PPA product were provided in the numerical experiments that involved a tandem of NLTLs. The first of these, NLTL1, was operated under the conditions just described as optimum for a single-segment line. The other one, representing segment 2 of the structure (hence, designated NLTL2), involved electrodes of diameters D_1 = 12 mm and D_2 = 26 mm, and ferrite rings of d_1 = 12 mm and d_2 = 20 mm. These diameters are listed in Table together with lengths and length variation ranges of the two NLTL segments.

Size parameters of the NLTL1 and NLTL2 coax lines

Coaxial line	D_1, mm	D_2, mm	d_1, mm	d_2, mm	L, mm
NLTL1	20	50	20	32	350
NLTL2	12	26	12	20	30…500

For a structure consisting of NLTL segments with apparently different impedances, it would be natural to expect a greater waveform intricacy at the output. Indeed, while the waveforms at the output of a solitary segment (NLTL1 in Fig. 3), all were of a bell-like shape, the other segment demonstrated a series of voltage peaks for every particular magnitude of the magnetizing field H_0 (Fig. 4).

Taken individually, only the first of these peaks (in one particular sequence) could be regarded as a PPA product, provided that its amplitude at the output were higher than the peak value at the input. To filter the amplified peak out, it is desirable to implement segment

2 of the NLTL as a physically short line, about 50 or 150 mm in length.

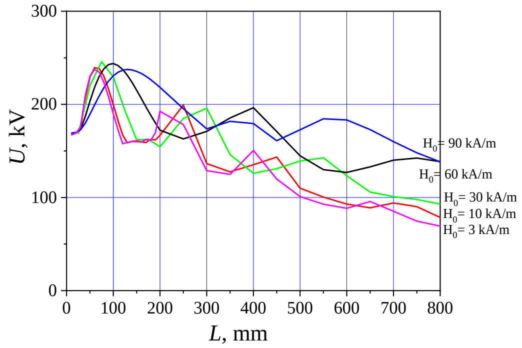

Fig. 4. Calculated maximum voltage magnitudes at the output of NLTL2 as functions of the line length L, for a variety of magnetization field magnitudes H_0

The dynamics of peaked waveform formation in the bi-segmented ferrite-filled coaxial line can be followed in Figs. 5 and 6.

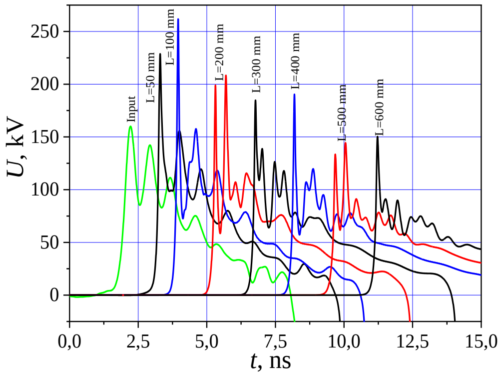

Fig. 5. Calculated variations in pulsed signals traveling along NLTL2 (H_0=60 kA/m)

As can be seen from the numerical analysis, high peak values of the pulsed signals traveling through segment 2 of the nonlinear line could be attained through the use of a rather short NLTL2, about 100 or 150 mm in length. Fig. 6 presents a waveform at the output of a 80 mm long NLTL2 operating in the PPA mode. For the sake of comparison, the same figure carries measured outputs (see Section 3 below) from NLTL2 lines 50; 200, and 500 mm long that were obtained in experiments involving tandems with an 'optimized' NLTL1.

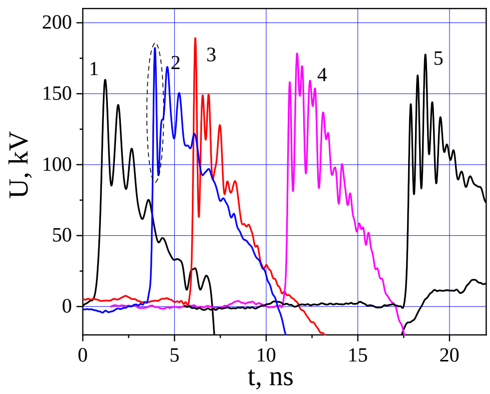

Fig. 6. Calculated pulse waveforms in NLTL2: 1 – line's input; 2 – output in a 50 mm long segment; 3 – output, L= 80 mm; 4 – output, L= 200 mm; 5 – output, L= 500 mm

2. EXPERIMENTAL

We are presenting here some results of real experiments aimed at transforming a high voltage video pulse into a broadband RF pulsed waveform with a controllable spectral content. The geometric parameters of the ferrite-filled transmission lines NLTL1 and NLTL2 employed in the experiments have been listed in Table above. The axial magnetizing field H_0 and the azimuthal magnetic field H_φ were both controlled and could be adjusted in the course of an experiment. The amplitude of H_φ was adjusted through variation of the pulsed voltage U_0.

The high voltage pulse generator present in the facility was capable of producing solitary pulses of a 6 ns duration (at half-maximum level) and variable amplitudes up to 300 kV. Unfortunately, this pulse duration did not ensure compliance with the $\tau_P > \tau_D \approx \tau_L$ condition, so the PPA regimen could not be fully implemented. Still, the series of experiments that have been completed permits understanding the principal particularities of the pulse conversion process and opportunities for spectral content control.

The longitudinal field H_0 for ferrite magnetization could be adjusted between 10 and 50 kA/m. The signals at the input and further along the line were measured with differentiating capacitive sensors disposed in the decoupling sections before and after the respective NLTLs (i.e., line segments 1 or 2). Oscillograms of the incoming voltage pulse, U_0, and such at the output from the NLTL1, i.e. U_1, are given in Fig. 2 (the case of a single segmented line). The electric and the geometric parameters of NLTL1 allowed obtaining intense microwave oscillations at the output characterized by a high amplitude of the first peak. In spectral terms, it was a broadband pulsed signal with a 'detached' oscillation frequency $f_1 \approx 1.4$ GHz (see Fig. 7). The upper and the lower edge frequencies of the band, evaluated at a half-amplitude level, were about 1.6 and 1.2 GHz, respectively, which meant a relative bandwidth $\Delta f/f \approx 0.28$.

Further experiments were conducted with a dual-segmented nonlinear transmission line in which the segment NLTL1 was of a pre-optimized length L_1=350 mm.

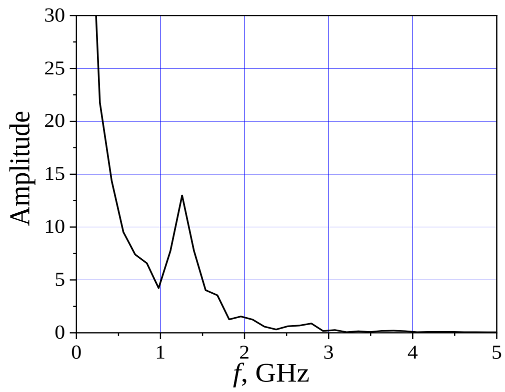

Fig. 7. Frequency spectrum at the output of NLTL1

The output voltage U_1 of NLTL1 was transmitted into NLTL2 via a conical matching junction. The geometries and sizes of the NLTL segments were selected so as to obtain a higher value of the frequency generated in NLTL2 after that had been fed with the pulse from the first segment. Preliminary tests showed that by feeding

NLTL2 with a U_1 pulse about 7 ns in length and maximum amplitude up to 270 kV, it was possible to obtain at the output a broadband signal U_2 characterized by oscillation frequencies in the interval $f_2 \approx 1.8…3.2$ GHz ($\Delta f/f \approx 0.55$).

The roughly 7 ns duration of the signal U_1 was greatly in excess of the oscillation periods in the NLTL1 line (~0.7 ns, cf. Fig. 7), which precluded us from following details of the peak power amplification regimen. Still, favorable conditions remained for investigating certain general circumstances concerning transformations of a unipolar signal in the nonuniform general NLTL structure (in other words, that consisting of two NLTL segments, see Table). Passing through NLTL1 the initial signal is enriched with an oscillatory component at the frequency f_1. Next, it may excite oscillations at a frequency f_2 in the NLTL2. The total signal at the output of NLTL2 is formed by coexisting oscillations at the frequencies f_1 and f_2. These are not exactly the true eigenfrequencies of the NLTLs, obtainable through independent excitation of each isolated line. First, because the lines that constitute the actual structure are electromagnetically coupled, even in the linear operation regime. Hence, the partial frequencies belonging to any of the transmission line segments are shifted from the correspondent eigenvalues. Second, the electromagnetic response of ferrite-filled NLTLs is not linear in signal amplitudes, which leads to a stronger coupling of oscillatory motions in the structure. In addition, nonlinear effects are accumulated as the signal travels along the line, thus bringing forth a pronounced dependence of spectral parameters upon the travel path.

Now, consider the frequency spectra at the output of the two-segmented transmission line that are presented in Figs. 8-10. They are given for a set of line lengths where L_1 = const =350 mm, while L_2 is varied from L_2 = 500 to 80 and 50 mm.

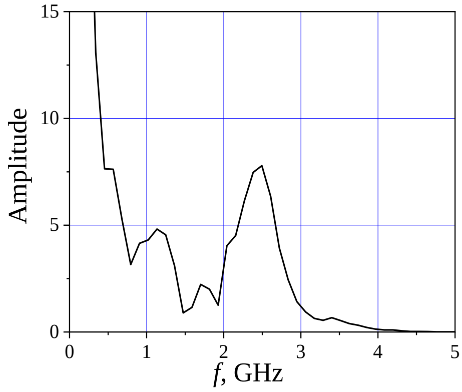

Fig. 8. Frequency spectrum of the voltage U_2: L_1 = 350 mm and L_2 = 500 mm

The oscillogram of $U_2(t)$ presented in Fig. 6 and its frequency spectrum (see Fig. 8) that were obtained for a relatively high value of the path length, L_2 = 500 mm, both reveal some prevalence of a group of high frequency oscillations concentrated near $f_2 \sim 2.2$ GHz.

In the case where the ferrite insert in NLTL2 is of length L_2 = 80 mm, the oscillations at f_2 =2.2.GHz in NLTL2 are of approximately the same amplitude as at $f = f_1$, which is equally well seen in the spectrum, (see Fig. 9). With the length L_2 shortened down to 50 mm, the prevailing oscillations in NLTL2 are those at $f_1 \approx 1.4$ GHz again.

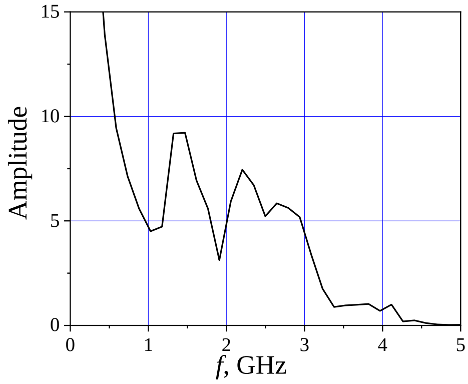

Fig. 9. Frequency spectrum of the signal U_2 with line segment lengths L_1 = 350 mm and L_2 = 80 mm

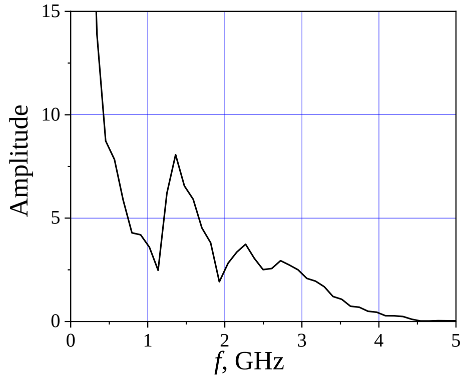

Fig. 10. Frequency spectrum of the signal U_2 with line segment lengths L_1 = 350 mm and L_2 = 50 mm

CONCLUSIONS

The nonlinear transmission line characterized by a longitudinal non-uniformity (like in the present case of two serially connected lines differing in diameter) can be used for shaping a broadband output signal with a controllable amplitude ratio of its constituent oscillating components. A possibility has been shown of altering the waveform and frequency spectrum in a broad range, like $\Delta f/f$ = 0.25…0.55, by means of varying the magnetizing fields H_φ and H_0, as well as geometric characteristics of either of the NLTLs.

In case of employing a feeding high-voltage signal of relatively short duration it may become possible to implement the PPA, or Peak Power Amplification operating mode. A numerical simulation, concerning a bi-segmented NLTL that operated with an incoming current pulse of duration Δt = 4 ns, demonstrated an increase in the signal amplitude from 120 to 160 kV over the first segment and to 220 kV over the second one. So, the total enhancement in the signal amplitude reached 83 per cent, which represents a 2.3 times power amplification. This is evidence for effective performance of the pulsed power amplifier implemented as a coaxial transmission line with a magnetized ferrite and operating as compact size devices at rather low voltages, as compared with the installations described in [5, 6] or [8]. In case of employing an incoming voltage pulse of several times longer duration than the optimum, a satisfactory result can only be achieved in the PPA mode if segment 2 of the NLPL were of a short length like 100 or 150 mm.

REFERENCES

1. J.E. Dolan. Simulation of shock waves in ferrite-loaded coaxial transmission lines with axial bias // *J. Phys. D: Appl. Phys*. 1999, v. 32, p. 1826-1831.
2. V.P. Gubanov, A.V. Gunin, O.B. Kovalchuk, V.O. Kutenkov, I.V. Romanchenko, V.V. Rostov. Efficient power transfer from high voltage pulses into high frequency oscillations, effectuated in a transmission line with a saturated ferrite // *J. Techn. Phys – Letters.* 2009, v. 35, is. 13, p. 81-87.
3. A. Vaselaar. Experimentation and modeling of pulse sharpening and gyromagnetic precession within a nonlinear transmission // *A dissertation in electrical engineering.* Texas Tech University, 2011.
4. D.V. Reale. Coaxial Ferrimagnetic Based Gyromagnetic Nonlinear Transmission Lines as Compact High Power Microwave Sources // *A dissertation in electrical engineering*. Texas Tech University, 2013.
5. J.J.-W. Ahn, S.Y. Karelin, H.-O. Kwon, I.I. Magda, and V.G. Sinitsin // *Korean J.Magnetics*. 2015, v. 20, № 4, p. 460-465.
6. S.Y. Karelin, V.B. Krasovitsky, I.I. Magda, V.S. Mukhin, V.G. Sinitsin. Quasi-harmonic oscillations in a nonlinear transmission line, resulting from Cherenkov synchronism // *Problems of Atomic Science and Technology.* 2019, № 4, p. 65-70.
7. A.I. Gusev, M.S. Pedos, S.N. Rukin, S.P. Timoshenkov. Solid-state repetitive generator with a gyromagnetic nonlinear transmission line operating as a peak power amplifier // *Rev. Sci. Instrum*. 2017, v. 88, p. 074703.
8. A.I. Gusev, M.S. Pedos, A.V. Ponomarev, S.N. Rukin, S.P. Timoshenkov, and S.N. Tsyranov. A 30 GW subnanosecond solid-state pulsed power system based on generator with semiconductor opening switch and gyromagnetic nonlinear transmission lines // *Rev. Sci. Instrum*. 2018, v. 89, p. 094703.
9. S.Y. Karelin. FDTD analysis of nonlinear magnetized ferrites: simulation of oscillation forming in coaxial line with ferrite // *Telecommunications and Radio Engineering.* 2017, v. 76, № 10, p. 873-882.

Article received 7.06.2022

ПЕРЕТВОРЕННЯ ВІДЕОІМПУЛЬСНОГО СИГНАЛУ НА РАДІОІМПУЛЬС СКЛАДНОЇ ФОРМИ

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

Досліджується можливість використання нелінійної хвилеводної системи на основі коаксіальної лінії з намагніченим феритовим керном для формування широкосмугового імпульсного сигналу з керованим радіочастотним спектром. Розглянуто систему двох послідовно з'єднаних ліній з різними діаметрами порядку 10^1 мм, у котрой на феромагнетик діють аксіальне магнітне поле підмагнічування та азимутальне поле первинного відеоімпульсу. Продемонстровано можливість цілеспрямованої зміни форми та частотного спектру вихідного сигналу (діапазону одиниць гігагерц) у широких межах, $\Delta f/f$ = 0,25…0,55. Зокрема, за малої тривалості первинного сигналу можливим є так званий режим підсилювача пікової потужності.

ПРЕОБРАЗОВАНИЕ ВИДЕОИМПУЛЬСНОГО СИГНАЛА В РАДИОИМПУЛЬС СЛОЖНОЙ ФОРМЫ

С.Ю. Карелин, В.Б. Красовицкий, А.Н. Лебеденко, И.И. Магда, В.С. Мухин, В.Г. Синицын, Н.В. Воловенко

Исследуется возможность применения нелинейной волноведущей системы на основе коаксиальной линии с намагниченным ферритовым керном для формирования широкополосного импульсного сигнала с управляемым радиочастотным спектром. Рассмотрена система двух последовательно соединенных линий разного диаметра порядка 10^1 мм, в которой на ферромагнетик действуют аксиальное поле подмагничивания и азимутальное магнитное поле первичного видеоимпульса. Продемонстрирована возможность целенаправленного изменения формы и частотного спектра выходного сигнала (диапазона единиц гигагерц) в широких пределах, $\Delta f/f$ = 0,25…0,55. В частности, при малой длительности первичного импульсного сигнала возможен так называемый режим усиления пиковой мощности.