https://doi.org/10.46813/2023-146-008

EXCITATION OF DURABLE VHF OSCILLATIONS IN FERRITE-FILLED COAXIAL LINES

I. Magda, V. Mukhin, V. Sinitsin, S. Karelin, O. Lebedenko, M. Volovenko, O. Rak
National Science Center “Kharkov Institute of Physics and Technology”, Kharkiv, Ukraine
E-mail: vgsin33@gmail.com

Effective methods are suggested for exciting gigahertz-range oscillations in coaxial lines that contain ferrite rings and isotropic material. Within the gyrotropic section, the primary pulsed waveform gets transformed from the TEM into a TM mode**.** Its further development is analyzed, following the results of real-life and numerical experiments. Special attention is paid to amplitude variations of the TM mode, owing to the nonlinear response of the ferrite.

PACS: 41.20 Gz; 41.20 Jb

INTRODUCTION

The methods of converting the power of short unipolar electric pulses into radio frequency oscillations of mega- or gigahertz ranges have been a subject of intense investigations for more than a decade [1 - 5]. Attention has been centered, for the most part, on non-vacuumized wave generating structures which do not employ accelerated electron beams in the capacity of a primary source of VHF energy.The essential structural element of such systems is the transmission line of a topology which allows admitting unipolar electric current pulses whose spectrum involves very low frequency components, including the d.c. The correspondent category of wave guiding structures embraces planar strips and cylindrical coaxials (as well as lumped parameter circuits which are not considered here). A great majority of papers on the subject are dedicated to analyses of specific wave forms in the coaxial cylindrical lines whose cross-sections are filled, either partially or completely, with dielectric materials showing a non-linear electro- or magnetodynamic response [2 - 6, 8, 9]. Most often, these are represented by ferromagnets, ferrites in particular, which are characterized by gyrotropic properties. In many works of the earlier period which presented both calculated and experimental results, researchers were oriented at exploring parameters of the shock wave alone, leaving the possible ‘by-products’ aside. Meanwhile, one of those has deserved attention because of its ability to produce voltage pulses with a VHF filling of the megahertz and higher-frequency range. Though, such oscillatory VHF waveforms often showed sizable attenuation rates [2, 4 - 6, 9], with the spectral lines' relative widths reaching 30 per cent and more. Our work of years 2021 to 2023 has been centered on identification and technical implementation of the conditions for provision of durable narrow-line oscillations of the megahertz range with the aid of ferrite-filled transmission lines of dual connectivity.

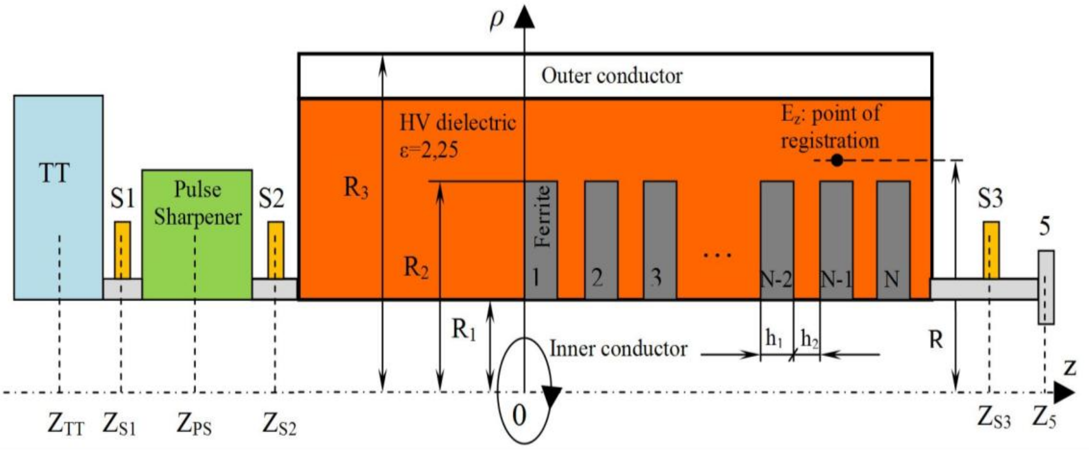

Fig. 1. The non-vacuum, high voltage coaxial line-based pulse generator

1. ANALYSIS AND MODELING

1.1. GENERAL STRUCTURE

Fig. 1 is a schematic view of the non-vacuum coaxial wave guiding structure intended for producing durable VHF oscillations. The geometry of the structure is presented in a cylindrical frame of reference with coordinates ρ, φ, and z. Along with this one, we have considered several other versions of the waveguide to be employable for real-life and numerical experiments. The essential part of the structure is the multi-layered coaxial line occupying the middle section. It is filled with an isotropic dielectric material, plus a variable number $N > 10$ of gyrotropic inserts shaped as ferrite rings of diameter $2R_2$ and width h_1. In most of our experiments the isotropic dielectric was transformer oil, characterized by a relative dielectric constant $\varepsilon = 2.25$ and scalar magnetic permeability $\mu = 1$. The ferromagnetic rings are supposed to be tightly set on the inner conductor (diameter $2R_1$), either with or without a non-zero spacing h_2

along the longitudinal axis z. In some of the experiments of a later period (specifically, May through July, 2023) the middle section also involved a metal periodic structure intended for slowing down specific spectral components of the pulsed signal. That metal structure is not shown in Fig. 1, as well as the externally disposed solenoids which provide the d.c. magnetizing field (of order 10^2 kA/m) for the ferrite inserts. The transverse sizes of the line's structural elements can be made variable, both in the real and in numerical experiments, tending to two basic configurations like R_1=10 mm; R_2=16 mm, and R_3=26 mm, or R_1=6 mm; R_2=10 mm, and R_3=26 mm. In those cases where the metal SWS (slow wave structure) was also present, the larger sized ferrites with R_1=10 mm and R_2=16 mm were used, such that the inner surface of the SWS (of radius R=22 mm) was separated from the ferrite core by only 6 mm. The front end of the entire system involves a Tesla transformer (TT) which produces the primary unipolar pulse for exciting the structure, and a section designated as Pulse Sharpener which serves to finally shape up the pulsed waveform, enriching its spectrum with high frequency components. Pulse voltages at the TT's exit and such of the sharpener are monitored with [differential] voltage sensors S1 and S2. A similar sensor designated S3 is located near the exit from the middle section. The lengths of individual structural units can be varied, depending on specific parameters of an experiment, such as total numbers and sizes of the ferrite rings and solid dielectric spacers between them, and lengths of the uniform parts of the coax lines at the exit. For example, the pulse sharpener's length (S2-S1) is 70 or 72 mm, while the principal middle section may measure 350 to 370 mm. (From this point on, the middle section will be referred to as NLTL, the nonlinear transmission line). The sharpener output is connected to the NLTL via a coaxial line of length L_0=1020 mm, such that the total size of the line, taken from the TT to the end sensor S3, equals 1620 mm. The rest of the structure, extending to the short circuiting shunt at the end (marked 5), involves coaxial sections of length close to 2000 mm.

1.2. WAVE MODES AND SPEED SYNCHRONISM CONDITIONS

Consider the unipolar voltage pulse $U(\boldsymbol{r},t)$ arriving from the TT to the NLTL input at $z_1=Z_{s2}+L_0$. Its spectral content includes a low-frequency component of magnitude close to the half-height level of the pulsed waveform. The initial portion of the coaxial ($z_1 < z < 0$) is filled with an isotropic liquid dielectric with parameters ε_1 and $\hat{\mu}_1$. It can support traveling waves in the form of TEM modes of all frequencies $\omega \geq 0$, as well as guided modes characterized by the presence of frequency cut-offs. Within that uniform part of the guide the TEM is the lowest-order mode involving two field components, namely the radial, E_ρ and the azimuthal, $B_\varphi=\mu_0 H_\varphi$. While traveling through this section which contains no inhomogeneities to violate its spatial uniformity, the electric pulse does not change its waveform. This means that all of its spectral components travel at the same phase velocity v_{ph}, hence the respective wavelength $\lambda=2\pi/k$ corresponds, at each of the frequencies ω, to the dispersion law $\omega = kv_{\text{ph}}$ of the TEM mode. As soon as the wave packet reaches the ferrite-filled section (of parameters $\hat{\varepsilon}_2$ and $\hat{\mu}_2$), it undergoes diffraction and spectrum transformation at the dielectric-ferrite boundary and further on, while moving through the layered material filling. The effect of scattering of the primary field components, E_ρ and B_φ, gives rise to the appearance of longitudinal components E_z and B_z, and their related wave modes other than the TEM [4, 5, 9]. In fact, one can speak here of two different (though related) physical effects that may lead to detachment of relatively narrow-band excitations from the single-speed shock-like waveform.

The first one can be described as a spatially localized modal transformation that occurs at the interface between the isotropic and uniform dielectric medium and the anisotropic and radially non-uniform one. The transmitted waveform is known to be comparatively wide in the frequency domain and quickly attenuating with time [4]. Compared with the initial TEM wave from the TT, the waveform is in possession of a new spatial component, specifically the E_z. Shown in Fig. 2 below is a 'cascaded' representation of the time and space development of the E_z component as traveling through the NLTL. The numerical simulations and analysis proceeded from the set involving a wave equation for the electromagnetic field vectors $\boldsymbol{E}$ and $\boldsymbol{B}$, and the Landau-Lifschitz-Gilbert equation for the magnetization vector $\boldsymbol{M}$,

$$-rotrot\boldsymbol{E}(\boldsymbol{r},t) - \frac{\partial}{\partial t} rot\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{Q}(\boldsymbol{r},t), \quad (1)$$

$$\partial \boldsymbol{M}/\partial t = -\gamma\mu_0[\boldsymbol{M}\times\boldsymbol{H}] - (\gamma\alpha\mu_0/M_s)[\boldsymbol{M}\times[\boldsymbol{M}\times\boldsymbol{H}]]. \quad (2)$$

Here γ is the gyromagnetic ratio, α the phenomenological relaxation factor, and M_S a characteristic parameter of the ferromaterial. The current density term $\boldsymbol{Q}(\boldsymbol{r},t)$ in the right-hand side of Eq. (1) represents the [unipolar] pulsed waveform generated in the Pulse Sharpener as a driver for the waves in the NLTL. The differential equations are solved with the aid of the adapted version [10] of the FDTD.

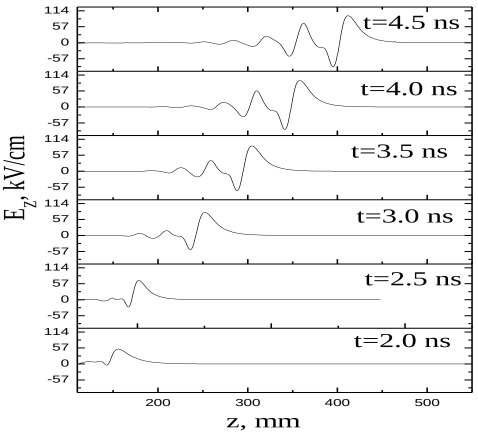

Fig. 2. Magnitudes of the HF electric field component E_z at points 1 mm 'above' a solid (h_2=0) ferrite core. (Simulation of an experiment with ferrite rings of parameters ε=16, α=0.1 and size 16×10 mm)

The other case of mode detachment can be regarded as an analog of Cherenkov's effect, i.e., generation of durable, comparatively narrow-band oscillations resulting from the time-synchronized, parallel propagation of the participant waves through the ferrite core and its adjacent dielectric layer. The part of Cherenkov‘s driver is played by the intense unipolar pulse from the TT.

Shown in Figs. 3 and 4 are spectral densities of the high-frequency E_z component calculated for generally similar electric conditions, however for a solid ferrite core in one case and for a rarefied ferrite-dielectric core (see Fig. 4) in the other. As can be seen, the frequency of the detached component is noticeably higher with the use of solid core.

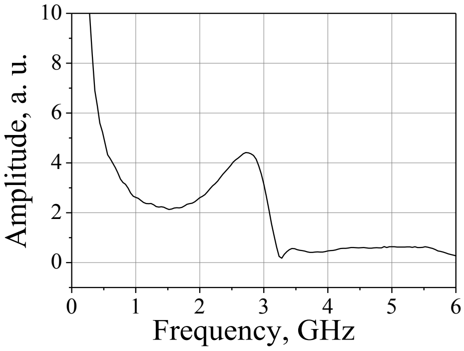

Fig. 3. Spectral density of the HF electric field component E_z at points 1mm ‘above’ a solid (h_2=0) ferrite core (calculated for H_0=30 кA/m; Ms=300 kA/m; α=0.1, ε_1=16, ε_2=2.25 and a 600 mm long NLTL)

Note that emergence of higher-order spatial harmonics in the non-uniformly filled coaxial guide is possible even at the early stage of process development, when the material relations $\boldsymbol{D}(\boldsymbol{r},t)=\varepsilon_0\varepsilon\boldsymbol{E}(\boldsymbol{r},t)$ and $\boldsymbol{B}(\boldsymbol{r},t)=\mu_0(\boldsymbol{H}+\boldsymbol{M})$ still remain linear with regard to the field amplitudes involved. The vector $\boldsymbol{M}$ here stands for the per-unit-volume magnetization of the ferromagnetic material. Its macroscopic dynamics can be described by approximate equations like the Landau-Lifschitz, Eq. (2) [7, 11], with account of both linear and weakly nonlinear solutions for the $\boldsymbol{M}$ and $\boldsymbol{B}$.

From the practical point of view, availability of a nonlinear electromagnetic response of the ferrite-filled structural sections is of importance for achieving two goals. First, the nonlinearity is an essential factor for shaping up suitable spectral and temporal content of the pulsed waveform, in particular, for increasing the spectral density of its higher frequency components. Second, it is necessary for ensuring power exchange between the low-frequency spectral components (including the d.c.) and the VHF oscillations one may seek to excite. The latter are associated with higher order guided modes of the coaxial line, hence determined by ‘electrical’ transverse sizes $(R-R_1)(\varepsilon\mu)^{-0.5}$ of the line’s structural elements and intrinsic dispersion properties of the ferrite core [12, 13].

The experiments of November, 2022 revealed some drawbacks in the then approach of ours to optimizing the duration of the HF pulse. It had been suggested to replace the continuous ferrite core by sets of ferrite rings and fill the gaps with some dielectric. The idea was to increase the propagation velocity of the pulse, leveling it up with the speed characteristic of the adjacent layer [14]. It was also anticipated that the rarefied ferrite core could operate in concert with the metal SWS within the line, no matter which be the ratio of periods of the two structures. In fact, the co-existence of several periodic structures offered some controversial results. The consequences of spatial rarefaction of the ferrite-dielectric array were acceptable until the rarefication step was not commensurate with either the wavelength (nearest in the spectrum) or period of the SWS. This can be clearly seen from comparing the measured spectrum of Fig. 5 here with the calculation of Fig. 4.

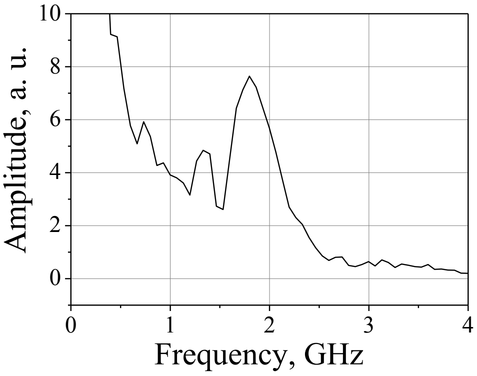

Fig. 4. Spectral density of the HF electric field component $E_{\boldsymbol{z}}$ at points 1mm ‘above’ a rarefied (h_2=1.5 mm) ferrite core (calculated for H_0=30 кA/m; Ms=300 kA/m; α=0.1; ε_1=16, ε_2=2.25)

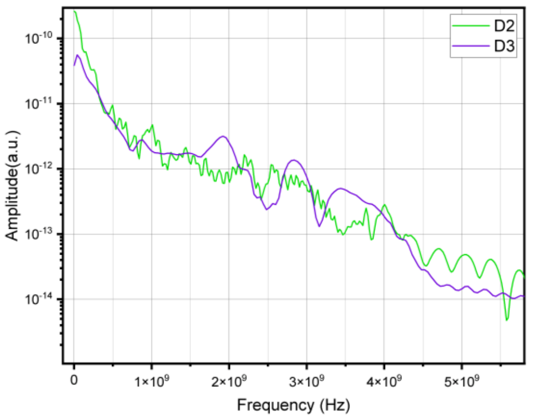

Fig. 5. Measured spectral density of the HF electric field $E_{\boldsymbol{\rho}}$ as read from output sensor S3 (a.k.a. D3 per oscillogram) for U_0 =240 kV and magnetic bias field of 51.6 kA/m, in the presence of a SWS of 6 mm period and with a 0.5 mm rarefication gap in ferrite core

Another question was, whether the spatial period of the HF field could be maintained constant for matching the period of the SWS despite amplitude-dependent variations in the refractive index.

CONCLUSIONS

To enable a Cherenkov-driven process of forming up long lasting oscillatory motions in the NLTL, it is necessary that the electromagnetic wave’s velocity in the dielectric were lower than such in the ferrite. The two materials demonstrate greatly different values of their respective magnetic and electric permeabilities. The signs (orientation) of those differences are utterly unfavorable for performing any leveling of their refractive indices by means of a ‘proper’ selection of the materials. Instead, it proves profitable to introduce a periodic etal grating in the capacity of a SWS, thus cutting down the wave speed in the isotropic dielectric.

Both numerical modeling and the latest series of experiments (May/July, 2023) have corroborated the reality of generating durable gigahertz-range oscillations under the conditions of a Cherenkov-type synchronism in the NLTL.

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. D.V. Reale. Coaxial Ferrimagnetic Based Gyromagnetic Nonlinear Transmission Lines as Compact High Power Microwave Sources. *A dissertation in electrical engineering*. Texas Tech University, December 2013.
3. V.V. Rostov, N.M. Bykov, D.N. Bykov, A.I. Klimov, O.B. Kovalchuk, I.V. Romanchenko. Generation of subgigawatt RF pulses in nonlinear transmission lines // *IEEE Trans. on Plasma Sci.* 2010, v. 38, p. 2681-2687.
4. J.-W. Ahn, S.Y. Karelin, H.-O. Kwon, I.I. Magda, and V.G. Sinitsin. Exciting high frequency oscillations in a coaxial transmission line with a magnetized ferrite // *Korean J. Magnetics*. 2015, v. 20, p. 460-465.
5. S. Furuya, H. Matsumoto, H. Fukuda, T. Ohboshi, S.Takano, and J. Irisawa. Simulation of Nonlinear Coaxial Line Using Ferrite Beads // *Jpn. J. Appl. Phys.* 2002, v. 41, p. 6536-6540.
6. I.V. Romanchenko, P.V. Priputnev, and V.V. Rostov. RF pulse formation dynamics in gyromagnetic non-linear transmission lines // *IOP Conf. Series "Journal of Physics"*. 2017, v. 830, p. 012034. doi:10.1088/1742-6596/830/1/012034.
7. G.V. Skrotsky. More on the Landau-Lifschitz equation // *Sov. Phys. Uspekhi*. 1984, v. 144, issue 4, p. 681-686 (in Russian).
8. S.Y. Karelin, V.B. Krasovitsky, I.I. Magda, V.S. Mukhin, V.G. Sinitsin. Quasi-harmonic RF oscillations in a gyrotropic nonlinear transmission line // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2018, № 6, p. 180-184.
9. J.-W. Ahn, S.Y. Karelin, V.B. Krasovitsky, H.-O. Kwon, I.I. Magda, V.S. Mukhin, O.G. Melezhik, V.G. Sinitsin. Wideband RF radiation from a non-linear transmission line with a pre-magnetized ferromagnetic core // *Korean J. Magnetics*. 2016, v. 21, p. 450-459.
10. S.Y. Karelin. A FDTD analysis of magnetized ferrites: simulation of the oscillations formed in a coaxial line with ferrite // *Telecommunications and Radio Engineering*. 2017, v. 76, № 10, p. 873-882.
11. J.O. Rossi, F.S. Yamasaki, E. Shamiloglu, J. Barroso. Analysis of nonlinear gyromagnetic line operation using LLG equation // *IEEE 21-st Int'l Conference on Pulsed Power*, June 2017. DOI: 10.1109/PPC. 2017.8291 172.
12. S.Y. Karelin, V.B. Krasovitsky, A.N. Lebedenko, I.I. Magda, V.S. Mukhin, V.G. Sinitsin, N.V. Volovenko. Video pulse conversion into a radio frequency pulsed waveform of complex composition // *Problems of Atomic Science and Technology*. 2022, № 3, p. 82-86. https://doi.org/10.46813/2022-139-003.
13. S.Y. Karelin, V.B. Krasovitsky, I.I. Magda, V.S. Mukhin, V.G. Sinitsin. Quasi-harmonic oscillations in a non-linear transmission line, resulting from the Cherenkov synchronism // *Problems of Atomic Science and Technology*. 2019, № 4, p. 65-70.
14. S.Y. Karelin, V.B. Krasovitsky, O.N. Lebedenko, I.I. Magda, V.S. Mukhin, V.G. Korenev, M.V. Volovenko. Cherenkov effect and narrow-line VHF oscil-la-tions in a ferrite-filled coaxial line // *IEEE 2nd Ukrainian Microwave Week.* 2022, Paper Collection, Section MSMW-13, № 094, 5 p.

Article received 21.07.2023

ЗБУДЖЕННЯ ДОВГОТРИВАЛИХ КОЛИВАНЬ НВЧ-ДІАПАЗОНУ В КОАКСІАЛЬНИХ ЛІНІЯХ З ФЕРИТОВИМ ЗАПОВНЕННЯМ

І. Магда, В. Мухін, В. Сініцин, С. Карєлін, О. Лебеденко, М. Воловенко, О. Рак

Пропонуються ефективні методи збудження осциляцій гігагерцевого діапазону в коаксіальних лініях, що містять уставки з феритових кілець та ізотропного матеріалу. У гіротропній частині лінії первинна імпульсна хвильова форма трансформується з моди ТЕМ у моду ТМ. Проаналізовано їх подальший розвиток за результатами відповідних натурних і числових експериментів. Особливої уваги приділено варіаціям амплітуди ТМ-моди, що пов'язані з нелінійністю електромагнітного відгуку фериту.