Propagation of Short Radio Pulses through Delay Line of a Cold TWT

A. V. Gritsunov, N. V. Skachkova
Department of Electronic Engineering
Kharkiv National University of Radio Electronics
14 Lenin Ave., Kharkiv, 61166, Ukraine. E-mail: gritsunov@gmail.com

Abstract: *A technique for the simulation of wideband non-stationary electromagnetic fields excited in a regular dispersive delay line by an electron beam is proposed. This is based on a generalized wave equation numerical solving. A particular case of the technique use is shown by the simulation of short radio pulse advance in the delay line of the Northrop-Grumman "cold" traveling wave tube.*

Keywords: numerical simulation; dispersive delay line; electromagnetic pulse propagation; traveling wave tube.

Introduction

Due to their exceptional broadbandness, traveling wave tubes (TWTs) theoretically can amplify very short radio pulses. These pulses might be used in UWB radars, digital telecommunications with high data transfer rates [1], *etc*. Simulation of such operating modes of TWTs demands new theoretical approaches like the spectral one [2]. As the first stage, a technique of evaluation of short radio pulse propagation in delay line of a "cold" TWT is considered in this paper. One allows separating distortions of the pulses caused by the line dispersion from effects produced by electron beam in amplifying TWT.

Simulation Technique

The continuous approximation of the regular dispersive delay line [3] is used. The vector potential $\vec{A}(t,x,y,z)$ for each wave mode (the line passband) can be calculated as a series in the longitudinal wavenumber β:

$$\vec{A}(t,x,y,z)=\vec{A}_{g0}(x,y,z)u_g(t,z)+\frac{i}{1!}\frac{\partial\vec{A}_{g0}}{\partial\beta}\frac{\partial u_g}{\partial z}-\frac{1}{2!}\frac{\partial^2\vec{A}_{g0}}{\partial\beta^2}\frac{\partial^2 u_g}{\partial z^2}-\frac{i}{3!}\frac{\partial^3\vec{A}_{g0}}{\partial\beta^3}\frac{\partial^3 u_g}{\partial z^3}+\frac{1}{4!}\frac{\partial^4\vec{A}_{g0}}{\partial\beta^4}\frac{\partial^4 u_g}{\partial z^4}+\ldots$$

where $\vec{A}_g(x,y,z,\beta)$ is so-called regular mode of the line [periodic with the line period D complex envelope of the line eigenmode $\vec{A}_e(x,y,z,\beta)$ in the longitudinal direction z, so that $\vec{A}_e(x,y,z,\beta)=\vec{A}_g(x,y,z,\beta)\exp(-i\beta z)$]. $u_g(t,z)$ is a temporal and longitudinal dependence of the regular mode instantaneous value. The subscript 0 implies that an item is taken at $\beta=0$. A generalized wave equation for u_g is

$$\frac{\partial^2 u_g}{\partial t^2}+2\frac{\partial}{\partial t}\left[\delta_{e0}u_g-\frac{1}{2!}\frac{d^2\delta_{e0}}{d\beta^2}\frac{\partial^2 u_g}{\partial z^2}+\frac{1}{4!}\frac{d^4\delta_{e0}}{d\beta^4}\frac{\partial^4 u_g}{\partial z^4}-\ldots\right]$$

$$+(\omega_e^2)_0u_g-\frac{1}{2!}\frac{d^2(\omega_e^2)_0}{d\beta^2}\frac{\partial^2 u_g}{\partial z^2}+\frac{1}{4!}\frac{d^4(\omega_e^2)_0}{d\beta^4}\frac{\partial^4 u_g}{\partial z^4}-\ldots$$

$$=\frac{1}{2D}\int_{z-D/2}^{z+D/2}d\zeta\int_{S_\perp}dxdy\left[\frac{\vec{A}^*_{g0}(x,y,\zeta)}{\tilde{W}_{g0}}\vec{j}(t,x,y,\zeta)-\frac{i}{1!}\frac{\partial}{\partial\beta}\left(\frac{\vec{A}^*_g}{\tilde{W}_g}\right)_0\frac{\partial\vec{j}}{\partial z}-\frac{1}{2!}\frac{\partial^2}{\partial\beta^2}\left(\frac{\vec{A}^*_g}{\tilde{W}_g}\right)_0\frac{\partial^2\vec{j}}{\partial z^2}+\frac{i}{3!}\frac{\partial^3}{\partial\beta^3}\left(\frac{\vec{A}^*_g}{\tilde{W}_g}\right)_0\frac{\partial^3\vec{j}}{\partial z^3}+\frac{1}{4!}\frac{\partial^4}{\partial\beta^4}\left(\frac{\vec{A}^*_g}{\tilde{W}_g}\right)_0\frac{\partial^4\vec{j}}{\partial z^4}-\ldots\right]$$

where $\vec{j}(t,x,y,z)$ is the exciting current density; $\omega_e(\beta)$ and $\delta_e(\beta)$ are the eigenfrequency and the damping factor of the line eigenmode respectively; $S_\perp$ is the line transverse (x,y) section. $\tilde{W}_g(\beta)$ is the linear unit pseudoenergy of the regular mode:

$$\tilde{W}_g(\beta)=\frac{\varepsilon_0}{2D}\int_D dz\int_{S_\perp}dxdy\vec{A}_g(x,y,z,\beta)\vec{A}^*_g(x,y,z,\beta).$$

Assuming $\delta_e\equiv 0$ and approximating the line dispersion characteristic within the TWT operating frequency band by a second-order polynomial $\omega_e(\beta)\approx b_0+b_1\beta+b_2\beta^2$, a finite-difference equation was constructed. This uses a second-order pattern along the time coordinate and second-order and fourth-order ones in the longitudinal direction:

$$\Lambda^2u_{gk}=(u_{gk-1}-2u_{gk}+u_{gk+1})/\Delta z^2;$$
$$\Lambda^4u_{gk}=(u_{gk-2}-4u_{gk-1}+6u_{gk}-4u_{gk+1}+u_{gk+2})/\Delta z^4$$

(the orders of the polynomial and of the equation in z direction may be increased, if needs). The equation is solved with an explicit three-layer finite-difference scheme. Expediency of implicit schemes application is under consideration now. The right-hand part of the wave equation is substituted with some source function $s(t,z)$, which emulates entering the pulse into the line by an input signal.

Numerical Results

As an example, advance of a short radio pulse excited by the function $s(t,0)$ (Fig. 1) having rectangular spectrum in the frequency range $f = 1\ldots7$ GHz (see Fig. 2) in the Northrop-Grumman TWT [4] delay line with $b_1 = 3.1\cdot10^7$ m/s was simulated. The shape of $u_g(t,z)$ function at $t = 6$ ns for $b_0 = 0$, $b_2 = 0$ (no dispersion) is shown in Fig. 3. With fitted for the line dispersive factors $b_0 = 0.5{\cdot}10^9$ rad/s, $b_2 = 2.5{\cdot}10^3$ m^2/(rad·s), the distortion of the pulse spectrum on the line length of 10 cm is visible, but not quite "pictorial". Therefore, the factors b_0, b_2 were augmented over the actual ones. Fig. 4 shows $u_g(t,z)$ function at $t = 6$ ns for $b_0 = 1.5{\cdot}10^9$ rad/s, $b_2 = 0$. In Fig. 5, the same function is shown for $b_0 = 0$, $b_2 = 5{\cdot}10^3$ m^2/(rad·s). Finally, the time spectrum of a certain "electric field function" $e_g(t,z) = -\partial u_g(t,z)/\partial t$ at $z = 10$ cm is shown in Fig. 6 for $b_0 = 1.5{\cdot}10^9$ rad/s, $b_2 = 5{\cdot}10^3$ m^2/(rad·s). It is obviously that the dispersion, causing "spreading" the pulse in the time and the space, lowers the upper-frequency part of the pulse spectrum.

Conclusion

The offered technique allows estimating "cold" distortions of pulses for regular lines. The next step is use of one for simulation of the pulses amplification in operating TWTs.

References

1. Goebel, D. M., R. R. Liou, W. L. Menninger, X. Zhai, and E. A. Adler, "Development of Linear Traveling Wave Tubes for Telecommunications Applications," *IEEE Trans. Electron Devices*, vol. 48, no. 1, pp. 74-81, 2001.
2. Gritsunov, A. V., "On a Spectral Approach to Simulation of Microwave Devices," *J. Comm. Technol. and Electronics*, vol. 49, no. 7, pp. 829-832, 2004.
3. Gritsunov, A. V., "On Evaluation of Unsteady Non-Harmonic Fields in Electrodynamic Lines," *J. Comm. Technol. and Electronics*, (to be published).
4. Freund, H. P., E. G. Zaidman, and T. M. Antonsen, Jr. "Theory of Helix Traveling Wave Tubes with Dielectric and Vane Loading," *Phys. Plasmas*, vol. 3, no. 8, pp. 3145-3161, 1996.

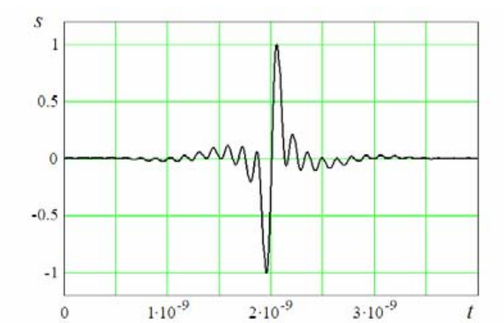

Figure 1

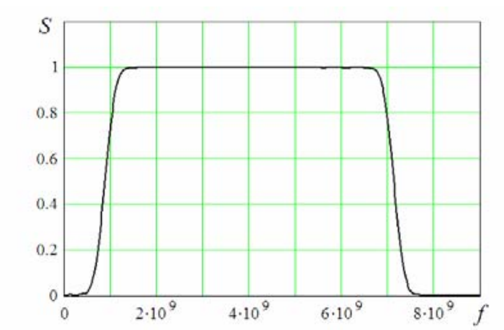

Figure 2

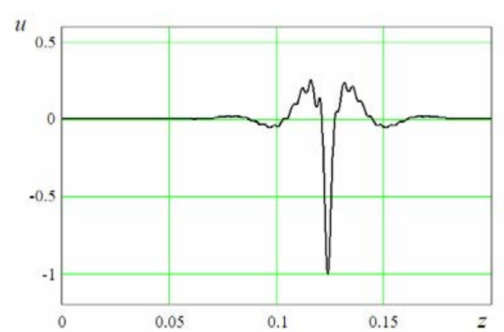

Figure 3

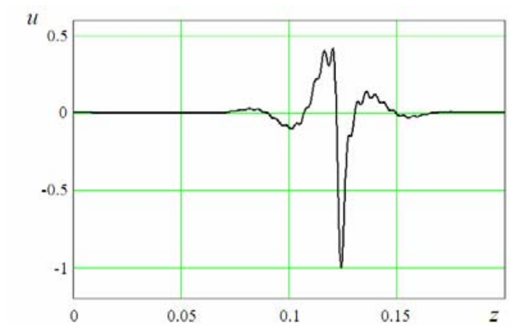

Figure 4

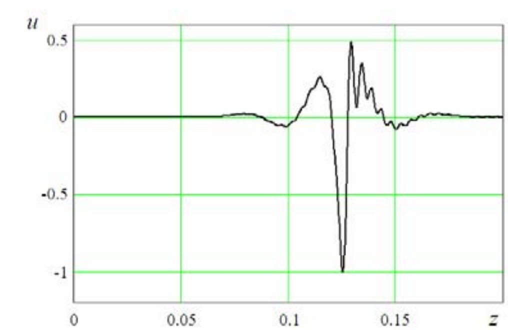

Figure 5

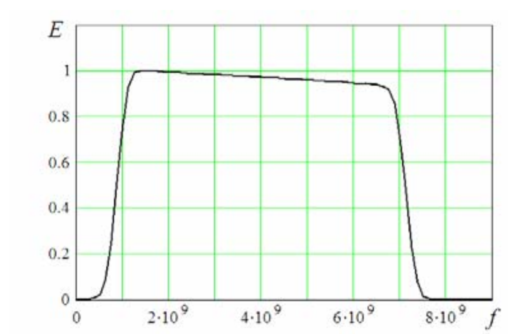

Figure 6