Journal of ELECTRICAL ENGINEERING, VOL. 52, NO. 9-10, 2001, 303–306

COMMUNICATIONS

ELECTROMAGNETIC SHOCK WAVES AND SOLITONS IN EXTREME SHORT TIMES TECHNOLOGY

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In the present contribution we concentrate on shock waves in nonlinear coaxial waveguides and on solitons in nonlinear ladder transmission lines. Some of our results prove to be interesting from the point of view of applied electromagnetism.

K e y w o r d s: electromagnetic shock waves, solitons, ns/subns delay elements, waveguides with ferrite filler with nonlinear capacitances, computer simulation of soliton propagation

1 INTRODUCTION

Electromagnetic shock waves and solitons belong to the class of phenomena connected with the propagation of electromagnetic waves in nonlinear media. Coaxial cable systems and ladder transmission lines with $L(i)$ or $C(u)$ nonlinearities represent a suitable tool in nonlinear electrodynamics both for physical investigation and for special technology. Power pulse generators producing shock waves at the output with remarkable power up to 10 MW were realized. An original soliton generator with well controlled delay times of individual solitons represents a new time base unit of a sampling oscillograph in subnanosecond time region.

2 PROPAGATION OF SHOCK WAVES IN HOMOGENEOUS COAXIAL LINE WITH NONLINEARITIES OF FERRITE FILLER

The shock wave pulse with a rise time of ns/subns is shaped on the coaxial waveguide with a homogeneous ferrite filler. The shaping of the shock wave with the mentioned width of real discontinuity zone progresses - depending on boundary conditions - as a results of a synergetic effect of two processes: - first of all, by nonlinear deformation of the input wave profile, an ordinary wave originates with successive shortening of the wave front -when changes of the magnetic field intensity $\mathrm{d}H/\mathrm{d}t = 10^8 \,\mathrm{to}\, 10^9\,\mathrm{Acm}^{-1}\,\mathrm{s}^{-1}$ are reached, nonlinear effects are determined by nonlinear dissipation with characteristic "gnaw" of electromagnetic energy on the discontinuity zone of the propagating shock wave pulse.

For the voltage U, current I, magnetic flux Φ, velocity v of the propagation of zone discontinuity then holds

$$\begin{aligned} U_2 - U_1 &= v_s(\phi_s(I_2) - \phi_s(I_1)) \\ I_2 - I_1 &= v_s C_0 (U_2 - U_1) \end{aligned} \tag{1}$$

$$v_s = \left(\frac{1}{C_0}\,\frac{I_2 - I_1}{\phi_s(I_2) - \phi_s(I_1)}\right)^{\frac{1}{2}} \tag{2}$$

where subscripts 1, 2 indicate electromagnetic values in front of or behind the zone discontinuity; C_0 is a capacitance parameter of the waveguide $[F/m]$. For the transient time of stationary shock wave it holds

$$\Delta t(I) = \frac{\ell}{v_s} = \ell\, \left(C_0 \frac{\phi_s(I_2) - \phi_s(I_1)}{I_2 - I_1}\right)^{\frac{1}{2}} \tag{3}$$

where ℓ is the total length of the waveguide. The relation

$$L_s = \frac{\phi_s(I_2) - \phi_s(I_1)}{I_2 - I_1} = \frac{\Delta\phi_s}{\Delta I_s} \tag{4}$$

is the difference inductance of the nonlinear waveguide $[H/m]$. For the equation (1b) then holds

$$v_s = (C_0 L_s(I))^{-\frac{1}{2}}\,. \tag{5}$$

The nonlinear wave resistance of the ferrite coaxial waveguide opposite to a shock wave discontinuity can be expressed as follows

$$Z_s(I) = \left(\frac{1}{C_0}\,\frac{\phi_s(I_2) - \phi_s(I_1)}{I_2 - I_1}\right)^{\frac{1}{2}} = \sqrt{\frac{L_s(I)}{C_0}}. \tag{6}$$

Exact methods for designing the nonlinear waveguides are very complicated. They are based on the equations of structure of the discontinuity zones of the shock waves [1]; their parametrisation by the elements of a geometrically identical linear coaxial waveguide leads to a simple calculation of the basic parameters of the coaxial line with a homogeneous ferrite filler [2]. At the same time, simple technology for realisation of the nonlinear waveguide is guaranteed.

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ISSN 1335-3632

By application of our results we obtain the parametrized equations (1) - (6) of the nonbiased homogeneous waveguide $(I_1, U_1 = 0, I_2 = I_s, U_2 = U_s)$ with magnetic nonlinearities [2]

$$I_s = \frac{v_0}{\sqrt{\Psi_s(I_s)}} C_0 U_s; U_s = \frac{v_0}{\sqrt{\Psi_s(I_s)}} \phi_s$$

$$v_s = \frac{v_0}{\sqrt{\Psi_s(I_s)}}; \quad \Delta t_s = \frac{\ell}{v_0} \sqrt{\Psi_s(I_s)}$$
$$L_s = L_0 \left(\Psi_s\left(I_s\right)\right); \quad Z_s = Z_0 \sqrt{\Psi_s(I_s)}. \tag{7}$$

The nonlinear parametrization factor is defined as

$$\Psi_s = \left(\frac{v_0}{v_s}\right)^2 \tag{8}$$

where v_0 is the velocity of the wave in the geometrically identical linear coaxial line. Equations (7), (8) can be successfully used to calculate the basic parameters of the nonlinear waveguide with the ferrite filler.

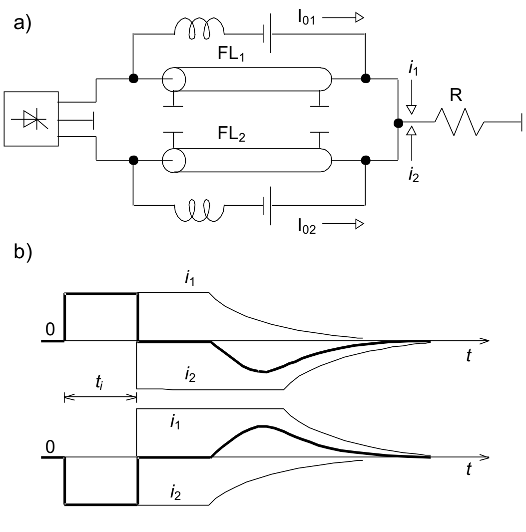

Fig. 1. (a)- The power pulse generator with two nonlinear waveguides with the ferrite filler, (b)- Time dependence of output pulses

2.1 Power Pulse Generators with the Shock Waves

The waveguides based on the nonlinearities $L(I)$ or $C(U)$ are the basic networks for the shaping of the high power shock waves (instantaneous power of $10^3\,W$ *to* $10^7\,W$) in extreme time domains subμs, ns, subns). The form of the input impulses is usually trapezoidal with an adequate duration of the horizontal part (of the order 100 ns), the front and trailing are usually 50 ns to 100 ns. The input voltage and currents are usually $10^3\,V$ *to* $10^4\,V$, $10\,A$ *to* $10^3\,A$, respectively.

2.2 Power Pulse Generator Based on the Ferrite Coaxial Waveguides

In [3], [4] a new technology and construction of the power pulse generators are described. The homogeneous distribution of the ferrite filler allows extremely low dispersion of the wave system. The new wave equipment was used for modulation of magnetrons in radar control.

The filler of the nonlinear waveguide consists of ferrite toroidal cores (5O/6/2 mm, $B_m = 0.33T, H_c = 100A/m$), H 11, PRAMET ŠUMPERK. The total length of the constructed waveguides is ℓ_s= 270 cm. A simplified scheme of the generator is shown in Fig. 1a. Parallel connection of two identical nonlinear sections with opposite polarity and controlled delay in the line FL1 (FL2) through bias current $I_{01}(I_{02})$ allowed us to create output pulses of variable lengths, as shown in Fig. 1b. Pulses with current amplitude 20 A and voltage $\approx$ 20 kV, lengths of order 10^{-7}s, rise fall time $\cong$ 250 ps and pulse repetition rate from 15 Hz to 500 Hz have been shaped. The instant power of pulses $\cong$ 0.4 MW is very remarkable.

2.3 Pulse Generator Using Ladder Line with Nonlinear Capacitors

In a similar way the evolution of shock waves in a ladder line with nonlinear capacitors was used for formation of rectangular puulses in the sub μs region [5]. The basic idea is evident from Fig. 2. The input pulse propagating along the nonlinear ladder line with nonlinear parameter $Z_n(U)$ changes from an ordinary wave to a shock wave.

For the velocity of the discontinuity zone now holds

$$v_s = \left(\frac{U_2 - U_1}{L_0(Q(U_2) - Q(U_1))}\right)^{\frac{1}{2}} \tag{9}$$

where U_1, U_2 *and* $Q(U_1)$, $Q(U_2)$ are voltage and charges, respectively, in front of and behind the discontinuity zone.

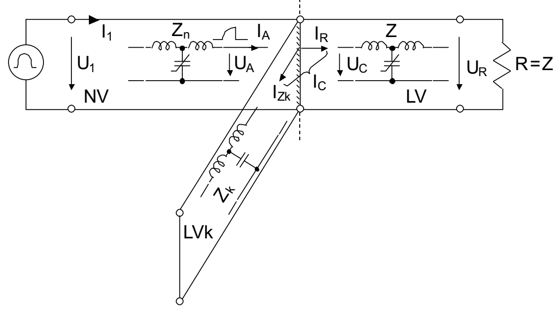

Fig. 2. Shock wave pulse generator with the nonlinear capacitors

At the end of a nonlinear line, two linear lines are connected in parallel. The output line with wave resistance Z is matched with resistor $R = Z$, and the second line with wave resistance Z_k working as a reflection line is shortened at the end. With appropriately chosen Z_n, Z_k, Z and the length ℓ_k, we obtained rectangular current pulses with amplitudes to 100 A, voltages up to 200 V and time parameters in the *subμs* range. The sixty elements with capacitors Ys 47n (permitit as dielectric), and linear inductances $L_0 = 0,14\ \mu H$ have been used. The reflection and transmission of shock waves at the transition from nonlinear to linear lines represents an interesting problem [6] [7].

3 SOLITON WAVES

When the influence of the dispersion predominates the influence of losses, the equilibrium of nonlinearity and dispersion is achieved and the shock waves disintegrates into soliton waves. Solitons of higher amplitudes propagate at higher velocities. When nonlinearity and dispersion predominate from the beginning, the ordinary wave of appropriate form immediately transforms into the soliton, skipping the shock wave formation.

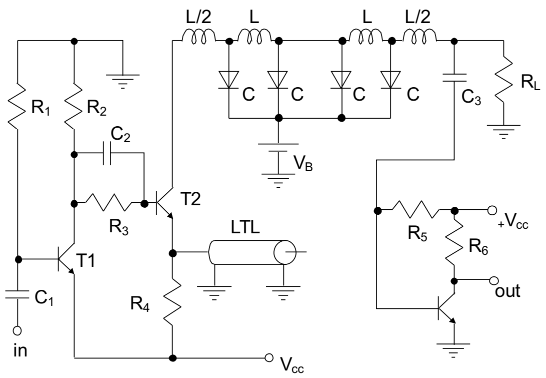

Fig. 3. The soliton delay circuit for subns times

The existence of ordinary solitons in transmission lines with lumped elements has been first proved by authors [8]. In the long wave approximation they are identical with the Korteweg-de Vries solitons.

In the present contribution we describe two new applications of the solitons produced in ladder lines with the $C(U)$ nonlinearity. First of all some results of the soliton theory can be used [8]. A nonlinear lumped network like that in Fig. 3 represents the ladder transmission line and has a steady-state pulse solution in the form

$$u_n(t) = U \sec h^2 \left(\sqrt{\frac{U}{LC_0U_0}}\, t - n \arg\sinh \sqrt{\frac{U}{U_0}} \right) \quad (10)$$

provided that the voltage dependence of varicap capacity $C(U)$ can be expressed by the equation

$$C(U) = \frac{C_0}{1 + \frac{U}{U_0}} \quad (11)$$

The solution (10), the so-called lattice soliton, describes a bell-shaped pulse with amplitude U, which propagates in the line with parameters L, C_0, U_0 as a function of time t and cell number n. The shape stability of the soliton, as obvious from the argument of the function (10), is due to opposite influences of nonlinearity and dispersion.

3.1 A Voltage Controlled Delay Circuit for Subnanosecond Area

A new delay line for very short times of subns order was constructed, using the process of soliton creation in a nonlinear lumped network with varicaps. A simplified circuit scheme is shown in Fig. 3. In [9] it is shown that by applying the bias voltage U_B the solution (10) can be rewritten as

$$u_n(t) = U_B + \\ + U \sec h^2 \left(\sqrt{\frac{U}{LC_0U_0}}\, t - n \arg\sinh \sqrt{\frac{U}{U_0 + U_B}} \right) \quad (12)$$

Comparison of equations (10) and (12) shows that the bias voltage does not result in any shape distortion of the soliton pulse; the velocity of its propagation v_B changes according to the equation

$$v_B = \frac{\sqrt{\frac{U}{LC_0U_0}}}{\arg\sinh \sqrt{\frac{U}{U_0+U_B}}}. \quad (13)$$

In the experimental function model, varicaps BB 105 G with parameters $C_0 = 25\ pF$, $U_0 = 2,8\ V$ and inductors with $L = 30$ nH were used. These parameters imply soliton half-width about 1,5 ns for the amplitude $U = 4$ V. The value of the load resistance is $R_L = 50\ \Omega$.

The measuring equipment of the function model presented in the paper [9] allows a very simple construction of the time base unit for the sampling oscillograph module to PC. Application of the faster sampling unit with strobe pulse width of about 20 ps allows to increase the bandwidth to 10 or more GHz, since equivalent sampling rate of the presented time base reaches up to 250 GHz.

3.2 Soliton Generator

A similar soliton line with a shock wave at the input has been used in the new soliton generator which produces soliton pulses in the picosecond region [10]. Since the input signal was not of the appropriate soliton shape, problem arises concerning the concept of stationary waveforms. Any arbitrary initial signal decomposes automatically into a well-defined series of individual solitons of total energy equal to the energy of the input signal. Separation of the main soliton of the highest amplitude from the "parasitic" solitons has been achieved by an additional line using the property of different velocities of different amplitudes.

3.3 Computer Simulation of Soliton Propagation

Consequently, a new idea how to suppress the parasitic solitons has been examined by computer simulation. It is well know that in a junction of two nonlinear lines the soliton coming from the first line disintegrates into several shorter solitons if the time parameter of the second line is smaller than that of the first line. This implies a new idea of construction of a nonhomogeneous line comprising a section with different parameters. Several types of nonhomogenities have been investigated [11].

Figure 4a shows an example of computer simulation results based on Runge-Kutta method obtained on a homogeneous line, and Fig. 4b illustrates the interesting effect of hyperbolic nonhomogeneity. The obtained results may have practical application since they show how to compress the pulse width and how to remove less "parasitic" effects than those appearing in a homogeneous line.

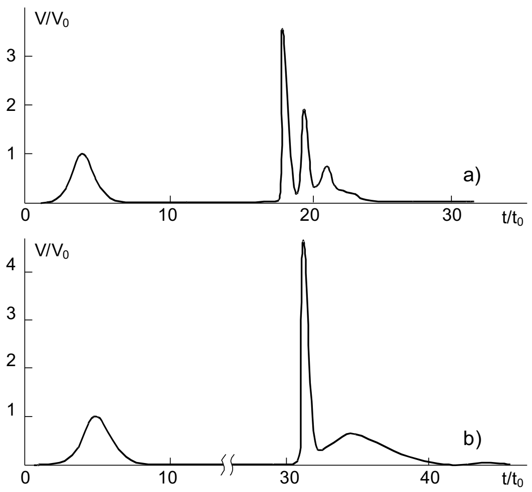

Fig. 4. (a)-Dissintegration of the input pulse into a train of solitons in the homogeneous ladder line, (b)- Suppression of "parasitic" solitons in the nonhomogeneous ladder line

4 CONCLUSIONS

In accordance with our experience, the shock waves in nonlinear coaxial waveguides with the ferrite are most suitable for construction of high power ($\geq$MW) pulse generators, and may be used in radar technique, for power plasma generation, and for electromagnetic launching processes.

The shock waves in a ladder line with nonlinear capacitors can be used in similar generators, with the difference that lower pulse levels can be achieved.

In both cases the variable delay of very short time ($\leq 10^{-9}s$) pulses can be controlled either by the bias currents or by the bias voltages, as it was done in our applications. Together with a special combination of nonlinear lines or with a combination of shortened and matched linear lines very flexible and exact regulation of the pulse duration can be achieved. The problem of pulse interactions at the line discontinuities represented by arbitrary connections of nonlinear and linear lines has been successfully solved.

The original generator of electrical solitons in combination with a nonlinear delay line based on nonlinear capacitances produces a very short pulses in the picosecond range with well controlled delay times. This offers the possibility to apply a usual PC computer as a sampling oscilloscope, limited only by the time base unit up to 1 GHz frequency range.

The computer simulation allows us to investigate the propagation of solitons in the nonlinear and nonhomogeneous ladder lines with the aim to separate the "parasitic" solitons from the main solitons after the disintegration process. The lattice solitons in nonlinear ladder lines, together with the envelope solitons in optical fibers and envelope solitons in transmission lines, may be expected to become effective tools of applied electromagnetism.

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Received 2 June 2001

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