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High-current Modulator with Nonlinear Coupled Tank Circuits

Contents

Abstract

Feasibility of the high-frequency modulator development is considered. The modulator is developed based on the system of circuits with nonlinear coupling. Results of computer simulation are presented with the ferrite as nonlinear element. Spiral MCG is used as a source of high currents. Performed simulation showed that these devices allow to obtain high-frequency current fluctuations in the frequency range from 40 MHz to 900 MHz. Performed comparison with the experimental results demonstrated rather good correlation between them.

1. Introduction

At present the generators of broadband microwave emission, using spiral MCG as the energy source evolve intensively [1,2]. In the majority of the existing designs, the attempt is made to obtain high-power radiation in the broad spectral range by directly connecting MCG to the transmitter antenna or using separate elements (spiral coil) in the capacity of the radiating element [2,3]. It is quite understood that the efficiency of these devices is very low, which is attributed to the impossibility to match the energy source with output characteristics changing with time with the antenna size no greater than tens of cm.

Operation efficiency of these generators is low also due to the fact that characteristic length of the MCG current pulse, driving the antenna, ranges from 10^{-7} to 10^{-6} s and maximum of energy in the spectrum of these pulses resides in the spectral range $10^6 \div 10^7$ Hz, which corresponds to the wavelengths $300 \div 30$ m. Since the effective length of the antenna for these devices comprises only the small part of the driving oscillations wavelength, the radiation efficiency is very small.

As the result it leads to the fact that the generators, designed as MCG directly loaded on the antenna, have very low level of the radiated power and virtually isotropic radiation pattern, which is unacceptable for a number of applications.

Mentioned problems can be solved by several different methods. One of them is design of modulator of MCG current, operating in the broad frequency range, corresponding to the wavelength less or closer than the size of the transmitting antenna. This kind of modulator should not only provide effective modulation of strong currents, generated by MCG, but also enrich the spectrum of current fluctuations upshifting it at the same time towards high frequencies [1].

The publication considers one of the possible types of these modulators and presents certain results of the computer simulation.

2. Equivalent circuit and mathematical model of modulator

Simplified equivalent circuit of the MCG output current modulator is shown at the Fig. 1.

In the considered schematics, two circuits have

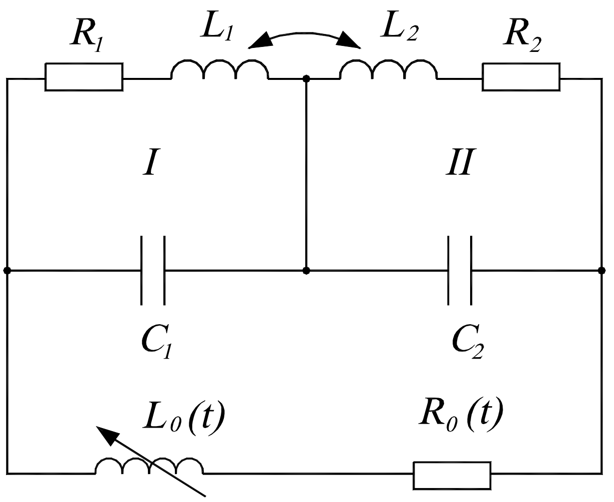


Fig. 1. Simplified equivalent circuit of the MCG output current modulator, based on the two circuits with nonlinear coupling: $L_0(t)$ is MCG inductance, changing with time; $R_0(t)$ is MCG resistance changing with time; L_1,C_1,R_1 is inductance, capacitance and resistance of the Ist modulator circuit; L_2,C_2,R_2 is inductance, capacitance and resistance of the IInd modulator circuit.

different resonant frequencies and their inductances and are coupled by the ferrite core. When the MCG is set off, oscillating currents are excited in the circuits Ist and IInd, whose frequencies are determined not only by the characteristics of elements of each circuit, but also depend on the MCG parameters, varying during its operation. This results in multiply sharp change of the ferrite magnetic permeability and, consequently, to the change of the coupling factor between the circuit inductors and the circuit switching to the nonlinear regime. As the result load characteristics of MCG change, which leads to modulation and the system switching to the nonlinear regime. As the result, load characteristics of MCG change, which leads to the modulation and enrichment of the current fluctuations spectrum, for the current flowing through the system, consisting of two ring circuits with nonlinear coupling.

Kirchgoff equations, describing the equivalent circuit, shown at the Fig. 1, have the form:

$$\begin{aligned} &R(t)I + Q^{-1}C_1^{-1} + Q_2C_2^{-1} = -\frac{L(t)I}{dt}, \\ &\dot{Q}_1 + I_1 = \dot{Q}_2 + I_2 = I, \\ &Q_1C_1^{-1} - I_1R_1 = \dot{\Phi}_1(I_1, I_2), \\ &Q_2C_2^{-1} - I_2R_2 = \dot{\Phi}_2(I_1, I_2), \end{aligned} \tag{1}$$

where I_1,I_2 are currents in the circuit, Q_1,Q_2 are capacitor charges C_1,C_2, I is output MCG current, Φ_1,Φ_2 are the flux linkages in the circuit inductors. Laws of the inductance and active resistance change are taken in the form for the spiral MCG [4]

$$\begin{aligned} L(t) &= L_0 \exp(-t\tau_L^{-1}) + l_0, \\ R(t) &= R_0 \exp(-t\tau_L^{-1}) + r_0 \end{aligned} \tag{2}$$

where L_0,l_0 and R_0,r_0 designate initial and final inductance and resistance of MCG coil and τ_L is characteristic time of MCG operation.

In order to produce high-frequency current fluctuations in the considered two-circuit system with nonlinear coupling, it is required to utilize ferrites with high speed of magnetization change, no worse than $1 \div 10$ ns. However during the simulation it is necessary to take the magnetic viscosity into account, which lowers the speed of the ferrite magnetization change in the circuits Ist and IInd [5].

The processes of ferrite magnetization in the alternating magnetic field are described either by the Bloch-Blumbergen equation or Landau equation [6]. During the simulation we have chosen Landau equation, which, although phenomenological, however allows to utilize certain constants, which can be measured experimentally. For simulation we chose the ferrite types with the greatest number of experimentally available data [7,8]. However, it has to be noted that the most complete sets of the measured constants are known for the ferrites with the low speed of the magnetization change.

However since the aim of this project is design of the specialized software and demonstrational computer experiments, showing the principal feasibility to expand spectrum and upshift it to the high-frequency spectral domain, we used low-frequency ferrites with the maximal number of known parameters.

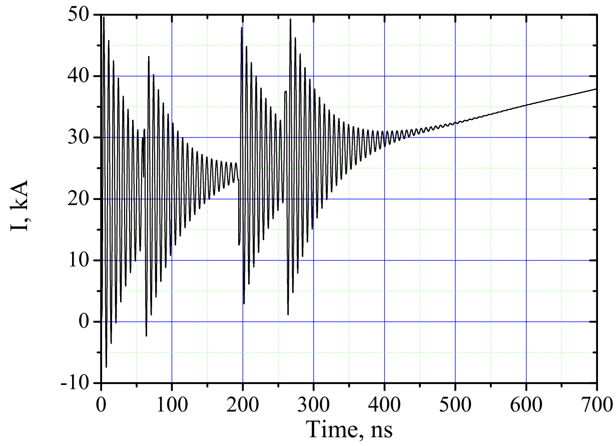
During the simulation, it was assumed that the nonlinear coupling between the circuits is performed using the long cylindrical ferrite rod in the alternating magnetic field $H_z(t)$ created by the circuit inductors and directed along the axis of the ferrite rod. The projection of magnetization vector $J_z(t)$ on the direction, inverse to the strength of the remagnetizing field, directed in parallel to the ferrite axis and is described by the Landau equation [6]:

$$\frac{dJ_z}{dt} = \gamma J_s \frac{\beta}{1+\beta^2}\left(1 - \frac{J_z^2}{J_s^2}\right) H_z(t), \tag{3}$$

where $\gamma = 2.2 \cdot 10^5$ m/As is gyromagnetic relationship for the electron, β is magnetic viscosity factor, measured experimentally for the specific ferrite, and $J_s \cong B_s\mu_0^{-1}$ is saturation magnetization.

Strengths of the magnetic fields H_1,H_2, created by the inductors L_1 and L_2 of Ist and IInd circuits, together with the ferrite core placed inside are described by the equations:

$$\begin{aligned} H_1 &= \beta_1\frac{N_1I_1}{l_1} - k\beta_2\frac{N_2I_2}{l_2}, \\ H_2 &= \beta_2\frac{N_2I_2}{l_2} - k\beta_1\frac{N_1I_1}{l_1}, \end{aligned} \tag{4}$$



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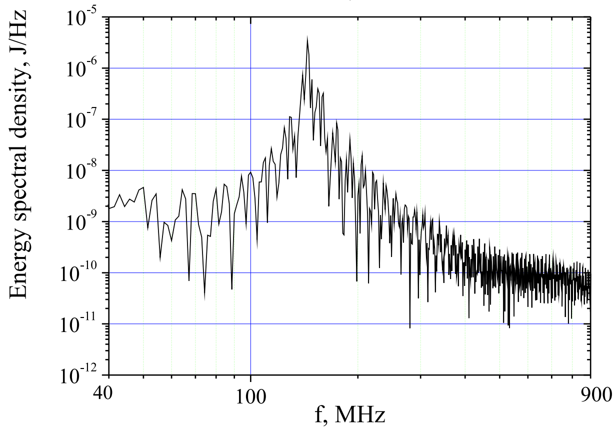
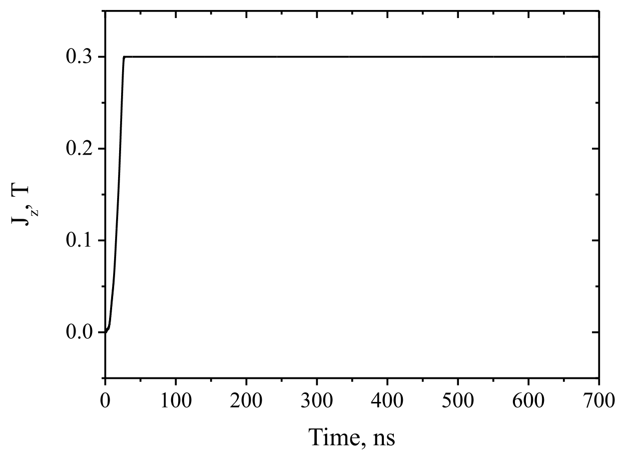


b)

Fig. 2. Time realization and spectrum of current fluctuations in the IInd high-frequency circuit for the countering interconnection of the inductors and in the coupled circuits through the BT ferrite core. Amplitude of the current pulse, generated by MCG is 20 kA. MCG parameters: initial inductance $L_0 = 10\ \mu$Hn, final inductance $l_0 = 2\ \mu$Hn, characteristic time of the inductance variation $t = 1\ \mu$s, initial resistance $R_0 = 0.1$ Ohm, final resistance is $r_0 = 0.001$ Ohm. Ferrite 0.16BT with 0.1 m length, 0.01 m radius, saturation magnetization is $B_s = 0.3T$, $\beta = 0.5$.



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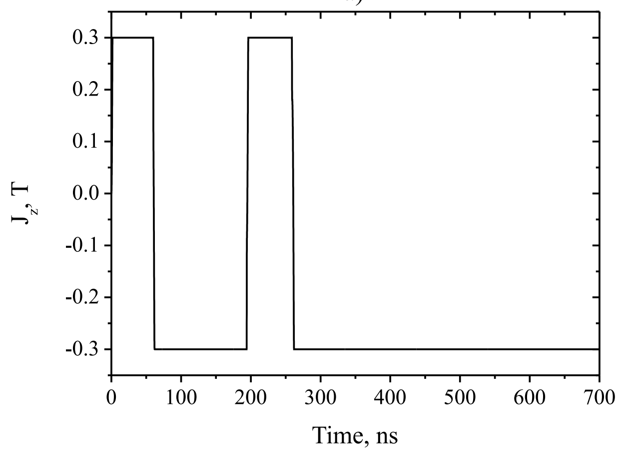

b)

Fig. 3. Magnetization of the BT ferrite core as a function of time in the first and second resonant circuits.

where N_1,N_2 is number of turns in the inductor coils, I_1 and I_2, and are the currents flowing through the inductors of the Ist and IInd circuits respectively, l_1,l_2 is the length of the inductor coil and part of the ferrite, implementing nonlinear coupling between circuits. It has to be noted that for the simulation inductors and capacitors in the circuits were selected so that their eigenfrequencies are essentially different.

3. Results of computer simulation

Substituting the expressions for the flux linkages in the circuits and core magnetization (3) in the system of Kirchgoff equations for the modulator (1) and performing its diagonalization, we obtain closed set of 7 equations, relatively to the variables I, Q_1,Q_2,I_1,I_2,J_1,J_2, which describes current fluctuations in the considered two-circuit system. The solution for this set of equations can be found only numerically. Since the set is extremely stiff we used Gear method to solve it. The simulation was done for the different pulsed currents, generated by MCG and different values of L_1,L_2, C_1,C_2 and R_1,R_2.

To perform computer simulation, software package has been designed to study the system operation for the different amplitudes and MCG current pulses, as well as for the different values of L_1,L_2, C_1,C_2 and R_1,R_2. determining eigenfrequencies of the ring circuits Ist and IInd. Designed software allows also to calculate influence of ferrite elements with different shapes and broad spectrum characteristics. However, since the target of the work was demonstration of the principal feasibility of the broadband spectrum generation and its shift to the domain of high frequencies in the system, whose equivalent circuit

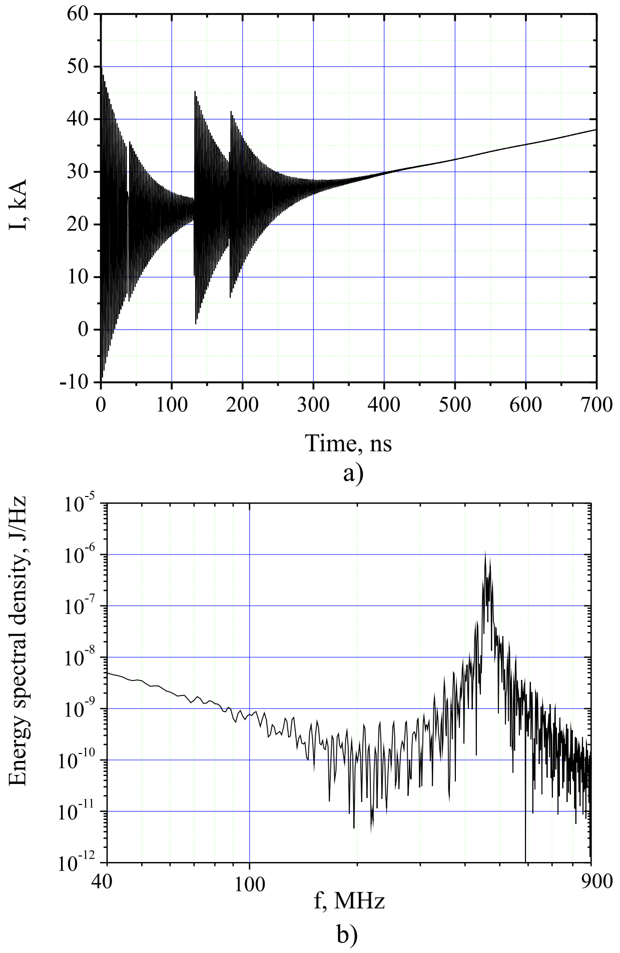

Fig. 4. Time realization and spectrum of current fluctuations in the IInd high-frequency circuit for the countering interconnection of the inductors and in the coupled circuits through the BT ferrite core. Amplitude of the current pulse, generated by MCG is 20 kA. MCG parameters: initial inductance $L_0 = 10$ μHn, final inductance $l_0 = 2$ μHn, characteristic time of the inductance variation $t = 1$ μs, initial resistance $R_0 = 0.1$ Ohm, final resistance is $r_0 = 0.001$ Ohm. Ferrite 0.16BT with 0.1 m length, 0.01 m radius, saturation magnetization is $B_s = 0.3T$, $\beta = 0.5$.

is shown at the Fig. 1, we have chosen modification where the circuits Ist and IInd have different lower eigenfrequencies. Low frequency ferrite BT have been also used in the capacity of the coupling element.

Eigenfrequency of the first circuit was chosen to be equal to 5 MHz, and the specific frequency of the second circuit 125 MHz. Basic characteristics of the ferrite, used for the implementation of the nonlinear coupling have the following values: length 10 cm, diameter 1 cm, magnetic viscosity $\beta = 0.5$ [5], magnetization of saturation $B_s = 0.3$ T [9].

Waveforms and spectra of current fluctuations in the second high-frequency ring circuit, obtained for the specified parameters, are shown at the Fig. 2.

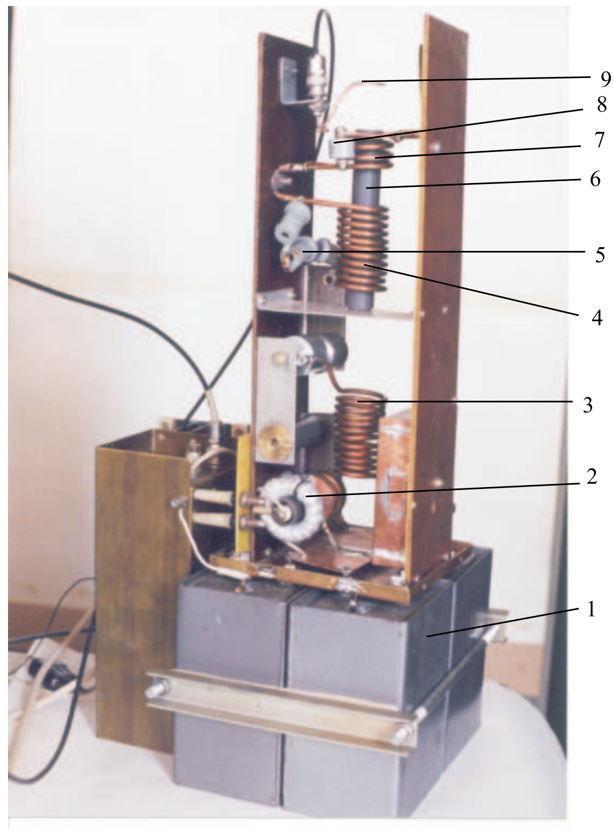

Fig. 5. Photograph of the experimental stand for the study of two-tank circuit, shown at the Fig. 1. 1 – Capacitor energy storage; 2 – Switching spark gap; 3 – Last MCG stage equivalent inductor; 4 – Inductor of the Ist ring circuit; 5 – Capacitor of the Ist ring circuit; 6 – Ferrite cartridge; 7 – Inductor of the IInd ring circuit; 8 – Capacitor of the IInd ring circuit; 9 – Coupling loop field sensor.

Magnetization of the ferrite rod in the first and second (high-frequency) ring circuit is shown at the Fig. 3.

It can be seen from the Fig. 3 that the magnetization of the ferrite core in the second circuit (similarly to the first one) changes in the leap like manner. As the result, substantially large share of the current fluctuations energy turns out to be concentrated in the high-frequency domain.

Fig. 4 shows waveforms and spectrum of current fluctuations in the first and second (high-frequency) ring circuits for the other eigenfrequencies of the ring circuits. In this case the eigenfrequency of the Ist circuit was chosen to be 7 MHz, while the eigenfrequency of the second one – 400 MHz.

Computer simulation of the Fig. 1 circuit proved that even in the case when the low-frequency ferrites are used as the coupling elements it is possible to generate current fluctuations in the second (high-frequency) circuit with the spectral content 40 ÷ 900 MHz and with total power of 24 MW in pulse for the pulse length 700 ns. For the equivalent circuit parameters with higher eigenfrequencies , total power in the spectral band $40 \div 900$ MHz was 15 MW for the same pulse length 700 ns.

Results of the computer simulation have been experimentally verified at the stand with the photograph shown at the Fig. 5.

Performed comparison of the computer simulation results and study of the current modulator confirmed correctness of the computer model and principal feasibility to expand the spectrum of current fluctuations and shift them to the domain of higher frequencies even for substantially long MCG pulses.

4. Conclusion

Specialized software package has been developed. Computer simulation of the high-current modulator operation has been performed for the system of circuits with nonlinear coupling, using ferrites with the high speed of magnetization change. These have been shown to be able to modulate effectively high pulsed currents and enrich spectrum of the current fluctuations at the same time upshifting it to the domain of higher frequencies.

Comparison of the computer simulation results with the experimental results proved basic results of computer simulation

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