Gyromagnetic source of high power wideband pulses

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Abstract. In this paper we present the results on simulation and experimental research of RF oscillations excitement in gyromagnetic nonlinear transmission line. The oscillations were observed in the frequency range 1.5–1.7 GHz. The choice of the appropriate ferrite type and irradiating helix antenna was followed by the development of high power RF source. The irradiated RF pulses were characterized by 80 kV effective potential and close to circular polarization. The gyromagnetic RF source has shown stable operation at 400 Hz repetition rate.

1. Introduction

There are different approaches to generation of high power microwave (HPM) radiation depending on the frequency bandwidth of the formed pulses. To produce narrowband HPM pulses the energy of high current relativistic electron beam is usually used in such relativistic electron devices as backward wave oscillators [1], magnetrons [2], and others. Another approach is based on a direct feeding of an ultrawideband antenna by a high voltage monopolar [3] or bipolar [4] pulses. In these solutions microwave power is formed by high voltage solid [3] or gas-gap [4] opening switches with rise times in subnanosecond timescale. Between high power narrowband and ultrawideband radiation there is the range of wideband radiation, for which the number of technical solutions seems to be quite limited. For the frequency range below 1 GHz the generation of decaying oscillation is possible by using a gas-gap switch in a LCR-circuit [5]. At higher frequencies, the gas-gap switch becomes unstable. A promising solution in this frequency range seems to be gyromagnetic nonlinear transmission lines (GNLTLs) [6-8]. These lines have usually coaxial geometry with partial filling by a saturated in a longitudinal direction ferrite. Propagation of a high voltage pulse with shock rise time through GNLTL excites in the ferrite gyromagnetic precession in a form of a decaying spin waves. The oscillating magnetic momentum creates in the transmission line an electromotive force, which leads to formation of current oscillations. The amplitude of these coupled electromagnetic-spin oscillations is growing while the shock front propagates through GNLTL up some saturation level at the GNLTL length close to 1 m. The incident high voltage pulse after propagation through GNLTL becomes modulated by decaying RF oscillations, which can be irradiated by an antenna with a corresponding bandwidth. In this paper we present the results on the research of the RF pulse formation in the frequency range 1.5–1.7 GHz by GNLTL and the development of a high repetition rate source of high power RF pulses.

2. Simulation

The analysis of a nonstationary dynamics of the electromagnetic shock wave with nonsinusoidal oscillations behind the shock front in GNLTL is generally very complicated. Simulation of this nonstationary dynamic as it is presented for instance in [9] is out of the scope of this paper. Here we present the calculation of a stationary electromagnetic shock wave in GNLTL. This stationary solution...
is possible for a quite long GNLTL, when nonlinearity, dispersion and dissipation together lead to formation of a stationary waveform, which does not change while moving through GNLTL.

The most correct approach is to write the exact Maxwell equations for GNLTL and integrate them. Nevertheless, when the cathode-anode gap in a GNLTL is much less than the wavelength of the excited RF oscillations the electromagnetic field can be averaged over this gap. This approach leads to formulation of the telegraph equations, which take into account only the main TEM-wave. Though the higher modes can play a certain role in RF oscillations formation inside GNLTL in the first approximation we will omit them.

The telegraph equations for GNLTL can be rewritten as a dimensionless wave equation:

\[
\frac{\partial^2 h_\varphi}{\partial \zeta^2} - \frac{\partial^2 h_\varphi}{\partial \tau^2} = \lambda \frac{\partial^2 m_\varphi}{\partial \tau^2},
\]

where \(h_\varphi\) – is dimensionless azimuthal component of the radially averaged magnetic field (which is proportional to the current and voltage of the propagating electromagnetic pulse), \(m_\varphi\) – dimensionless azimuthal component of the radially averaged magnetization of the saturated ferrite, \(\tau\) and \(\zeta\) – dimensionless time and longitudinal coordinate, \(\lambda\) – the parameter of the filling coaxial line by ferrite. The solution of the equation (1) with zero initial conditions in a form of a stationary wave depending only on one variable – the phase leads to direct proportionality between \(h_\varphi\) and \(m_\varphi\).

Substituting \(h_\varphi\) for \(m_\varphi\) in the Landau-Lifshitz equation

\[
\frac{\partial \mathbf{m}}{\partial \tau} = -[\mathbf{m} \times \mathbf{h}] - \alpha [\mathbf{m} \times [\mathbf{m} \times \mathbf{h}]],
\]

allows to calculate it numerically for the ferrite initially saturated in the longitudinal direction, \(m_\varphi=0, m_r=0, m_z=1\). Taking into account the parameters of the chosen GNLTL geometry and placing the phenomenological parameter of magnetic losses \(\alpha=0.05\) \([10]\), the solution of the equation (2) can be recalculated into the waveform of the high voltage pulse, Figure 1.

![Figure 1. Calculated stationary waveform in GNLTL](image)

This waveform is calculated for the amplitude of the high voltage pulse of -130 kV and corresponds to the center frequency of excited oscillations of about 1.7 GHz. In the next section we present the results of experimental investigation of high power RF oscillation in GNLTL.

3. RF oscillations in gyromagnetic nonlinear transmission line

For the investigation of RF oscillation formation in GNLTL an experimental setup has been developed, which schematic diagram is presented in Figure 2.
As a high voltage driver SINUS-160 has been used, which produces high voltage pulses with duration of about 5.5 ns and amplitude up to -140 kV by using a Tesla transformer incorporated in a forming line equipped by a self-breakdown gas-gap switch. The rise time of the high voltage pulses produced by this switch was of about 1.2 ns. We have tested two types of NiZn ferrite rings with different saturation magnetization: 0.35 T and 0.4 T. The ferrite rings were placed in an oil-filled coaxial line of about 1 m length embedded into solenoid, which saturates ferrites in the longitudinal direction. The waveform of the high voltage pulse at the output of GNLTL was measured in a quite long transmission line loaded onto the matched resistive load. The RF pulse generation was tested for two amplitudes of the incident pulse: 120 and 140 kV for GNLTL with 0.4 T saturation ferrite, Figure 3.

We observe that at lower amplitude of the incident pulse the efficiency on RF generation remains at the same level as for the higher amplitude while the center frequency of oscillations is decreased. The observed waveforms are very similar to the calculated ones, Figure 1, which validates the theoretical model and the value of the magnetic losses constant $\alpha$ close to 0.05. The waveforms of the incident pulse and output pulses for two types of ferrites under optimal bias axial magnetic field of about 40 kA/m are shown in Figure 4.

![Figure 2. Schematic diagram of the experimental setup: HVD – high voltage driver; TL – transmission line; NLTL – nonlinear transmission line; $R_L$ – resistive load.](image)

![Figure 3. Waveforms of the high voltage pulse at the input and output of GNLTL for two amplitudes of the incident pulse at the optimal bias magnetic field (40 kA/m)](image)

![Figure 4. Waveforms of the high voltage pulse at the input and output of GNLTL for two ferrite types at optimal bias magnetic field (40 kA/m)](image)
As follows from Figure 2 the ferrite with 0.4 T exhibits high efficiency of RF oscillations excitation. Probably these two ferrite types differ in other significant parameters but the manufacturer does not control them. The center frequency of oscillations is little lower than in simulation and is of about 1.5 GHz and 1.6 GHz for 0.4 T and 0.35 T respectively.

4. High power RF wideband radiation

After choosing the most efficient ferrite a conical helix antenna with center frequency of 1.5 GHz and bandwidth of 0.8 GHz (SWR lower than 2) has been developed and installed. The appearance of the developed high power RF source is presented in Figure 5.

![Image of gyromagnetic source](image)

**Figure 5.** Appearance of gyromagnetic source of high power wideband pulses.

The radiation pattern has of about 56° width at -3 dB level, and polarization was close to circular. A typical waveform of a measured signal by TEM-antenna in the vertical polarization is shown in Figure 6 as the product of electrical field strength multiplied by the distance to the receiving antenna (for 140 kV incident pulse amplitude).

![Image of waveform](image)

**Figure 6.** Waveforms of RF pulse at the receiving antenna as the product of electrical field strength multiplied by the distance and its spectrum for 140 kV incident pulse amplitude.

The center frequency of the irradiated RF pulse was of about 1.6 GHz and bandwidth of about 0.6 GHz at -10 dB level. For the reduced incident pulse amplitude to 120 kV the measured irradiated RF pulse waveform and its spectrum are presented in Figure 7.
Figure 7. Waveforms of RF pulse at the receiving antenna as the product of electrical field strength multiplied by the distance and its spectrum for 120 kV incident pulse amplitude

The effective potential of radiation was close to 80 kV for both cases, but at lower incident pulse amplitude the duration of the RF pulse was reduced from 4 to 2 ns. The frequency at lower amplitude was decreased to 1.4 GHz. The tests of the RF source at 400 Hz pulse repetition rate did not lead to electrical breakdown and was accompanied by stable operation.

5. Conclusion
In this paper we presented results on the research and the development of the high power RF gyromagnetic source. The simulation of RF oscillation excitement showed good agreement with experimental result both in frequency and in amplitude. The estimation of the magnetic loss constant $\alpha$ gives value of the order of 0.05. The generated RF pulses are characterized by 80 kV effective potential, duration up to 4 ns and almost circular polarization. Together with 400 pulse repetition rate and relative compactness the developed RF source seems to be a promising solution as a high power RF generator.

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