Multiunit UWB Radiator of Electro-Magnetic Waves with Controled Directional Pattern

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Abstract – New technology used semiconductor elements for generating of high power pulses of sub-nanosecond duration develops successfully during last few years. Such generators are compact (> 10 MW/kg), can work long time (resource > 10^{10} pulses), generate pulses with high repetition rate (1–1000 kp/s). The short pulses (< 1 ns) can be effectively radiated in free space by non-large antenna as the electromagnetic waves of the video pulse shape with ultra wide band wavelength range (so-called UWB radiation).

One module of the «FID Technology» high power generator has a peak power by level ~ 40 MW (output pulse ~ 45 kV on 50-ohmic load). A short pulse duration and limited level of the voltage have allowed us to make a relativity non-complex device without oil insulation. Such module practically does not require service. Each generator module is connected to a radiating antenna that is built as flat-plate TEM horn with an aperture size of the 28×14 cm. One module of the generator is used average electrical power on ~ 40 W range from the unit power supply. The functionally completed unit has become after it included a device for auto synchronization and a control of the output pulse time-delay. An assembly of few this units is used as the multiunit UWB-radiator with controlled direction of the radiation patterns.

1. Introduction

The high power nano-second pulse generators are developed successfully last years using semiconductor technology [1, 2, 3]. Now pico-second pulsed high power generators are constructed also (see website: www.fidtechnology.com). They are applied as power source with high repetition of pulses in laser technique and into the devices for electromagnetic sub-nanosecond pulsed radiation with ultra-wideband frequency spectrum (UWB radiators). The UWB radiators are used in a radar technology of high spatial resolution and for checking of electromagnetic compatibility.

2. Problems of Impulse Radiators

Usual the high power UWB radiation is produced on an antenna array exciting by spike pulses of electrical power of multi-megawatt level. The high voltage pulses are supplied on the antenna feeders by coax cables (typical impedance is 50 Ω). The feeder must hold a high voltage and provide a passing of sharp pulses. The UWB radiator technique is partially like the microwave radar but it has principle differences. A microwave radiation in the radar is formed as electromagnetic processes of stationary oscillations [4–6] and the high effective radar operates on or near a resonance frequency. A classic radar antenna is made as a parabolic reflector witch is irradiated from open face of pyramidal type metallic horn. Half angle of a radiation pattern may be estimated by one factor: $\Delta\theta \approx 16° T/a_1$ (T – oscillation period, ns; a_1 – size of radiation surface, *m*) [6].

Opposite the UWB radiation may be presented as a combination of many electromagnetic waves with ultra wideband frequency spectrum. The pulse radiation from antenna is being formed as electromagnetic process of non-stationary oscillations. Various approximate analytical and numerical methods are used now to calculate it [7–10]. A time variation of radiated pulse depend at first on few parameters of a voltage excited pulse: τ_f – rise-time, τ_p – pulse duration, and type of pulse shape. At last it depend on a direction of observation. In particular, the pulse radiator will be close to the microwave radar in a case of bi-polar pulses of the voltage exciting pulsed antenna [11].

We have used a mono-polar voltage pulses with parameters: $\tau_f = 0.06$–0.2 ns, $\tau_p < 1$ ns, amplitude is 10–100 V for test generators (www.trimcom.ru) and high power of 2–50 kV (www.fidtechnology.com). It notices that pulsed radiators to compose with the mono-polar short pulse generator and TEM-horns of square aperture are exploited successfully during last years at All Russian NIIOFI [7, 8]. In the IHED RAS are also used the TEM-horns array as the high power UWB radiator [12, 13].

3. Approximate Calculation for Pulse of Electrical Field Radiating by TEM-Horn

A TEM-horn for pulsed radiation is usual made with two metallic flat electrodes with increasing gap between electrodes with a moving from a place of a feeder voltage lead-in to a horn face of so-called the open radiating surface. A coordinate plane (x, y, z_1) is set on the horn face, and axis z is set on symmetric axis of horn with plus direction outside the face. A cross-section of the horn has a rectangular form with sizes: $a(z)$ – electrode width (along x-axis) and $h(z)$ – gap between electrodes (along y-axis). As a rule typical horns have small divergence angles ($0.5\ da/dz$, $0.5\ dh/dz < 0.3$). Sizes of the horn face (at z_1-point) equal a_1 and h_1. On radiated surface at z_1-point the horn electrodes are cut short.

The TEM-horns compared with the microwave horns have specific character of losses for transported wave power. The losses are occurred due to the margins open sides in the TEM-horn. "Useful" wave power ($\eta_0(z)$ part of total wave power) is transporting between electrodes in "useful" area of the $A(z) = ah$. Other ("non-useful") part of the total wave power is transporting outside the two-electrodes area. Also radiated losses on the margins sides are occurring. The $\eta_0(z)$ part of useful power regarding total power is limited approximately by ratio of $\eta_0(z) = (R_0 - R(z))/R_0$, where $R(z)$ is the wave two-electrodes impedance and $R_0 = 377\ \Omega$. In a case of the square horn aperture ($a_1 = h_1$) the $\eta_0(z)$ is equal to 0.5 and for the aperture ($a_1 = 2h_1$) it equal to 0.7. High efficiency of the TEM-horn is arriving for aspect ratio of the $a_1/h_1 \geq 2$.

For a field approximate calculation at far zone (a distance of $z_f >> a_1$, h_1) one can use time domain method of the equivalent surface current [7, 8]. It is a widening of known Huygens-Kirchhoff method developed for microwave radars [4–6]. Instead currents of real sources are used the secondary currents. They are determined by means of data for the $\boldsymbol{E}_s(s,\ t)$ – electrical and $\boldsymbol{H}_s(s,\ t)$ – magnetic fields on some surface placed around the real sources. For shortness we write the final expression for electrical field at far zone

($z_f = r$) on z-axis of the horn symmetric axis (omit time delay by $\Delta t = r/c$, $c = 0.3$ m/ns – wave velocity):

$$E_y(r,t) = \iint_s \left[\frac{\partial E_y(s,t)}{1.2\pi\cdot\partial t} - R_0\frac{\partial H_x(s,t)}{1.2\pi\cdot\partial t}\right]\frac{dx_s dy_s}{r}. \quad (1)$$

We use the following units: r – m; t – ns; c – m/ns; E – kV/m; H – kA/m; $P = E\cdot H$ – MW/m^2; V – kV; I – kA; R – Ω; $W = V\cdot I$ – MW; $E/H = R_0 = 120\pi\ \Omega$ – impedance of electromagnetic wave in free space.

Some problems arise for a choice of the s – surface and a calculation of the field intensity on this surface. Simple way to solve they will be apply known assumptions used in the radar analysis [5, 6]: 1) the $s \equiv s_1$, 2) neglect the reflected currents on the external electrode surfaces, 3) use the moving transverse electromagnetic (TEM) wave as a source of the (E_y, H_x)-fields ($-R_0H_x = E_y$, $-V_1(z_1,\ t) = h_1\cdot E_y(z_1,\ t)$). This approach is used in [7, 8] for a calculation of an antenna array with the TEM-horns excited simultaneously. The authors suppose that the currents on electrode edges overflow from one horn to the other without any reflections. Same approach may be used for rough calculations. In practice estimation of the electrical field value at far zone is obtained usually by approximate formula [12]

$$FOM = r\cdot E \approx \frac{E_1\cdot h_1 a_1}{0.6\cdot\pi\cdot\tau_{1f}} \approx \frac{(\eta_{1g}W_{g0}h_1a_1)^{0.5}}{0.1\cdot\tau_{1f}}, \quad (2)$$

where are $FOM = rE$ – Factor of Merit (kV), η_{1g} –radiation efficiency for W_{g0} – generator power, τ_{1f} – effective rise-time of pulsed radiation. It is some problems how to estimate values of the η_{1g} and τ_{1f}.

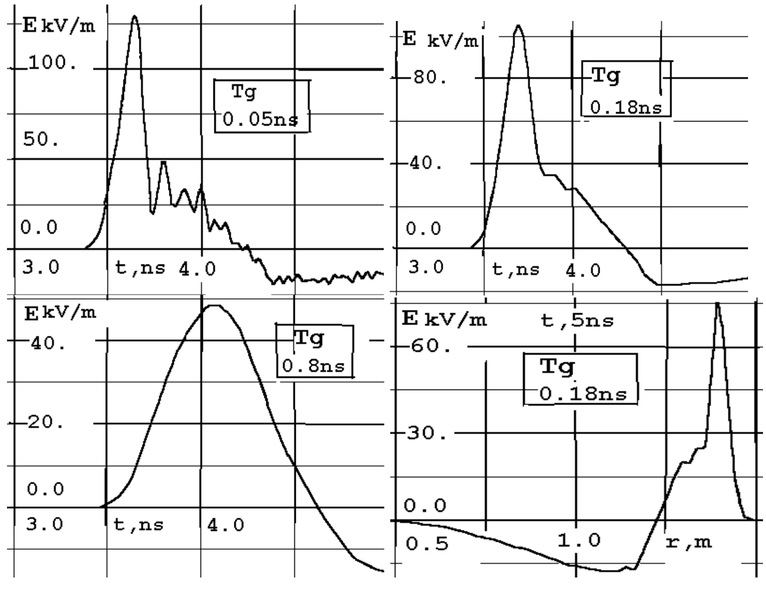

Fig. 1. The numerical results of the electrical fields $E_z(t,\ r = 1\text{ m})$ and $E_z(t = 5\text{ ns},\ r)$ are shown for UWB radiator with TEM-horn in the (r, z)-geometry

The dynamics of a forming for pulsed electromagnetic radiation may be simulated by known numerical full-electromagnetic PIC code KARAT [9, 10] (karat@tarak.msk.su). Some results are given in Fig. 1.

In Fig. 1 the horn has the ring radiation surface $s_\varphi = 2\pi \cdot r_1 h_1$ ($2r_1 = 0.2$ m – diameter of the electrode edges and $h_1 = 0.15$ m – gap between electrodes). Parameters of pulse generator are: power W_g ($T \geq T_g$) = 360 MW, and a time profile of pulsed voltage $V_g(T)/V_0 = (\sin(\pi T/2T_g))^2$ for $T < T_g$ and 1 for $T \geq T_g$ with various full rise-time: $T_g = 0.05$, 0.18 and 0.8 ns. The calculation results are clear shown on the non-stationary processes in pulsed radiator. They are developed as a shock exciting of wave oscillations particularly in a case of sharp front ($T_g << h_1/c$). This processes produce due to self-inductance of H_φ-field (a term with $\partial H/\partial t$ in eq. (1)). It form a rapid slump rear side on an pulse shapes of the $E(t)$ and $H(t)$. Besides this one can see in Fig. 1 a formed a reverse polarity field in the electromagnetic wave bunch (see $E(r)$ at the $t = 5$ ns).

4. Experimental Sensors for UWB Electromagnetic Wave and System Registration

A registration of the UWB electrical signals has been produced as high speed oscilloscopes of the S-7-19 and SRG-7 (not less 5 GHz bandwidth) as the "TRIM" (production by “TRIM Ltd.”) digital sampling oscilloscope with 10 GHz bandwidth. We use various the voltage divider and sensors with the voltage strength up to 100 kV and with high frequency bandwidth [13]. The coaxial cables are tested and measured a weakening of the voltage pulse after passed through a cable. The computer programs (made by V.E. Ostashev using cable model in [14]) was used for simulations the weakening and reshaping of the pulse signal.

The $E(t)$ fields in electromagnetic wave traveling in a free space were measured by sensors of the linear strip transducer [15]. The original strip transduser was made at All Russian NIIOFI. It has sensitivity of 0.5 V/(kV/m) with a communication cable of 12 m length and a “hard” frequency correction provided low distortions for an measurements of the field $E(t)$ with a pulse duration from 0.1 ns up to 5 ns. In measurements of the sub-nanosecond pulses we use also the strip transduser of production by IHED RAS.

5. Set-up of Multiunit UWB Radiator

The multiunit UWB radiator (Radiator) with a controlled direction of the radiation pattern is constructed by using few units of the pulsed radiators with a control system for a time-delay of output pulses. Each radiator-unit composes by the radiating antenna-unit connected with the high power generator-unit (GIN70) and the auto-synchronizing-unit (ASU) provided a stabilization of time delay (between input pulse, which starts the ASU and output power pulse from the GIN70). The ASU was synchronized by starting-pulse from the multi-channel synchronizing master generator (MSG). The MSG does also in accordance of outer controlled signal a change of the time-delay between any its channels. The tested Radiator was composed on base of two generators of GIN70 and four antenna modules. The ASU and MSG devices were made by “TRIM Ltd.” Company.

The GIN70 (production by “FID Technology”) has two coaxial feeders (each with impedance 50 Ω) produced two synchronized power pulses. Pulsed power parameters on each feeder are given at table.

No Unit of GIN70	Pulse voltage, kV	Pulse Power, MW
1	34–36	48–55
	35–38	
2	40–42	64–72
	40–43	
Total Synchronized Power		112–127

Other parameters of the pulsed voltage on each channel were a rise-time: $\tau_{0g} \approx 0.14$ ns on 0.1–0.9 levels of peak voltage, and a duration: $\tau_p \approx 0.6$ ns on half level of peak voltage. GIN70 in mode 100 Hz repetitions of pulses consumed 1.6 A from DC 24 V source. GIN70 is placed in metallic box with 11×12×17 cm sizes.

The one antenna module (production by IHED RAS) is constructed as the flat-plate TEM-horn with outer dimensions of the 0.28×0.14 – radiated aperture and a 0.5 length. As there was noted in sec. 3 the TEM-horn with aspect ratio of $a_1/h_1 \geq 2$ is better than such with square aperture. Assembly from two the antenna modules connected with the GIN70 is presented one the radiator unit with square aperture. The tested Radiator was presented two this unit joined one with other on horizontal plane.

6. Experimental Data for the Radiator

The $E(t)$ electric fields were measured by the strip transduser sensors at distance 6m (between sensor and antenna face). Experimental results are given in Fig. 2.

Waveforms in Fig. 2 there were are produced at tumbling of Radiator on various azimuth angles (in horizontal plane). The (A, B, D) pictures of Fig. 2 were made in a case of synchronizing the units (i.e. without a change of the time-delay). The (C, E) pictures were made with the changes of the time-delay ($\Delta t \approx 0.25$ ns for C-picture, and $\Delta t \approx 0.55$ ns for E-picture). Direction radiated pattern (for comparative peaks of electrical field of $E_{\max}(\varphi)/E_{\max}(\varphi = 0)$) with and without elektronics scanning is given below in table.

Angle φ, grad	0	7.5	15	30
Without electronics scanning	$E_{\max}(\varphi)$/ $E_{\max}(0)$ 1.0	≈ 0.7	≈ 0.36	≈ 0.2
With electronics scanning		≈ 0.9	≈ 0.8	≈ 0.5

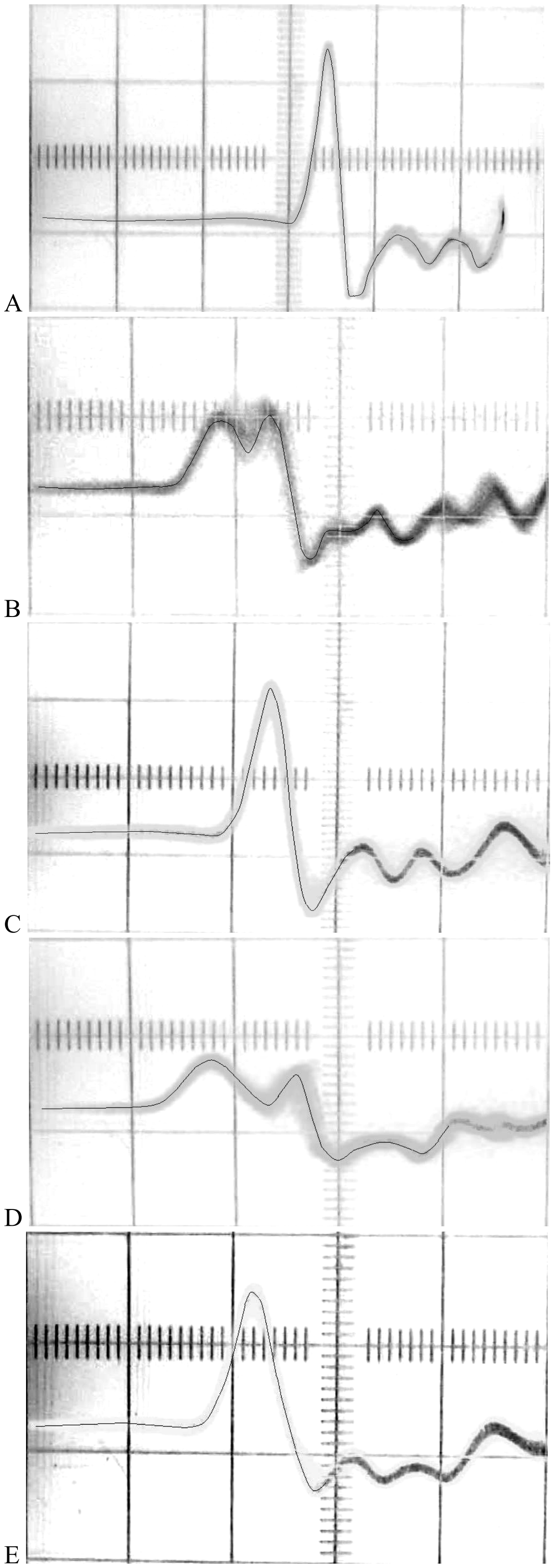

Fig. 2. (A–E). Electric field $E(t)$ at $r = 6$ m from Radiator, and for angles: A – 0°; B, C – 15°; D, E – 30°. Horizontal scale of t – 0.6 ns/div, vertical scale of $E(t)$ – 9 kV/div

So the angle divergence of pulsed radiation for the tested Radiator equal $\Delta\varphi_E \approx \pm 12°$ – for peaks of electric field, and $\Delta\varphi_P \approx \pm 7°$ – for peaks of Poynting flow of pulsed power (estimations for level 0.5 from maximum value). Maximum angle of electronics scanning is limiting the angle divergence of pulsed radiation for one antenna module. But antenna with high angle divergence of pulsed radiation will produce lower field intensity.

The $E_{\max}$ – peaks for pulsed radiation from the separate modules were also measured. They are presented below.

No module	$E_{\max}$, kV/m	*FOM*, kV
1	8.5	≈ 50
2	13	≈ 80
together	≈ 21.0	≈ 130

The No. 1 module was made with lower parameters both a pulsed power value and not good synchronizing between its channels.

The *FOM* parameters for few pulsed radiators are given at comparing. In sec. 2 there are the computer simulation results (see Fig. 1) for the (r, z)-horn with a ring radiation surface. This radiator has a rounding direction pattern. The *FOM* parameters for the (r, z)-radiator and the tested Radiator will be identical if attitude of values their pulsed powers will not less 4. There were received comparative experimental data for our antenna module and "typical" antenna composed with TEM-horns of square aperture (production by All Russian NIIOFI). For same pulse power generators the antenna module produced the *FOM* approximately in 1.5 times more compared with the *FOM* value for the "typical" antenna.

7. Conclusion

The system with a controlled direction of the radiation pattern was built and successfully tested for high power radiator of 130 MW pulsed power.

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References

[1] V.M. Tuchkevich, I.V. Grekhov, *New principles of pulse power commutation by semiconducter device*, Leningrad, Nauka, 1998, 116 pp. (in Rus.).

[2] S.K. Luibutin, G.A. Mesyahz, S.N. Rukin et al., Rus. Instr. and Techn. Exp., No. 5, 106 (2001).

[3] E.A. Alichkin, S.K. Lubutin, A.V. Ponomarev et al., Rus. Instr. and Techn. Exp., No. 4, 106 (2002).

[4] J.A. Stretton, *Electromagnetic Theory*, N.Y., 1941 (Rus. transl., Moscow, Gostechizdat, 1948, 539 pp.)

[5] L.A. Wainstein, *Electromagnetic waves*, Moscow, Sov. Radio, 1957, 581 pp. (in Rus.).

[6] G.T. Markov, D.M. Sazonov, Antennas, Moscow, Energy, 1975, 528 pp. (in Rus.).

[7] S.A. Podosenov, A.A. Sokolov, Radiation and Measurement of Electromagnetic Fields, Moscow, Sputnik, 2000, 249 pp. (in Rus.).

[8] O.V. Mikheev, S.A. Podosenov, K.Yu. Sakharov. IEEE Trans. Electr. Compat. 43, 1, 67 (2001).

[9] V.P. Tarakanov, Mathematical Simulation. Problems and Results, Moscow, Nauka, 2003, p. 456.

[10] V.M. Fedorov, E.F. Lebedev, V.E. Ostashev et. al., Rus. J. Techn. Phys. 70, 6, 84 (2000).

[11] V.I. Koshelev, V.I. Buynov, B.M. Kovalchuk et al., SPIE Proc. **3158**, 209 (1977).

[12] V.E. Ostashev, A.V. Ulyanov, V.M. Fedorov et al., *in: Trans. Inst.of IHED RAS*, V. 4, p. 67, M., 2002. 381 pp.

[13] E.F. Lebedev, V.E. Ostashev, A.V. Ulyanov et al., *in: Trans. Inst.of IHED RAS*, V. 5, p. 81, M., 2003. 446 pp.

[14] P.P. Deichuli, V.M. Fedorov, A.A. Yahzenko. *Preprint 86-56, Inst. Nucl. Phys*, Novosibirsk,. 1986, 24 pp.

[15] S.A. Podosenov, K.Yu. Sakharov, Ya.G. Svekis, et al., IEEE Trans. Electr. Compat. 35, 4, 566 (1995).