Arrays of combined antennas excited by high-voltage bipolar pulses

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Abstract. The main characteristics of the TEM antenna and the combined antenna (KA) with extended bandwidth are compared using numerical simulation. The influence of the high-voltage coaxial-strip junction on the KA characteristics is shown. The effective radiation potential is compared relative to the utmost one for high-power UWB radiation sources based on KA arrays, as well as single IRA, HIRA, TEM, and KA antennas.

1. Introduction
Theoretically and experimentally, it was shown [1, 2] that the combination of electric and magnetic radiators allows minimizing the reactive energy and expanding the passband towards low frequencies. The passband of the antenna based on a combination of an electric monopole and a magnetic dipole (frame) was limited in the high-frequency region by the destruction of the pattern [1]. To expand the passband to the high-frequency region, a combined antenna based on the TEM horn was developed [3, 4]. The antenna was designed for high-power sources of ultrawideband (UWB) radiation. Single antennas and KA arrays were excited by bipolar voltage pulses with a duration of 0.2–3 ns and an amplitude of 100–200 kV at a repetition frequency of 100 Hz [5]. The transverse dimensions of the KA are approximately equal to half the wavelength at the central frequency of the bipolar pulse. The radiated pulse has three time lobes. The energy efficiency of the KA reaches 90%.

The main parameter used to evaluate high-power UWB radiation sources is the effective potential, which is defined as the product of the peak electric field strength by the distance r in the far-field zone.

The main task of this work is a comparative evaluation of the effective potential of high-power UWB radiation sources based on KA arrays relative to the utmost one.

2. The model KA
The KA antenna is a combination of a TEM horn and a magnetic dipole with a common input. We illustrate the differences between the characteristics of the TEM antennas and KAs using numerical simulation. Figure 1 shows the geometries of the TEM antenna (a) and a KA (b, c) with cross dimensions of 15 cm, corresponding to the KA optimized for the radiation of a bipolar pulse with a duration of 1 ns. The TEM horn had an exponential shape. To control the KA characteristics in the upper frame, a plate (c) is used, which divides the magnetic dipole into active and passive. In an active magnetic dipole, the current from the local source is closed to the back plate along the upper one. Passive magnetic dipoles are excited by fields of currents flowing through the plates of the TEM horn. The gap between the plates at the TEM horn input is small, which corresponds to radiation with low peak power limited by an electrical breakdown.
Figure 1. Geometry of the simulated antennas, 1 – TEM horn, 2 – active magnetic dipole, 3 and 4 – passive magnetic dipoles.

The results of the antenna simulation are shown in Figures 2 and 3. The voltage standing wave ratio (VSWR) of the KA (Figures 2b and 2c) is shifted toward lower frequencies relative to the VSWR of the TEM antenna (Figure 2a), as predicted by the theory [1, 2]. The front-to-back ratio of radiation (Figures 3b and 3c) increases compared with the TEM antenna (Figure 3a). The calculations show that the patterns of the model antennas are not destroyed until the 5 GHz frequency. Thus, the KA passband is significantly wider than the passband of the antenna based on a combination of an electric monopole and a magnetic dipole [1].

Figure 2. VSWR versus the frequency of the TEM antenna (a) and KA (b, c).
Thus, the KA is the optimal choice for the element of UWB arrays by the ratio of geometric dimensions to the passband and the value of the backward power.

3. Array element
Since the array elements of high-power UWB radiation sources are excited by high-voltage bipolar pulses, their inputs should provide the necessary electrical strength. For this purpose, the diameter of the coaxial feeder is increased and an insulator with a coaxial-strip junction at the KA input is used (Figure 4). This results in degradation of the passband, especially in the high-frequency region. VSWR of an experimental KA [6] with dimensions similar to the model KA (Figure 1c) is shown in Figure 5. One can see that the VSWR value in the high-frequency region has increased sharply compared to the VSWR of the model KA (Figure 2c).

Figure 4. KA for a 1 ns high-voltage bipolar pulse.
4. KA arrays
The arrays consist of a feeder system and KA radiators. The feeder system is used for matching the real part of the radiating system resistance with the wave impedance of the bipolar pulse generator and the equal-amplitude distribution of voltage pulses across the array elements. In the experiments, we used wave transformers, power dividers, and feeders with a 50-Ohm wave impedance of various designs. This influences the energy losses in the feeder system. Figure 6 shows the design of the 8×8 KA array for a high-power UWB radiation source [7].

An expression for estimating the utmost effective radiation potential was obtained in [8]:

\[ rE_{r}(r,0,0,0) = \frac{Z_{0}W}{2\sqrt{2\pi}} \sqrt{\int_{0}^{N(\omega)} \sum_{n=1}^{(2n+1)} d\omega} , \]
where $rE_\theta$ is the product of the electric field strength $E_\theta$ at a distance $r$ in the far-field zone; $Z_0$ is the wave impedance of the medium surrounding the antenna; $W$ is the total radiated energy. Integration is performed using positive and negative frequencies $\Omega$: $N = [\omega_0a/c + 2\pi]$, $a$ is the radius of the minimum sphere in which the antenna or array is placed, and $c$ is the velocity of light.

It is of interest to compare IRA [9], HIRA [10], TEM [11], KA [12] antennas and KA arrays by the selected criterion. Below we will consider $2 \times 2$ arrays [13] excited by a 3 ns bipolar pulse, $4 \times 4$ arrays [12] and $3 \times 3$ arrays [14] excited by a 2 ns bipolar pulse, $4 \times 4$ arrays [6] and $8 \times 8$ arrays [7] excited by a 1 ns bipolar pulse, and $4 \times 4$ arrays excited by 0.5 ns [15] and 0.2 ns [16] bipolar pulses. Based on the information presented in these papers, the following parameters were estimated: the energy and the spectrum of radiation for IRA and HIRA (Table 1 in parentheses shows estimations of the energy of electric pulses at the inputs of the antennas), as well as the energy and the spectrum of the voltage pulse at the TEM and KA inputs. In the latter case, the energy efficiency of the antennas was assumed to be 100%. The frequency band was estimated by the level of -10 dB, and $\omega_0$ was selected as the average value in this band. The spectrum width for the studied antennas was in the range of 100-200%.

For a comparative analysis, the $rE_0 = rE_{2n}$ was estimated for various radiators. The values of the efficiency coefficient as the ratio of the experimentally measured radiation potential to the utmost one $rE_{exp}/rE_{0}$ were obtained. Table 1 shows the initial data and the calculation results. Here, $\tau_p$ is the duration of the bipolar voltage pulse, $W$ is the total radiated energy, $f_i$ and $f_i$ are the upper and lower boundary frequencies of the radiation pulse spectrum, $a$ is the radius of the minimum sphere in which the antenna or array is placed, $U_{g max}$ is the maximum value of the pulse voltage at the antenna/array input, and $rE_p$ is the measured effective potential of radiation.

The efficiency coefficient $rE_{exp}/rE_0$ for single antennas IRA, HIRA, TEM, and KAs is 0.5, 0.45, 0.35, and 0.26, respectively. As it follows from the results obtained for KA arrays, the relative efficiency increases when the the number of elements increases. For a 9-element array of combined antennas excited from a 2 ns bipolar pulse generator [14], the maximum value of $rE_{exp}/rE_0 = 0.58$ was obtained due to a decrease in energy losses in the feeder system when using gas (SF$_6$) insulation. The results of the obtained efficiency evaluations $rE_{exp}/rE_0$ are also shown in Figure 7.

Table 1 also shows efficiency estimations by the peak electric field strength $k_E = rE_p / U_{g max}$ and by the area $k_S = rE_p / S$, where $S$ is the area of the antenna/array aperture. Here $k_E = 21.5$ is the maximum for the $8 \times 8$ KA array, and the efficiency by the area $k_S = 1.6 \cdot 10^7$ kV/m$^2$ is the maximum for the $4 \times 4$ KA array excited by a 0.2 ns bipolar pulse.

![Figure 7](image-url)  
**Figure 7.** Measured effective radiation potential relative to the utmost one versus the number of combined antennas in the array.
Table 1. Parameters of antennas and arrays.

|       | KA   | IRA  | HIRA | TEM  | 2×2 KA | 4×4 KA | 3×3 KA | 4×4 KA | 8×8 KA | 4×4 KA | 4×4 KA |
|-------|------|------|------|------|--------|--------|--------|--------|--------|--------|--------|
| \(\tau_p\), ns | 2    | -    | -    | 1    | 3      | 2      | 1      | 1      | 0.5    | 0.2    |        |
| \(W\), J       | 1.17 | 0.015(2) | 1.1(26) | 0.175 | 0.94   | 1.18   | 0.8    | 0.36   | 1.2    | 0.169  | 0.037  |
| \(f_s\), MHz    | 100  | 50   | 50   | 50   | 53     | 96     | 60     | 207    | 210    | 436    | 413    |
| \(f_h\), MHz    | 934  | 2900 | 2100 | 2110 | 570    | 942    | 770    | 1589   | 2100   | 3394   | 8078   |
| \(f_0\), MHz    | 517  | 1475 | 1075 | 1080 | 311.5  | 519    | 415    | 898    | 1155   | 1915   | 4245   |
| \(\Delta f/f_0\), % | 161  | 193  | 191  | 191  | 166    | 163    | 171    | 154    | 164    | 154    | 180    |
| \(a, m\)        | 0.266| 1.83 | 1.525| 0.716| 0.629  | 0.928  | 0.696  | 0.494  | 0.247  | 0.119  |        |
| \(rE_{eq}/rE_0\) | 0.26 | 0.5  | 0.45 | 0.35 | 0.383  | 0.56   | 0.582  | 0.385  | 0.5    | 0.331  | 0.268  |
| \(U_{g_{max}}\), kV | 230  | 130  | 1000 | 150  | 90     | 230    | 100    | 210    | 200    | 200    | 120    |
| \(rE_p\), kV    | 440  | 1280 | 5300 | 530  | 530    | 1700   | 1000   | 780    | 4300   | 700    | 450    |
| \(k_{E_0}/U_{g_{max}}\) | 1.9  | 9.8  | 5.3  | 6.1  | 5.9    | 7.4    | 10     | 3.7    | 21.5   | 3.5    | 3.75   |
| \(k_{E_0}/E_0, kV/m^2\) | 4.9E6 | 1.2E5 | 1.4E6 | 5.4E6 | 6.2E5 | 1.0E6 | 1.1E6 | 1.6E6 | 2.2E6 | 5.9E6 | 1.6E7 |

5. Conclusion

The obtained estimations show that the relative effective potentials of high-power UWB radiation sources based on KA arrays and single IRA and HIRA reflector antennas are comparable. The ratio of the effective radiation potential to the aperture area for KA arrays is 1–2 orders of magnitude higher than the one for IRA and HIRA at the same UWB pulse duration of ~ 100 ps. This is due to the uniform distribution of the field at the array aperture and the use of bipolar voltage pulses to excite the antennas.

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