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A concept of an isotropic probe for measuring the parameters of an electromagnetic field emitted by the transmitters of pulsed microwave signals

Abstract. *Krytycznym elementem urządzeń pomiarowych do badania parametrów pola elektromagnetycznego pochodzącego od impulsowych nadajników jest sonda sygnałów mikrofalowych. W artykule przedstawiono koncepcję budowy oraz wstępne wyniki badań izotropowej sondy 3D. Przedstawiona koncepcja jest podstawą wykonania kilku wersji sondy zapewniających pomiary w szerokim paśmie częstotliwości i dużym zakresie dynamicznym natężeń pola EM. (**Koncepcja sondy izotropowej do pomiaru parametrów pola elektromagnetycznego emitowanego przez nadajniki impulsowych sygnałów mikrofalowych**)*

Abstract*: A critical element of measuring devices for studying the parameters of an electromagnetic field emitted by pulsed transmitters is a microwave signal probe. The research paper reviews a construction concept and preliminary research results involving a 3D isotropic probe. The presented concept is the basis for implementing several probe versions ensuring measurements over a broad frequency band and vast range of dynamic EM field intensities. (**A concept of an isotropic probe for measuring the parameters of an electromagnetic field emitted by the transmitters of pulsed microwave signals**)*

Słowa kluczowe: pomiary mikrofalowe, pole impulsowe, sonda izotropowa.
Keywords: microwave measurements, pulsed field, isotopic probe.

Introduction

A number of regulations governing OHS principles in the field of microwave technology have changed in recent years (2016, 2018). Standards set out by the Minister of Family, Labour and Social Policy of 12 June 2018 apply in the military sector. They are related to, among others, intervention limits for degrees of exposure to electric fields and magnetic fields emitted by military technology devices. Military Centres of Preventive Medicine deal with observance of OHS regulations within the Polish Armed Forces.

Measuring instruments used today to determine critical values of exposure to pulsed electromagnetic fields (EM) at the stage of determining protection zones around military technology devices (radar devices, in particular) – Fig. 1, despite their undoubted usefulness are unfortunately obsolete.

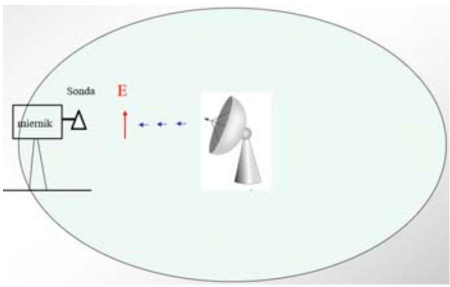

Fig. 1. Determination of protection zones surrounding radar devices
sonda – probe; miernik - meter

Given the dynamic development of this technique (e.g. antennas with an electronically controlled beam, adaptive antennas, so-called silent radars), it should be expected that they lose their performance features within the next few years. In the light of the fact that there are no meters available on the market that enable measuring EM field strength within a pulse, especially with a moving antenna beam, this article proposes a concept of a new design, based on a 3D isotropic probe.

Characteristics of pulsed EM fields around radar devices

Microwave radiation in radar equipment occurs at the measuring point in cycles (with an interval ofT_{opr}), and for a very short time, which depends on the antenna directional width, rotational speed and observation sector. Moreover, pulse duration (t_i) is very short relative to the interval between the pulses (T_p) – Fig.2.

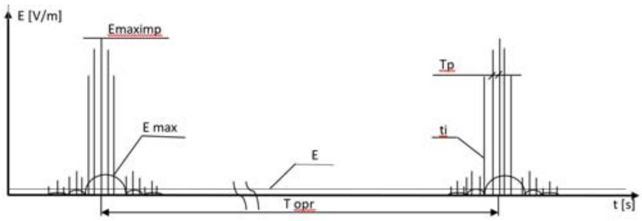

Fig. 2. Time and amplitude dependencies of pulsed radiation at the measuring point during irradiation measurement by a radar device

A correct determination of potential personnel exposure to an electromagnetic field requires the knowledge of three field strength parameters E [V/m], i.e., E_{sk}, $E_{\max\_rep}$, $E_{\max\_imp}$, where:

- E_{sk} [V/m] – electric field strength RMS (average for any measurement time – usually several minutes),
- $E_{\max\_rep}$ [V/m] – maximum electric field strength root mean square (RMS) value averaged over the pulse repetition period, determined by (1)

(1) $$E_{\max\_rep} = E_{\max\_imp} \cdot t_i / T_p$$

where:$E_{\max\_imp}$ [V/m] – maximum root mean square value of an electric field in a pulse, t_i – pulse duration, T_p – pulse repetition time.

All these values should be taken into account for proper exposure assessment. It follows that a measuring device used for pulsed fields should measure both time and amplitude parameters of the pulses (pulse envelopes), calibrated relative to corresponding EM field intensities [1].

Required probe parameters

The designed probe for a device measuring EM field strength parameters during normal radar operation should be characterized by the following parameters:

- Operating frequency band of measured devices 100 MHz – 18 GHz,
- Range of measured pulse field intensities 30 V/m – 7 kV/m,
- Range of measured signal durations (0.2– 300) μs, continuous signal,
- Measured pulse repetition range (200–7000) μs,
- Measurements taken during normal operation of a radiation source (e.g., a radar), without stopping the antenna beam,
- Operating temperature range (0 ÷ +50) ^{0}C.

Role and significance of a probe within an EM field meter

Typical EM field parameter meter consists of a probe, measuring device and interconnecting wiring. The task of the probes is to detect an EM field. Regardless of the type, the probe is made up of a detector (sensor), such as a conventional antenna (usually dipole) or another element sensitive to an EM field, as well as a detecting element. EM field meter parameters and application largely depend on the design and parameters of the sensor and detector. From the detection element, a signal is sent to the measuring device via wires. The wire design must ensure the lack of coupling (interference minimization) with the surrounding EM field. Due to their RC parameters, the wires also act as a low-pass filter (carrier frequency signal attenuation). The task of a measuring device is processing detected signals and displaying the values of the measured field parameters. The meters can measure the E electrical or M magnetic component of an EM field. Dipole antennas are used to measure the E electrical component. They react to an electric field by generating voltage proportionally to field strength. An antenna in the form of a loop is used to measure the M magnetic component. In a zone distant from a transmitter antenna, where the dependencies between the electrical and magnetic components of a field are strictly defined, it is enough to measure the E electrical component to determine EM field power density and strength. In the light of a simpler sensor design and technical feasibility of its fabrication for the entire operating frequency band, the subject matter of further considerations will be sensors measuring the E component. There are no sensors on the market, which measure the M magnetic component of a field, for a frequency above 3 GHz. Most frequently, EM field meters are characterized by broadband and isotropic directional features of the sensor head [2].

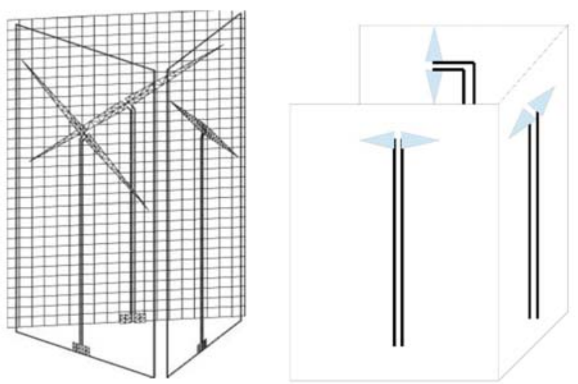

Fig. 3. Arrangement of receiving antennas within a probe (regular triangular prism, regular rectangular prism)

In order to achieve isotropic directional characteristics, the sensor contains three receiving antennas over three planes, arranged in such a way so that all three spatial field components, regardless of incident wave direction and polarization, cumulatively provide a resultant field strength, which has been shown in Fig. 3.

Probe detection elements

Depending on the EM field meter's purpose and field parameters, the meters use several types of detection elements:

Optoelectronic sensors

Optoelectronic (photonic) sensors display a number of advantages, which include eliminating interference within the measured field caused by the measuring system (particularly by connection wires) and preserving signal amplitude, spectral and phase information. Their operation involves using an HF signal from an antenna or directly from the measured EM field to modulate the light ray. The original envelope shape of the measured EM field is preserved in the course of modulation. The modulated light signal is sent to a photodetector, and further on to a measuring system. Its disadvantages include unsatisfactory sensitivity, too low dynamic range, and structural complexity.

Thermocouples

A detection element in such sensors is a thin-film thermocouple. The signal constant component on its output is proportional to the square of the electromagnetic field strength. Thin-film thermocouples can operate over a very broad microwave frequency band. Their disadvantage is the high time constant, which makes them unsuitable for pulse measurements (short pulses, in particular), and the fact they are easy blown in strong EM field.

Schottky diodes

Schottky diodes are still commonly used as field strength detectors owing to their properties. They can be used over a very broad dynamic field strength range of the order of 60 dB. The operating frequency band in selected Schottky diodes ranges from acoustic frequencies to tens of GHz. Their breakdown voltage depends on the diode type, and is from 1V to 5V [3], [4].

Voltage induced in dipole antennas used in the probes can exceed breakdown voltage for high-strength EM fields, therefore, a special solution presented further herein is suggested in the case of strong fields.

Probe detectors are also in the form of Schottky diodes that do not require bias voltage, so-called zero bias diodes [5]. A schematic drawing of a measuring antenna with a diode detector is shown in Fig. 4.

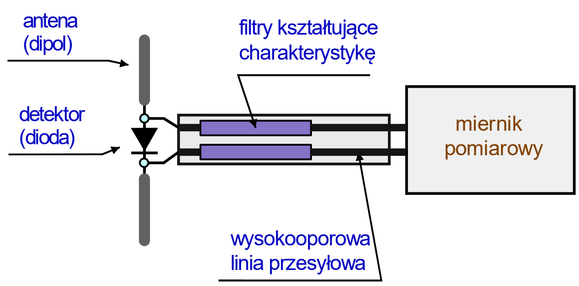

Fig. 4. Measuring diode with a diode detector [1].
antena (dipol) – antenna (dipole); filtry kształtujące charakterystykę - characteristic-shaping filters; detektor (dioda) – detector (diode); miernik pomiarowy – measuring meter; wysokooporowa linia przesyłowa - high-resistance transmission line

Cables connecting the detection head and the measuring device

The cables that connect the detection head and the measuring device must ensure the lack of coupling (interference minimization) with the surrounding EM field. They are made of high-resistance material, usually in the form of sputtered paths on a dielectric substrate (e.g., corundum ceramics or microwave laminate). Path resistance selection is extremely important in terms of the parameters exhibited by the entire head. Selecting excessive current resistance, expressed in kΩ/cm, makes the time constant of the cables, due to their RLC parameters, become too high, and prevent measuring time and amplitude parameters of the pulses. On the other hand, a too low current resistance, expressed in Ω/cm makes the cables act as antennas and distort the measurement results.

Probe dielectric substrate

Formerly domestic probes were executed on a corundum ceramics base. However, the presented solution involves corundum ceramics plates, approx. 20 cm long, that are additionally protected against mechanical impacts.

Schottky diodes for the designed probe

The type of diodes for the planned head should be selected taking into account the following requirements [6]:
a *beam lead* or *flip chip* housing, due to the minor dimensions of a dipole antenna and a low solder pad area,

- operating frequency band at least equal to the operating frequency bands of the measured devices (100 MHz – 18 GHz),
- diode dynamic characteristics (relationship between output voltage and input power) above 50 dB,
- no pre-polarization voltage required for operation,
- possible high breakdown voltage (order of at least 3 V for fields below 3 kV/m and above 10 V, for higher EM field strengths),
- maximum forward current of at least 50 mA,
- DC dissipation power of at least 50 mW,
- operating temperature range broader than the meter operating range (0 ^{0}C ÷ +50 ^{0}C).

Broadband short dipole antennas

Short dipole antennas used in the postulated probe were placed on a substrate (corundum ceramics) and made of silver. The antennas must satisfy the broadband requirements and ensure correct operation over a band ranging from 100 MHz to 18 GHz. Their length is significantly higher than the wavelength for the upper operating frequency band of the meter for the purpose of preventing the resonance phenomenon, as is the case with a dipole that has a length equal to half the wavelength. It is impossible to use rod dipoles in the probe due to their narrowband nature. Based on [2], the authors of which simulated several short antenna shapes to be used in ultra-wideband (UWB) radio systems, it is suggested to use three antenna shapes in further research:
- dipole antenna in the shape of a diamond (DIPOL 3 in Fig. 5),
- two rectangular structures marked as DIPOL 1 with a triangle base and DIPOL 2 with an elliptical base.
- in addition, the authors also suggest a rectangular structure with an elliptical base marked as DIPOL 4, with twice the dimensions of the DIPOL 2, to be potentially used when operating within the lower frequency band of weaker fields.

The authors of [2] have optimized the proportions of individual dipole elements using a CST Microwave Studio electromagnetic field simulator. The ultimate selection of the dipole antenna shape among the ones in Figure 5 will be made after tests in an anechoic chamber, over a full operating frequency band.

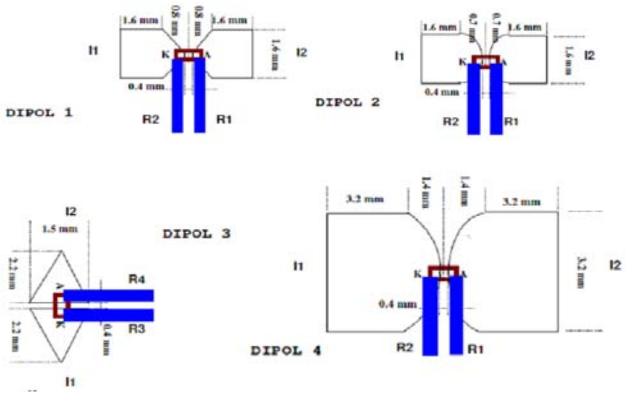

Fig. 5. Short antennas on the plates of 100 MHz – 18 GHz probes (X, Z, Y axes)
dipol - dipole

Probe structure

An isotropic probe consists of three individual paths, arranged close to each other in three planes, forming a regular triangular prism (Fig. 3), so as to sum up all field components regardless of the incident wave direction and polarization. The solution where dipole antennas and the detection diode are installed at an angle of 54.7^0 (so-called *miracle angle*) relative to the substrate edge is common. Laboratory research and tests will enable determining the minimum dimensions of the prism triangle sides, so as to prevent the coupling of antennas from different path – Fig. 6.

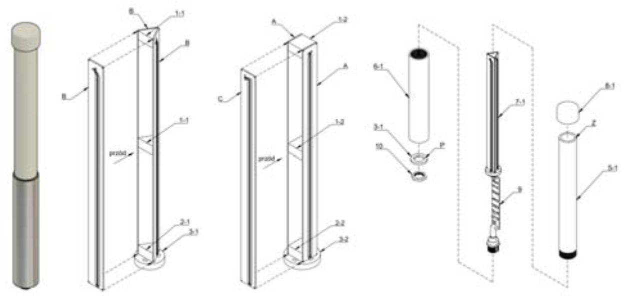

Fig. 6. Construction of a measuring probe shaped as a regular triangular prism and a regular rectangular prism
przód - front

Processing measurement chain data

Detection diodes used within the probe are of non-linear nature, with a varying character of the dependencies between diode output voltage and field strength (nature close to linear in the low voltage range, followed by a transition interval and a square nature for the highest voltages). Diodes in each of the chains, due to their spatial location relative to the E vector of the EM field, operate over different characteristics areas. For this reason, the voltage from each chain must be subject to individual transformation onto field strength, prior to summing up and determining the total field strength.

Tests

The tests were conducted in accordance with a pre-developed test plan and methodology. All measurements were taken using a laboratory bench equipped with an anechoic chamber and a TEM TBTC1 chamber – Fig. 7. The bench was pre-calibrated pursuant to a calibration procedure.

The purpose of calibration is to determine setpoints (signal levels) in a microwave generator and microwave amplifier required to achieve a specific field strength for a given carrier frequency in a TEM chamber (or at a specified distance from the transmitter antenna, measured along its free space symmetry axis). A measurement standard for the 100 MHz – 12 GHz band was a PM-HPM1 meter, while a Narda EMR 300 meter was used for the frequency band of 12 GHz – 18 GHz.

Two types of measuring probes were prepared for testing:

1. The probe design is based on a triangular, equilateral prism (dipole antennas placed at a "sweet" angle relative to guiding lines).
2. The probe was built on a square prism base. Dipole antenna placed relative to each other and relative to guiding lines, at an angle of 90 degrees.

Fig. 7. Diagram of a test bench for testing elements of antenna-detection probes

The dynamic and frequency characteristics for the 100 MHz – 1000 MHz band were measured in a TEM TBTC1 chamber using a KB00819M47A power amplifier and a ROHDE SCHWARZ signal generator of the SMB100A type. Frequency responses in the anechoic chamber were measured using a KB1060M43A microwave power amplifier for the 1 GHz – 6 GHz band and a KB60180M44B power amplifier for the 6 GHz – 18 GHz band with an increment of 500 MHz. Field strengths for frequencies up to 12 GHz were adjusted by the level of the output signal from a ROHDE SCHWARZ SMB100A signal generator based on a pre-calibration with a PM-HPM1 meter, and a Narda EMR 300 meter for the 12 GHz – 18 GHz band.

Examples of frequency response and dynamic characteristic measurement results are shown in Fig. 8.

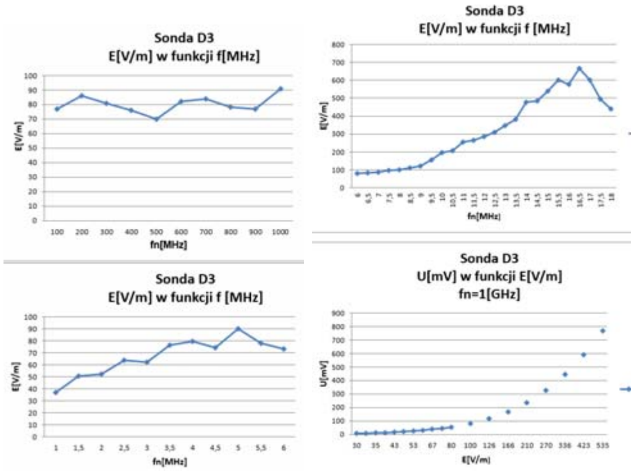

Fig. 8. Test results for measuring probe elements
sonda D3 – D3 probe; E[V/m] w funkcji f[MHz] - E[V/m] as a function of f[MHz]

Conclusions

The presented solution is assumed to enable detecting and measuring pulsed electromagnetic fields without shutting down antennas and without required knowledge of radar operating parameters. Probes can operate over the entire frequency range (100 MHz - 18 GHz). Minimum detectable pulsed EM field strength is approx. 7 V/m.
It is a parameter sufficient to measure pulsed fields.

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