Detection of High Power Microwaves

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Abstract

The growing threat to critical infrastructure by high power microwaves (HPM) also increases the importance of detection facilities for electromagnetic fields with high field strength. We discuss HPM detection principles as well as capabilities and limitations of existing HPM detectors. Then we describe the basic requirements for a system for the detection and identification of HPM threat signals and a demonstrator of a single-channel HPM detection system for mobile and stationary use. The system allows the measurement of amplitudes within a very high dynamic range, the pulse width, pulse repetition frequency and the number of pulses.

1 Introduction

The availability of components to build low-tech high power microwave (HPM) sources together with the increasing dependence on electronic devices and systems has lead to a situation where all microprocessor controlled electronics can be disabled with HPM attacks at least temporarily with medium sized device within distances from several 10 m to a few hundred meters. This is crucial all the more due to the reliance of critical infrastructures on electronics. The examples of vulnerable systems range from commercial IT electronics and network equipment used also in the military area and in civilian security applications as commercial off the shelf (COTS) electronics to electronic systems in vehicles, surveillance equipment and logistics.

Because of their easy availability, it is very likely that also persons or groups with criminal or terrorist intentions can acquire such HPM systems. These then could be used for burglaries, raids, blackmails and attacks in cases where electronics is responsible for the safety of persons and property. Without detection and alarm systems it is easy for attackers to test their HPM devices without being discovered. For this reason failures and malfunctions of own electronic systems cannot be traced back to an electromagnetic attack. This is the case the more so because of the general lack of awareness of the electromagnetic threat. Therefore, it becomes increasingly important to develop and investigate detection techniques for this threat.

For intentional electromagnetic interference (IEMI) mainly the following procedures come into question:

- Pulsed radio frequency (RF) emissions (narrow-band sources), most conveniently at frequencies between 30 and 3000 MHz, with pulse widths of about 0.1 to 10 µs.
- Single or repetitive ultra-wideband pulses (UWB) with rise times and pulse widths in the range 10 ps to 1 ns.
- Single and repetitive broadband pulses, maybe also damped sinusoidal (DS) signals, etc.
- Continuous wave (CW) RF emissions in the lower GHz range.

At the target device electromagnetic field strengths must be generated which are sufficiently far above the immunity of the unit. For CW signals and digital electronic devices the necessary field strength is roughly in the range above 100 V/m, for pulsed RF or microwave signals and damped sinusoidal oscillations approximately 1000 V/m and for very narrow, steep-edged pulses a few kV/m.

The paper gives a short overview of detection principles and previous detector development in the second section. Section 3 describes development at Fraunhofer INT of a demonstrator of a detection system with high amplitude dynamics based on logarithmical amplifier/detector ICs which is able to cover a large frequency range with broad-band antennas and can be deployed stationary or vehicle mounted. The paper concludes with summary and outlook.

2 HPM Detection: Principles and Previous Developments

2.1 Detection Principles

In the past, basically only low-impedance broad-band diode detectors have been available as actual detection elements as both high-impedance diode detectors and thermal power meters have much too large response times for short pulses and are useful only for the recording of time averaged signals. The disadvantage of these detectors is the limited amplitude dynamics for pulse measurements which strongly limits the detectable range of amplitudes and consequently the possible detection range [1,2]. The voltage vs. power characteristics of a typical Schottky diode detector head [3] gives an achievable dynamic range of about 20 to 25 dB under the realistic assumption that pulsed voltages lower than 1 mV can not be identified with a digital oscilloscope. This can be hardly increased even with low-noise signal preamplifiers. The measurement of the transient response of such a Schottky diode detector shows that it is possible to resolve rise and fall times of some nanoseconds [3]. Special detectors as resistive sensors based on the electron heating effect in semiconductors in a strong electric field or lithium niobate crystals utilising the electro-optical effect are mainly useful for high field strengths [1,4,5].

Recently, a number of highly broad band and at the same time in part relatively inexpensive logarithmical amplifier/detector ICs have entered the market which allow to avoid the disadvantages of diode detectors. In principle, these devices consist of a large number of linear broadband amplifiers with defined gain, which are connected in series. At the output of each amplifier is a linear diode detector. The output signals of all detectors are added via an analogue summing circuit, so that a quasi-logarithmic detector characteristic is achieved. The measurement of the detector characteristic of such a logarithmic amplifier/detector module shows a dynamic range above 60 dB [3], which represents a significant improvement over the previously used diode detectors. The frequency spans from 1 MHz to 8 GHz with an amplitude correction of a few dB above 5 GHz. Also the rise and fall times of the detected signals meet the requirements for HPM detection completely [3]. With such characteristics the properties of these ICs considerably surpass some of the conventional logarithmic amplifier/detector units as employed e. g. in radar warning systems.

2.2 Previous HPM Detector Developments

For surveillance of the surroundings of electronic facilities against electromagnetic attacks detection systems are needed, which register at least the occurrence of HPM signals as such. Those devices, optionally enhanced by a coarse display of amplitude levels and number of threat pulses, are in many cases sufficient as pure alarm units. Such small-sized low-cost systems already have been realised in different implementations in form of battery-powered pocket or hand-held units with integrated omni-directional broad band antennas [1].

As a first example Canary is a prototype sensor designed and developed by Qinetiq, United Kingdom. According to the Canary datasheet [6] the specifications of the detector are as follows:

- Signal types: HPM, High Altitude Electromagnetic Pulse (HEMP), Non-Nuclear Electromagnetic Pulse (NNEMP), DS (for repetition rated waveforms), UWB (for repetition rated waveforms, minimum pulse width detected: ~ 300 ps).
- Frequency range: 10 MHz - 8 GHz (calibrated), up to 40 GHz has been detected.
- Sensitivity threshold:
  - Low level: 1 mW/m^2 (E_{eff} ~ 1 V/m).
  - High level: 1 W/m^2 (E_{eff} ~ 20 V/m).
  - Electromagnetic Pulse (EMP): 1 kW/m^2, single pulse (E_{eff} ~ 615 V/m).
- Maximum input level: not known.

The sensitivity levels can be tailored to meet requirements for specific applications.

- The ‘LO’, ‘HI’ and ‘EMP’ detection levels of 1 mW/m^2, 1 W/m^2 and 1kW/^{2} correspond to an effective field strength (E_{eff}) of 0.6 V/m, 19.4 V/m and 614 V/m, respectively. According to datasheet [6] these levels are based on the following:
  - ‘LO’ warning; Low alarm threshold indicating that an EM event has been detected of sufficient magnitude to cause IT upset or degradation (indication visible and audible).
  - ‘HI’ warning; High alarm threshold indicating that an EM event has been detected of sufficient magnitude to cause IT prolonged disruption or damage (indication visible and audible).
  - ‘EMP’ warning: Indication that a single EMP event has occurred. Description of the physical operation (indication visible and audible).

The second example is the microwave microphone, a first generation high power microwave detector designed and developed by Market Central, USA. According to the product sheet the specifications of the detector is as follows [7]:

- Signal types: Transient Electromagnetic Device (TED), UWB and CW.
- Frequency range: 900 MHz - 2.9 GHz (flat response), 400 MHz - 3 GHz (-10 dB).
- Sensitivity threshold: ~ 100 V/m.
- Visual indication via a 10-segment LED covering a 30 dB range (up to ~ 3 kV/m).
- Maximum input level: not known.

The detector can sense signals in all three polarisation axes and has the capability to indicate detection realtime or in a peak hold mode. It has an audible alarm with a false alarm indication. The internal antenna can be replaced by external antennae optionally [7]. The detector contains a rechargeable battery and USB connectivity. USB connectivity is presently used to recharge the battery, but will be used for networking and remote reporting at a later stage. The detector is relatively light in weight and consumes very little power [7].

The third example is a high power microwave detector prototype designed and developed by TNO, The Netherlands [8]. The detector has been designed to meet specifications on signal types, flat frequency response, omni-directionality and response time. Moreover, the detector was designed to be low-cost. Less attention was paid to the maximum input level the detector is resilient too. The characteristics of the detector are as follows:

- Signal types: Carrier-based pulses, UWB and CW.
- Frequency range: 100 MHz - 8 GHz (flat response).
- Sensitivity threshold:
  - Low level: 3 V/m.
  - Medium level: 10 V/m.
  - High level: 40 V/m
- Visual indication via 3 LEDs, separate indication CW and carrier-based pulses.
- Maximum input level: > 1000 V/m (carrier based), > 3 kV/m (UWB).

The detector has shown to have a flat frequency response in the frequency range tested. The detector is fast enough and sensitive enough to detect CW, carrier-based and UWB pulses in all directions (in current set-up only one polarisation axis). The maximum input level is not stated in the specifications but has been further researched [9].

Sensitivity and robustness tests of some of the existing detector prototypes show that developers should take special care of robustness of detectors against HPM [9].

3 HPM Detector for Mobile and Stationary Use

3.1 Detector Requirements and Development Concept

For permanent surveillance of high-value or mission-critical stationary facilities and especially for search and identification of HPM sources such devices should, however, feature an extended scope of performance. These additional features include the display of field strength of the threat signal, an amplitude dynamics (i. e. detection range), which should be as large as possible, the counting of pulse number or display of pulse repetition rate, the display of pulse width, preferably a frequency independent display of field strength in a wide frequency range, and finally the directional and polarisation independence of the receiving antenna or a radiation pattern with defined wide angular range of constant gain for sector surveillance. The detectors should be able to detect pulsed electromagnetic fields with threat field strengths above 1 kV/m independently of frequency, be immune to field strengths of some 10 kV/m and be able to detect HPM sources at medium distance (i. e. field strengths down to at least 100 V/m). The detection of all signal types from CW via narrow band and damped sine pulses to ultra wide band (UWB) pulses ideally requires response times in the upper picosecond range. The classification of detected incidents according to pulse form, i. e. amplitude, pulse width and pulse number or repetition rate can help to identify false alarms.

Further development stages should realise a coarse to medium display of the direction of HPM impact for localisation of an attacker and of the HPM frequency via filter benches. The devices should be operable with batteries for a certain time in addition to a stationary or on board power supply for operation from vehicles.

The detection system developed at Fraunhofer INT meets the following criteria in the first phase:

- Notification that a pulsed electromagnetic field was detected independent of frequency with threat level field strength (> 1 kV/m).
- Damage immunity against field strengths of up to several 10 kV/m.
- Frequency independent detection of HPM sources in medium distances (e.g. detection of E > 100 V/m) for warning and searching.
- Measuring dynamics preferably > 60 dB.
- Polarization independence.
- Directional independence (at least in the horizontal plane) or in a defined sector (e.g. 90 degrees).
- Classification of the detected events by amplitude, pulse duration, pulse repetition frequency, form, etc.

In the first stage the system is built as a single-channel assembly with a polarization-independent broadband antenna and a logarithmic amplifier/detector module. To stay within the usable range of the amplifier/detector module an attenuator of 60 dB is necessary between antenna and amplifier input. A fast PIN diode limiter is connected at the entrance of the IC in order to avoid damage of the device even in the worst case. **Figure 1** shows the block diagram of the system. Accordingly values for field strength can be obtained between < 100 V/m and > 10 kV/m.

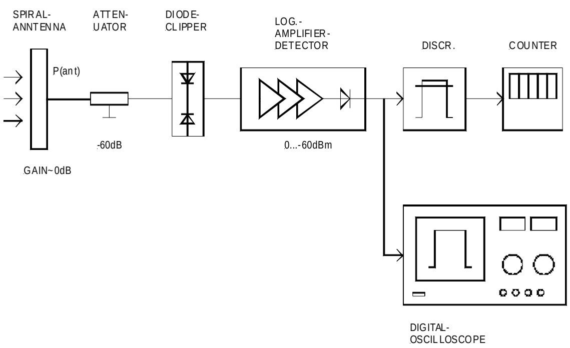

Figure 1 Block diagram of the first development stage of the HPM detection system

The signal amplitude and pulse shape are measured with a high-speed digital oscilloscope, which in turn is read out by a PC via GPIB. In addition to the graphical representation of the envelope of the HPM pulse the evaluation software shows amplitude and field strength, pulse width and pulse repetition rate. Furthermore, the number of the threat pulses can be registered by a separate counter or by counting the trigger events of the oscilloscope.

3.2 Demonstrator of a Single Channel HPM Detection System

Figure 2 shows the layout of the demonstrator. One recognizes the spiral antenna on the left, the battery-powered multi-channel oscilloscope for signal processing and the RF part in the middle and the computer with GPIB interface and the necessary analysis and display software in the right. The shielded RF part contains the logarithmic amplifier/detector module and an appropriate input circuit for self-protection.

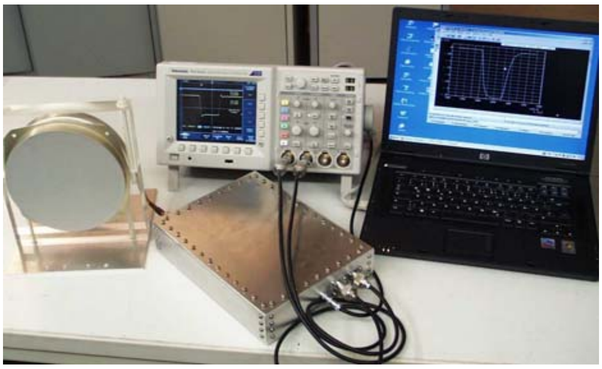

Figure 2 Demonstrator of overall system

The spiral antenna is designed for the frequency range 0.5 - 2 GHz but can also be used between 0.5 and 10 GHz without significant gain changes and has a directional pattern with a width of greater than 90 degrees (-1 dB to -2 dB). Due to the circular polarization the spiral antenna receives linear polarized signals independent of the polarization plane.
The system can be operated by mains or on-board power supply and with internal batteries, respectively. For this reason the oscilloscope has a built-in battery, from which also the RF part can be supplied. The computer can also run with its internal battery. In this way the detection system can be flexibly moved around, without relying on an external power supply. The antenna and the RF part can be placed outside protected zones. At expected high field strengths the oscilloscope and the computer should be primarily used within a shield. In the search mode at low field strengths the screening of a motor vehicle should be sufficient.

3.3 First Tests of the HPM Detection System

Tests of the detector have been carried out in the TEM waveguide of Fraunhofer INT using pulsed HPM sources with frequencies between 150 MHz and 3.4 GHz and a pulse width of 1 µs and low power sources up to the upper frequency 8 GHz of the TEM waveguide. The field strength has been measured and compared with the detector characteristic in the measurement setup as in **Figure 3**. The test setup with the spiral antenna in front and the shielded RF part of the detection unit behind it in the TEM waveguide is shown in **Figure 4**. The digital oscilloscopes and the controlling computer were positioned outside the shielded hall.

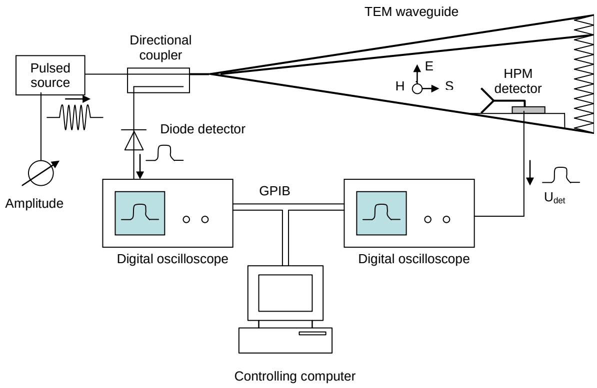

Figure 3 Measurement setup for detector tests

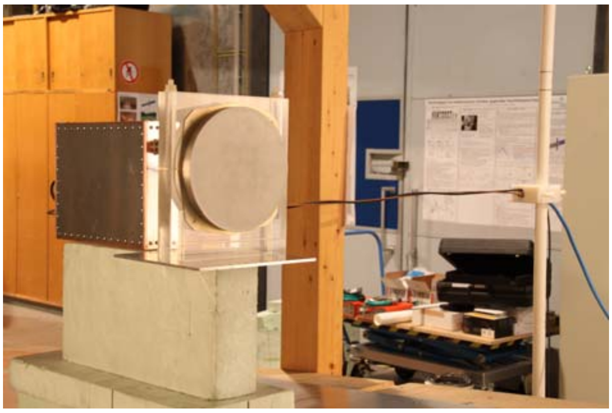

Figure 4 Test setup in TEM waveguide

The detector characteristic was calculated considering the measured antenna factor of the spiral antenna and the 60 dB attenuator besides the characteristic of the logarithmic amplifier/detector module itself from a minimum frequency of 500 MHz limited downward by the antenna factor to 8 GHz as maximum frequency of the logarithmic amplifier/detector module. In parallel, the field strength was measured using a directional coupler and a diode detector to determine the input power into the waveguide (cf. **Figure 3**). The latter is related to the field strength at different measuring points inside the waveguide by calibration

measurements. As an example, **Figure 5** shows the comparison between measured and calculated results for the frequency f = 1.2 GHz. Field strengths between some 100 V/m and about 1.5 kV/m have been generated at the chosen measuring point inside the waveguide for this frequency.
Finally, **Figure 6** shows the frequency dependence of the HPM detector characteristic determined at constant detector voltage for frequencies between 500 MHz and 8 GHz with $E_0 = E(f = 1.0 \text{ GHz})$. The sensitivity of the detector, derived from the necessary field strength to obtain a certain detector voltage, decreases with increasing frequency. One reason for that is the frequency dependence of the antenna factor at constant gain, another reason is the frequency dependence of the gain itself.

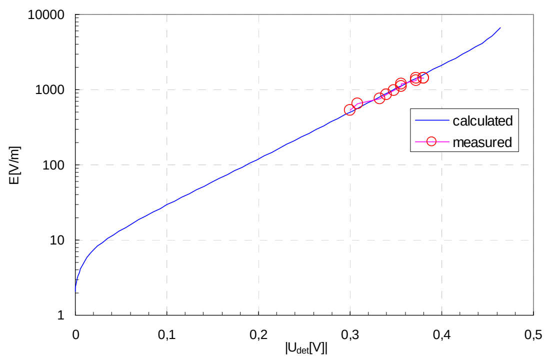

Figure 5 Comparison of measured and calculated results for f = 1.2 GHz

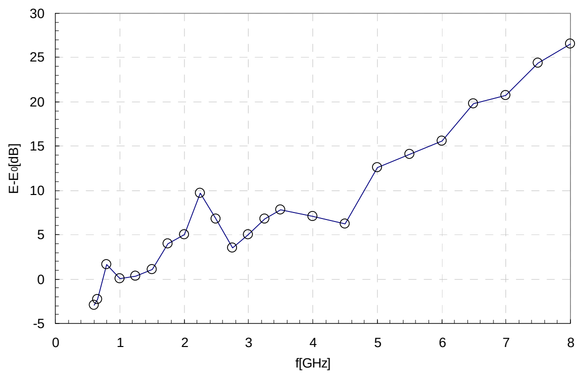

Figure 6 Frequency dependence of detector characteristic

So far, tightness and robustness (electromagnetic immunity) of antenna and RF part of the HPM detector (cf. **Figure 4**) have been tested against field strengths up to 1.5 kV/m for frequencies between 150 MHz and 3.4 GHz. In the future, robustness tests will be carried out also in the reverberation chamber for field strengths above 10 kV/m.

4 Summary and Outlook

For security reasons it is very important to have available a detection system to protect critical equipment, systems and infrastructure against IEMI threats. For this purpose we have given an overview of HPM detection principles as well as capabilities and limitations of existing HPM detectors. Sensitivity and robustness tests of some representatives show that robustness of detectors against HPM is an important issue. We have described the basic requirements for a system for the detection and identification of HPM threat signals and have discussed single-channel demonstrator of an HPM detection system at Fraunhofer INT. In its first stage it enables the detection and identification of HPM threat by measuring the field strength within a very high dynamic range, the pulse width, pulse repetition rate and the number of pulses.
In future a number of multi-channel detection systems will be developed at Fraunhofer INT on the basis of the single-channel demonstrator. The first step will be a rough determination and display of the direction of the incident threat pulse. For this purpose four detection channels can be used with four spiral antennas and logarithmic amplifier/detector modules. As angular ranges of 90 degrees can be covered with the previously described antenna types the detection in the entire 360 degree azimuth range is possible with four antennas. The direction of incidence can be roughly evaluated and displayed by analyzing the amplitudes in the four channels. The azimuthal information can be determined in more detail through the use of antennas with narrower antenna diagrams and the increase of the number of channels.
To obtain more precise information about the carrier frequency of the threat pulse, the signal of an antenna can be split to a larger number of channels via a coaxial power divider, whose outputs are each equipped with a band pass filter. Depending on the bandwidth of the filter and number of frequency channels the carrier frequency can then be determined from the amplitude ratios of the individual channels. This method was used in principle already in [2] for a rough determination of the unknown frequencies of pulsed microwave signals, but at that time with a much smaller dynamic range compared with modern logarithmic amplifier/detector modules.
In the demonstrator systems discussed up to now only the antenna and the RF part can be exposed to the full threat field strength, whereas the signal acquisition and processing with a digital oscilloscope and a portable PC have to be operated in a shielded environment in most cases. In a further expansion stage the analogue-digital conversion and analysis of the pulses could also be conducted in the highly shielded RF module instead by an external oscilloscope. The readout of the computer implemented in the RF module would then be carried out over fibre optic cables to an also highly shielded control unit. In this way the over-

all system will be usable in any environment without restrictions.

Such an HPM detection system is flexible enough to be used vehicle mounted but also stationary for protection of fixed critical infrastructure installations. It complements the necessary shielding and protection measures and alternatively the hardening of critical infrastructure components against high power microwaves.

References

[1] Rieter-Barrell, Y.: “Review on HPEM Detection techniques”, Final Report of NATO RTO SCI-198 Task Group on “Protection of Military Networks against High Power Microwave Attacks”, to be published

[2] Braun, Ch.; Clemens, P.; Schmidt, H.-U.; Taenzer, H.-J.: Ein Mehrkanal-Mikrowellen-Spektrometer zur Messung einmaliger Mikrowellenfelder im Frequenzbereich 1 – 26 GHz. Fraunhofer INT Arbeitsbericht IB-7/00, 2000

[3] Adami, Ch.; Braun, Ch.; Clemens, P.; Schmidt, H.-U.; Suhrke, M.; Taenzer, H.-J.: “HPM Detection System for Mobile and Stationary Use. Demonstrator of a Single-Channel Device”, Fraunhofer INT Arbeitsbericht IB-08/11, 2011

[4] Dagys, M.; Kancleris, Ž.; Simniškis, R.; Schamiloglu, E.; Agee, F. J.: “Resistive Sensor: Device for High-Power Microwave Pulse Measurement”, IEEE Antennas & Propagation Magazine, Vol.43, No 5, 64-79, 2001

[5] Braun, Ch.; Suhrke, M.; Taenzer, H.-J.: “Testing of Resistive Sensors at INT EME Facility”, Fraunhofer INT Arbeitsbericht IB-18/10, 2010

[6] Qinetiq. Datasheet Canary EM detector; issue 3

[7] Market central. Product sheet Microwave microphone

[8] TNO: User manual HPM detector, 2009

[9] Adami, Ch.; Braun, Ch.; Clemens, P.; Rieter-Barrell, Y.; Schmidt, H.-U.; Suhrke, M.; Taenzer, H.-J.: “ Detection of High Power Microwaves“, NATO RTO SCI-232 Symposium on “High Power Microwaves and Directed Energy Weapons”, Virginia Beach, USA, 2011