Differences in the Coupling Behavior of Fast Transient Pulses to short PCB Traces

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***Abstract*—Ultra wideband (UWB) pulses cover a large frequency range up to several GHz, thus they are able to cause malfunctions or even destructions of complex electronic systems. Previous investigations of the coupling effects of fast transient pulses to complex electronic systems have shown, that increasing the system dimensions leads to an increased coupling efficiency. This statement seems to be universally applicable for all electronic systems, but susceptibility measurements of a generic microcontroller board with UWB pulses show surprisingly different results. In this contribution, this effect is investigated by measurements and numerical methods. Measurement results of the generic microcontroller board are presented as well as numerical results of the coupling behavior of different fast transient pulses to short PCB traces. Furthermore, the results of both measurement and numerical methods are compared to each other.**

Key words: Intentional electromagnetic interference (EMI), UWB pulses, coupling to PCB traces.

I. INTRODUCTION

UWB techniques are not only used in high speed communication systems, but also in the field of intentional electromagnetic interference (IEMI). An impact of modern electronic systems, that are of particular importance under many aspects like security, medicine, economy, traffic, communication and armed forced, could lead to malfunctions as well as destruction of the electronics. Thus, the susceptibility of electronic devices to fast transient electromagnetic influences like electromagnetic pulses (EMP) and ultra wideband (UWB) pulses is of great interest. Previous investigations of the coupling effects of fast transient pulses to complex electronic systems have shown, that an increase the system dimensions leads to a higher vulnerability [1]. In case of microcontroller boards, especially the length of the reset line has an effect on the susceptibility of the system: A longer reset line leads to a higher vulnerability of the electronics. This result seems to be universally applicable for electronic systems, but susceptibility investigations on different generic microcontroller boards (GMB) show surprisingly different results: Microcontroller boards with shorter reset lines are less susceptible to UWB pulse than boards with longer reset lines, whereas vulnerability to EMPs increases with the length of the reset line.

This contribution deals with the different coupling behavior of EMP and UWB pulses to short printed circuit board (PCB) traces. The coupling effect mentioned above is investigated more detailed by additional measurements. Furthermore, numerical field calculations are carried out in order to get an understanding for the coupling effects. Essential results of these investigations are presented and discussed in this contribution. It is pointed out, that the coupling behavior of EMP and UWB pulses is very different in case of short PCB traces.

II. SUSCEPTIBILITY MEASUREMENTS

As mentioned in the introduction, the susceptibility of a generic microcontroller board is investigated by measurement. In this section, the device under test (DUT) is described as well as the measurement setup and definition of the measurement quantity. In addition, the measurement results for fast transient pulses will be presented.

A. Generic Microcontroller Board (GMB)

As DUT serves a generic microcontroller board (GMB) that has been developed for the investigation of the breakdown failure rate. In order to minimize electromagnetic interferences due to parasitic coupling to the supply lines, the GMB is battery powered. Furthermore, the GMB is remote controlled via a fiber optic link, thus it is well suited for investigations inside enclosures. In principle, the GMB illustrated in Fig. 1 is a printed circuit board (PCB) which contains three functional groups: microcontroller, coupling structure and transceiver unit. These functional groups are described in detail in the following.

The GMB is equipped with an 8-bit microcontroller in advanced RISC architecture, which can be operated with clock frequencies up to 20 MHz. While the microcontroller is an 8-pin device with six programmable I/O (input/output) ports and an internal calibrated oscillator, the number of possible interference paths is small. Thus the usage of this controller delivers well defined conditions for the investigations. The different I/O ports are connected to the transceiver unit via a coupling structure. Four of these ports serve as output ports in order to signalize the different states of the microcontroller. The two residual ports are used as input ports for resetting the microcontroller and starting the test program.

During the susceptibility tests, a program is running on the microcontroller, which drives the controller into three different states. After switching-on the power supply or resetting of the microcontroller, it stays in state 1 until it receives a signal on the input line “start”. In this case, the controller changes into state 2 for approximately 1 second and then turns to state 3 for the same time. Afterwards, it switches between these two states. The test program is implemented this way in order to observe a reset of the microcontroller due to the impact with fast transient pulses.

The coupling structure is realized by parallel transmission lines on the top layer of the PCB which connects the microcontroller with the transceiver unit. A metallic ground plane is located on the bottom layer. In order to vary the length of the coupling structure, three PCBs with different coupling length (l = 4cm, 6cm and 8cm) are built up.

The transceiver unit transforms the electrical signals to optical ones and is used for remote control of the GMB. It is equipped with optical transceiver and receiver devices that are connected via a fiber optic link to a remote station which is placed outside the test site.

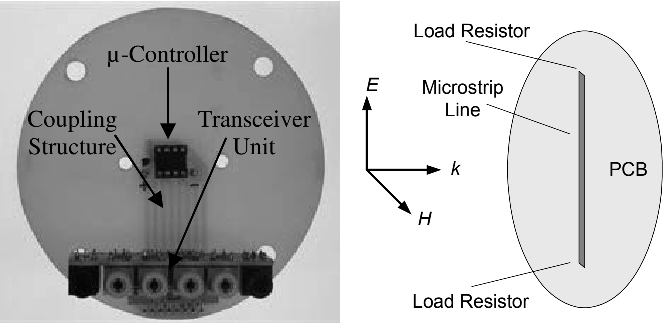

Fig. 1 DUTs for experimental and numerical investigations of the coupling behavior. Generic microcontroller board (left) and simulation model (right)

B. Measurement Setup

The susceptibility measurements are performed on two different test sites. In contrast to the setup in [1], the measurements are not carried out in an open TEM waveguide, but on an open area test site (OATS) and a GTEM cell. A UWB pulse generator serves as feeding source for an impulse radiating antenna (IRA) respectively a GTEM cell. The applied UWB pulse has in general a double exponential unipolar shape with a rise time of approx. $t_r = 100$ ps and a pulse duration at half maximum of approx. $t_{fwhm} = 1.6$ ns (see Fig. 2). It can be assumed the pulse propagates as a transverse electromagnetic (TEM) wave on the OATS respectively inside the GTEM cell.

The DUT is positioned in a way that the coupling structure is orientated parallel to the electric field strength of the incident UWB pulse, as shown in Fig. 1 (illustration on the right side). Since the amplitude of the UWB pulse generator is not continuously adjustable, the amplitude of the pulse which illuminates the generic microcontroller board is varied by using attenuators and by changing the distance between the IRA and the DUT on the OATS respectively the distance between the feeding section and the DUT in the GTEM cell.

In addition, it should be mentioned that the shape of the incident pulse depends on the test side, although the same pulse source is used for the different measurements. While the GTEM cell forms a TEM waveguide in which the UWB pulse propagates with the same unipolar pulse shape, the transmission function of the IRA leads to a differentiation of the pulse. Thus, the EUT is stressed with an UWB pulse of bipolar shape on the OATS.

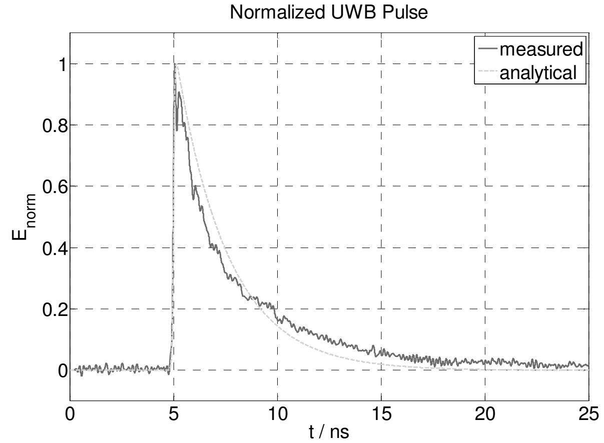

Fig. 2 Normalized representation of UWB pulse in time domain (measurement and analytical description, time shift t_s = 5 ns)

The quantities which are observed during the measurements are the electric field strength and the so called breakdown failure rate (BFR), which will be described in the next subsection.

C. Definition of the Breakdown Failure Rate

In order to classify the different failure effects of electronic devices, which can range from interference only during the RF illumination to permanent damages, the two quantities breakdown failure rate (BFR) and destruction failure rate (DFR) have been defined [1]. The BFR is defined as the number of breakdowns $N_{breakdown}$ of a system divided by the number of pulses N_{pulse} applied to it.

$$BFR = \frac{N_{breakdown}}{N_{pulse}} \tag{1}$$

A breakdown of a system means that the system is unable to perform the function for which it is designed originally. Physical damages do not occur, thus the systems is going back into function after a reset (self-, external- or power reset). In contrast to this is the DFR, which is defined as the number of destructions divided by the number of pulses applied to the system. Destruction means a physical damage of the system so that the system will not recover without a hardware repair. In general, a breakdown of an electronic system can be reached with lower pulse amplitudes than the destruction of the system.

It should be mentioned that the BFR and DFR only describe failure effects of single components and subsystems very well, but do not take the impact of the whole system or mission into account. Therefore, an extended classification of effects by duration and with respect to the complex system is given by Sabath in [2]. Nevertheless, the DFR is a sufficient measurement quantity for this work in order to describe the susceptibility of the generic microcontroller board.

D. Measurements Results

The breakdown failure rate of the GMB is determined for different coupling lengths on both test sites (OATS and GTEM cell). Therefore, the GMB is exposed to 100 single shot UWB pulses for each field strength step and the total number of breakdowns is recorded. Since a semiconductor pulse generator is used for the measurement, it can be assumed that the variation of pulse shape and magnitude is negligible.

The measurements on both test sides point out, that the PCB with shortest coupling length is most sensitive, whereas the one with the longest coupling length shows the highest interference immunity. Fig. 3 presents the result of the BFR measurement carried out in a GTEM cell for three different coupling lengths. The investigation shows, that the determined BFR behaves in principle according to the Weibull-distribution. Thus, a breakdown threshold (BT) can be introduced which specifies the values of the electric field strength that is necessary to reach a BFR of a certain percentage of the maximum value. A breakdown threshold of e.g. 10 % will be reached at an electric field strength of 1.25 kV/m in case of the GMB with the smallest coupling length and at field strength values of 1.45 kV/m respectively 1.7 kV/m for longer coupling lengths.

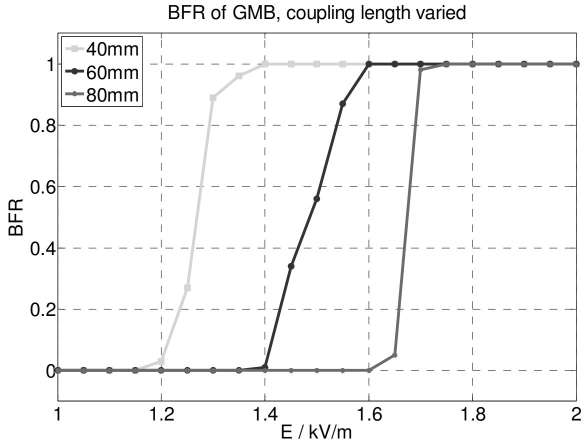

Fig. 3 Breakdown failure rate of generic microcontroller board for different coupling lengths, impact with unipolar UWB pulses in a GTEM cell

As mentioned above, the measurement on the OATS shows in principle the same behavior than the one inside a GTEM cell, although the pulse shape is different due to the differentiation of the pulse caused by the IRA. In addition, it should be said the susceptibility measurements with EMP pulses show the behavior that was initially expected: The vulnerability of the GMB increases with the coupling length. Furthermore, the BR of 10 % will be reached for electric field strength values of 20 kV/m and more.

III. NUMERICAL FIELD CALCULATIONS

In order to get an explanation of the unexpected coupling behavior of UWB to PCB traces, further investigations are performed with a numerical field calculation program that is based on the finite difference time domain (FDTD) method. In the following, the modeling of the problem is described as well as numerical results for both EMP and UWB pulses are presented and discussed.

A. Analytical Description of the Excitation Function

The UWB pulse that is used for the measurements in the GTEM cell can be described with mathematical expressions presented in [3]. While the commonly used expression of a transient pulse with double exponential pulse shape given by the difference of two exponential functions causes several problems during the numerical field calculations, the following expression is applied for the calculations:

$$E(t) = E_0 \cdot \frac{K(\alpha,\beta)}{\exp(\alpha \cdot (t-t_0)) + \exp(\beta \cdot (t-t_0))} \tag{2}$$

In this formula, α and β are variables that influence the pulse shape and t_0 is a time shift parameter. The correction factor $K(\alpha,\beta)$ serves as a normalization factor so that the maximum magnitude of the fraction is normalized to 1 and the peak value of the electric field strength is only given by E_0. Fig. 2 shows the UWB pulse that is given by (2) and used for the numerical field calculations. Furthermore, an EMP with a double exponential unipolar shape is used for the calculations, too. Its characteristic parameters are $t_r = 1.5$ ns and $t_{fwhm} = 80$ ns. Both the EMP and UWB pulse have in common that the peak value of the electric field strength is set to $E_0 = 1$ kV/m.

B. Simulation Model

The simulation model of the GMB is kept very simple in order to minimize the simulation time. Since the reset line of the generic microcontroller board is the most critical PCB trace, it is sufficient to model only one signal track. Thus, the simulation model consists of a circular PCB with a microstrip line on the top layer, a metallic ground plane on the bottom layer and a dielectric substrate made of FR-4. The length of the microstrip line is varied in the range between 10 mm and 90 mm with a step size of 5 mm for the different calculations as well as the value of load resistors which terminate microstrip line at both ends. A principle image of the simulation model is shown in Fig. 1 on the right side.

C. Simulation Results

The voltage drop at the load resistors which terminate the microstrip line is calculated numerical. The simulations with an EMP as excitation signal point out that the peak value of the voltage drop at the 50 Ω load behaves linear to the length of the microstrip line (see Fig. 4). Applying an UWB pulse as excitation signal delivers a completely different result. Fig. 5 shows the voltage drop at the 50 Ω load resistors in time domain. Since the PCB trace is designed as a 50 Ω microstrip line that is terminated with its characteristic impedance at both ends, only small reflections appear. (In theory, there should not be any reflections, but the transition from the microstrip line to the resistor is not realized perfectly.) Furthermore, it becomes clear that there is no linear dependency between the length of the PCB trace and the peak value, as shown in Fig. 6, too. Increasing the length of the microstrip line leads to the following behavior: The peak value of voltage drop rises in case of short trace lengths, reaches a maximum at 35 mm and increases in the range above.

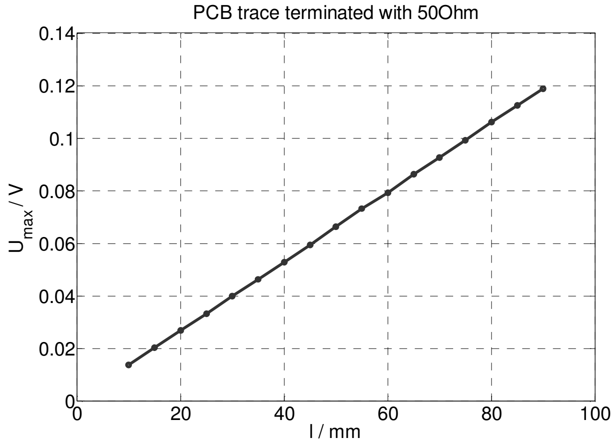

Fig. 4 Peak value of voltage at EMP expostion

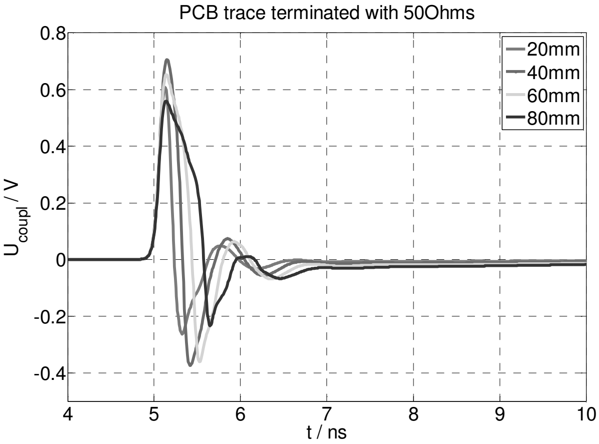

Fig. 5 Voltage drop at load resistor for UWB exposition

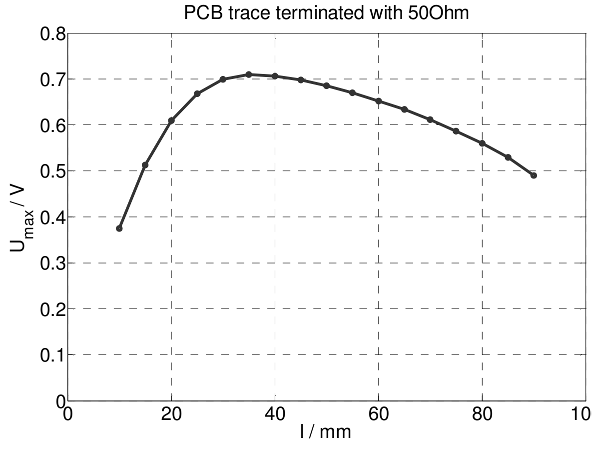

Fig. 6 Peak value of voltage for UWB exposition

Another interesting result can be achieved when the numerical calculated voltages are transformed into frequency domain. Fig. 7 shows the spectrum of the voltage drop at a 10 kΩ loads that terminate the microstrip line. The spectrum shows pronounced resonances for discrete frequencies.

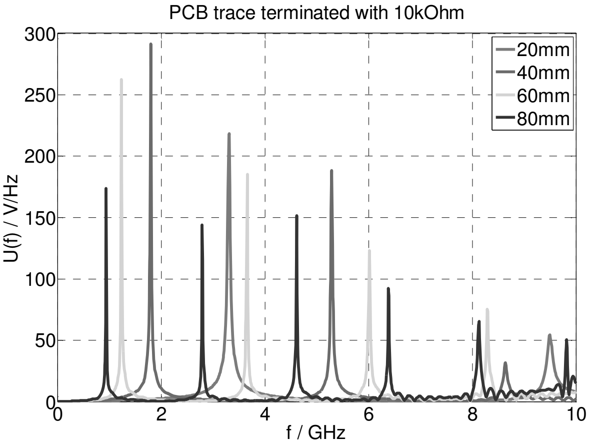

Fig. 7 Spectrum of the voltage for UWB exposition

These resonance effects occur since the microstrip line and the terminations form a line resonator. It should be mentioned that the resonances are not pronounced in case of a 50 Ω load because the line resonator is terminate quite good, thus the resonator is dumped very well and the quality factor is small.

IV. CONCLUSION

The numerical investigations of the coupling behavior of fast transient pulses validate the results determined by measurement: While the EMP shows as expected a higher coupling efficiency for longer PCB traces, the coupling of an UWB pulse behaves different because of resonance effects. Since a UWB pulse covers a large frequency range to several GHz in comparison to an EMP with a range up to approximately 300 MHz, the UWB pulse is able to couple to a PCB trace very well, because the resonant frequency of the in range that is covered by the UWB pulse. In case of the generic microcontroller board, the critical PCB trace is the reset line that causes a breakdown of the electronics for the smallest electric field strength. The imperfect termination of this PCB trace due to input port of the microcontroller and out of the optoelectronic device effects the building of a line resonator with a more or less high quality factor that could be excited with UWB pulses very well.

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