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Design and analysis of ultra-wideband antennas for transient field excitations

Miroslav Kotzev[1], **Matthias Kreitlow**[2], **and Frank Gronwald**[1]

[1]Institute of Electromagnetic Theory, Hamburg University of Technology, Harburger Schloss Str. 20, 21079 Hamburg, Germany
[2]Bundeswehr Research Institute for Protective Technologies and NBC Protection, Humboldtstr. 100, 29663 Munster, Germany

Correspondence to: Miroslav Kotzev (miroslav.kotzev@tuhh.de)

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Abstract. This work addresses the design of two ultra-wideband antennas for the application of transient field measurements that are characterized by frequency spectra that typically range from a few MHz to several GHz. The motivation for their design is the excitation of high power transient pulses, such as double exponential or damped sinusoidal pulses, within highly resonant metallic enclosures. The antenna design is based on two independent numerical full-wave solvers and it is aimed to achieve a low return loss over a wide range of frequencies together with a high pulse fidelity. It turns out that antennas of the conical and discone type do achieve satisfactory broadband characteristics while limitations towards low frequencies persist. Also the concept of fidelity factor turns out as advantageous to determine whether the proposed antennas allow transmitting certain broadband pulse forms.

1 Introduction

Ultra-wideband (UWB) applications still continue to be of considerable interest for the development of communication systems (Yang and Giannakis, 2004). Also in Electromagnetic Compatibility (EMC) the study of UWB electromagnetic fields is of great importance, e.g., in the context of intentional electromagnetic interference (Lee, 1995; Nitsch, 2005). This involves, in particular, to study the coupling of electromagnetic fields into and within metallic enclosures. While this is a classic problem of EMC, the development of corresponding measurement setups can be challenging.

Electromagnetic field coupling into an enclosure via aperture coupling is possible if devices under test are put into a TEM-waveguide, for example. Alternatively, conducted coupling via transmission lines and antennas is feasible as well. This has been exemplified in a recent study where small monopole antennas have been mounted inside a resonator which externally can be excited via SMA connectors (Vogt et al., 2015). In this study, focus was put on the steady-state in frequency domain and the corresponding setup is shown in Fig. 1.

Besides the steady-state it is also of interest to study transient system responses. Several studies are found in the literature where transient electromagnetic field behavior inside metallic enclosures analytically and numerically is considered (Nitsch et al., 2012, 2010). An experimental and numerical study, which involves aperture coupling of transient pulses within a TEM waveguide, recently was published in Kotzev (2016). In this context it would be desirable to also utilize, along the lines of Vogt et al. (2015), conducted coupling via antennas to study transient effects in the absence of apertures. This involves to design antennas which are more broadband if compared to the already existing narrowband monopole antennas that are shown in Fig. 1 and it is the subject of this paper to study this possibility.

The paper is organized as follows: In the next section (Sect. 2) the expected narrowband characteristics of the already existing monopole antenna is shown and two designs of alternative broadband antennas are introduced. These alternative antennas are of the conical and discone type and analyzed by means of the Finite Integration Technique (FIT) and Finite Element Method (FEM). In Sect. 3 the concept of

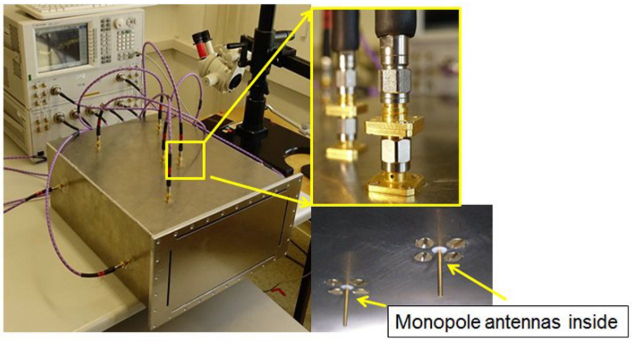

Figure 1. Metallic enclosure connected to a 12-port vector network analyzer (VNA), as used in the study of Vogt et al. (2015). Internal electromagnetic fields are excited by monopole antennas on the inner side of the resonator walls.

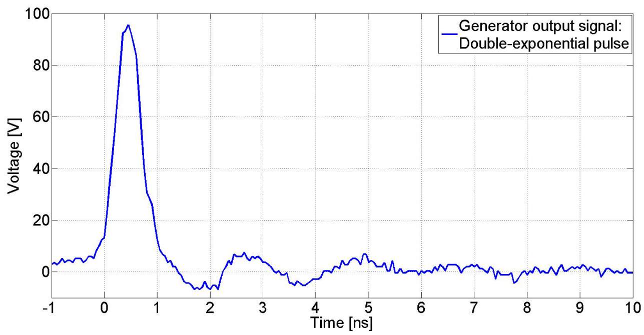

Figure 2. Measured double-exponential pulse, generated by a transient source used for EMC investigations.

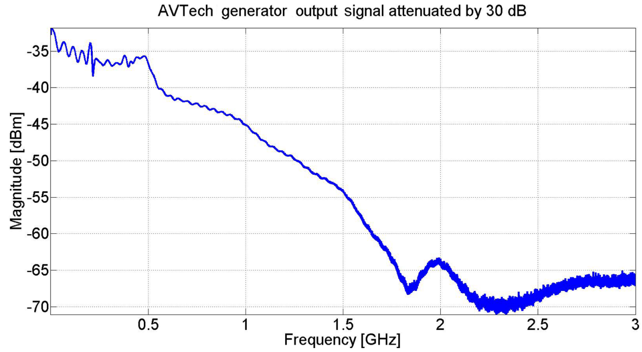

Figure 3. Spectrum of the generated double-exponential pulse.

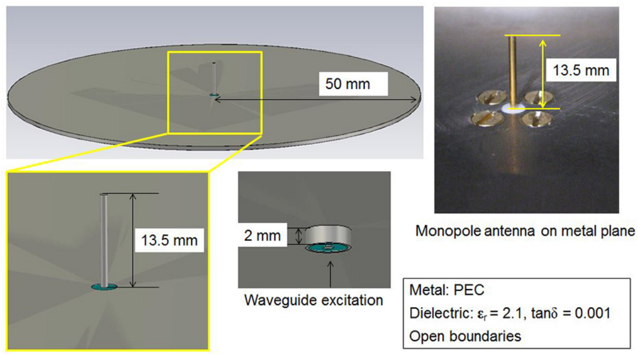

Figure 4. Full-wave model of the monopole antenna.

pulse fidelity is shortly introduced and applied to estimate the different antenna transmission properties with respect to different pulse forms. A short conclusion is provided by Sect. 4.

2 Antennas for transient field excitations

As mentioned in the introduction, the desired widebands antennas are intended to couple transient electromagnetic fields into a system. To get an impression of what is required, Fig. 2 shows a typical generator output that is used as primary source for EMC investigations. The generator produces an approximate double-exponential pulse with a voltage amplitude of 100 V, a signal rise time of approximately 250 ps, and a pulse width of 1 ns. The corresponding spectrum is shown in Fig. 3, where it can be clearly seen that a broadband antenna is required if this signal has to be fed into a system. The maximum usable frequency, in this case, should be in the range of 3 GHz.

2.1 Monopole antenna characteristics

As a reference for further analysis, the monopole antennas introduced in Fig. 1 are modeled by means of the FIT (CST Corporation, http://www.cst.com) and FEM (ANSYS Inc., http://www.ansys.com), compare Fig. 4. Also their return loss is measured by means of a vector network analyzer. It is seen in Fig. 5 that both the numerical models and the measurement reproduce the expected narrowband characteristics with pronounced resonances.

2.2 Conical antenna design

To achieve a higher bandwidth it is an apparent strategy to modify the monopole antenna towards a conical shape and to enlarge its overall dimension. The corresponding geometry is sketched in Fig. 6. Different length parameters have been considered and it was found that an antenna of height 90 mm yields a good compromise between antenna length and bandwidth. Corresponding numerical and measured data, refering to a fabricated prototype, are given in Fig. 7 up to a frequency of 5 GHz. While the antenna obviously is well-matched beyond 0.5 GHz it turns out to be difficult to achieve a good matching for lower frequencies.

2.3 Discone antenna characteristics

As an alternative antenna type, the model of a discone antenna has been investigated. The general geometry of this type is depicted in Fig. 8. Again, numerical and measured

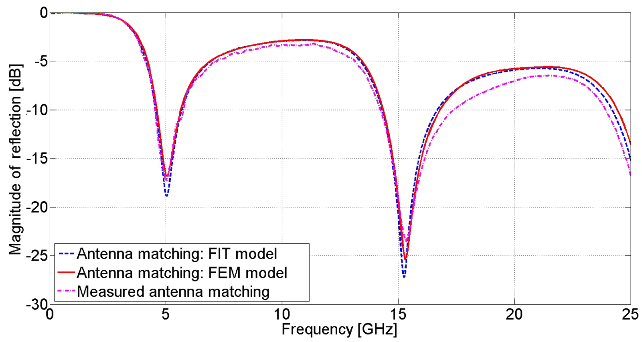

Figure 5. Model-to-hardware correlation of the measured antenna matching (reflection, magnitude of S_{11} parameter) and the computed S_{11}-parameters using full-wave numerical models.

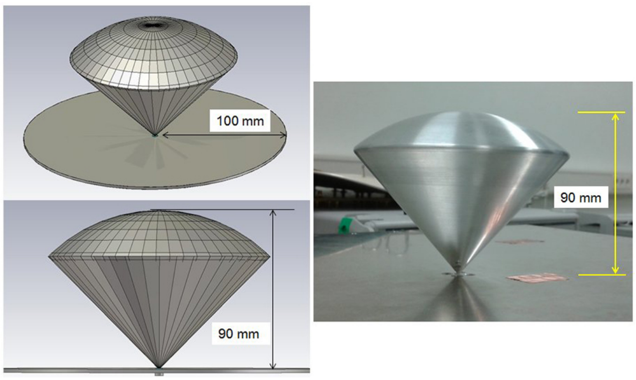

Figure 6. Geometry of the proposed conical antenna type: FIT model (left) and fabricated antenna (right).

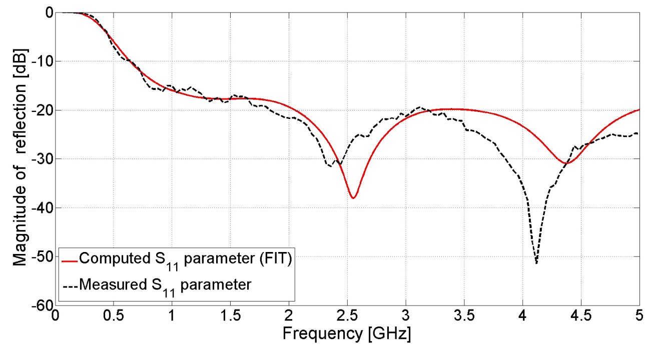

Figure 7. Numerical and measured return loss of a conical antenna of height 90 mm.

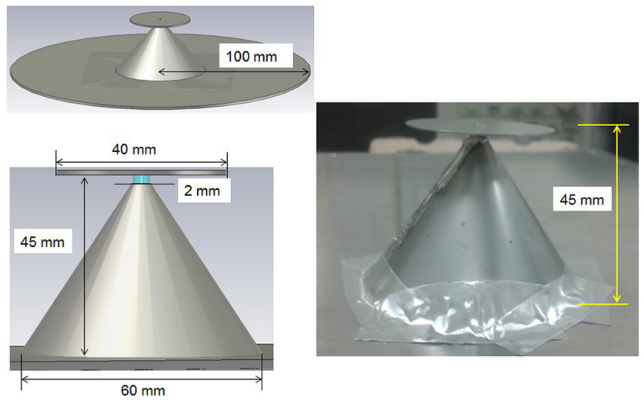

Figure 8. Geometry of the proposed discone antenna type: FIT model (left) and fabricated antenna (right).

data have been obtained and are shown in Fig. 9. As for the discone antenna it proves to be difficult to achieve a good matching in the lower frequency range. On the basis of numerical models, however, it is seen in Fig. 10 that the discone antenna is well matched up to a frequency of 17 GHz which, incidentally, makes it well-suited for UWB-communication applications.

3 Antenna fidelity characteristics

While for the purpose of coupling electromagnetic energy into an interior region the antenna matching certainly is an important parameter, the directive properties of an antenna, expressed by means of the gain, are less crucial. However, when it comes to UWB applications, another parameter turns out to be of importance and this is the system fidelity factor (SFF), as described in Lamensdorf and Susman (1994), Quintero et al. (2011), and Koohestani et al. (2014), for example. The concept of SFF is based on the cross-correlation function between the input signal $f(t)$ fed to an antenna and the corresponding signal $r(t)$ transmitted by the antenna and measured at a certain distance. Therefore the SFF is a measure of signal distortion during transmission, refering to a certain input signal.

In order to compare the shapes of transmitted and measured signal rather then their magnitudes, the signals usually are normalized according to

$$\hat{f}(t) = \frac{f(t)}{\left[\int\limits_{-\infty}^{+\infty} |f(t)|^2 \mathrm{d}t\right]^{1/2}} \quad (1)$$

and

$$\hat{r}(t) = \frac{r(t)}{\left[\int\limits_{-\infty}^{+\infty} |r(t)|^2 \mathrm{d}t\right]^{1/2}} \quad (2)$$

The cross-correlation between the signals is computed at every point in time and the maximum value of correlation is taken as SFF,

$$\mathrm{SFF} = \max_{\tau} \int\limits_{-\infty}^{+\infty} \hat{f}(t)\hat{r}(t+\tau)\mathrm{d}t \quad (3)$$

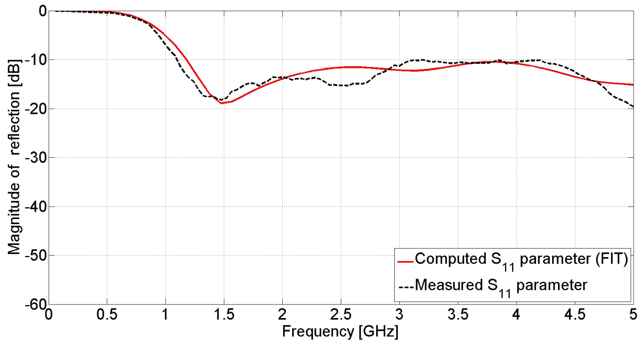

Figure 9. Numerical and measured return loss of a discone antenna of height 45 mm.

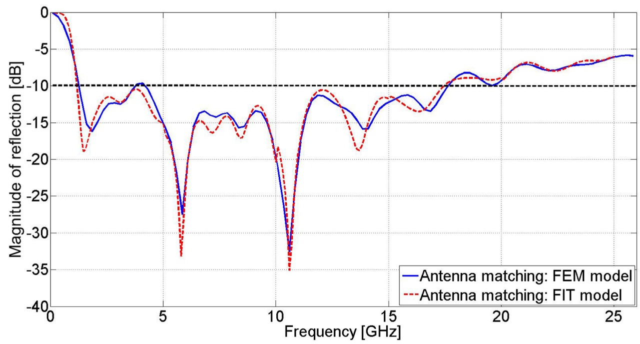

Figure 10. Antenna matching of the discone antenna obtained from both FIT and FEM up to a frequency of 26 GHz.

It follows that a maximum correlation corresponds to SFF = 1 and a minimum correlation corresponds to SFF = 0. Antennas with SFF > 0.9 usually are considered as antennas that transmit a certain pulse with acceptable low distortion.

It also is meaningful to correlate the 1st derivative or even higher derivatives of the input signal to the measured signal. Correlating the 1st derivative, for example, is meaningful if a differentiating behavior of an antenna is expected. In this case, the corresponding SFF indicates how much the actually measured signal deviates from the expected measured signal.

In the following, the SFF of the proposed antennas is computed for two different broadband signals. Since it was not possible to design antennas which are matched to very low frequencies, being required to properly transmit a double exponential pulse, a Gaussian pulse of bandwidth 100 MHz to 3 GHz and a damped sinusoidal pulse of center frequency 150 MHz are chosen as broadband pulses, compare Figs. 11 and 12.

To compute the scalar function $\hat{r}(t)$ of a measured vector field one needs to define some kind of scalar average. In our case, eight field probes were distributed around the antennas, each of which recording three independent electric field components. For each field component at each position the SFF is calculated, yielding 24 different SFF values. Then

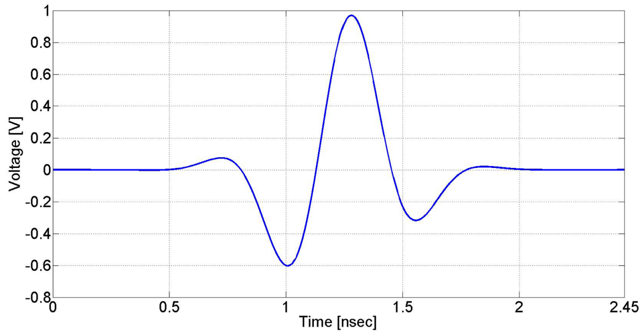

Figure 11. Gaussian broadband pulse of bandwidth 100 MHz to 3 GHz.

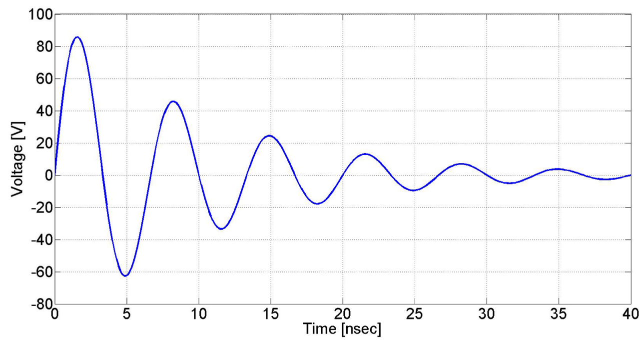

Figure 12. Damped sinusoidal pulse of center frequency 150 MHz.

Table 1. Antenna fidelity factors obtained from models using FIT and different pulse forms. The maximum values are marked bold.

Gaussian pulse (100 MHz to 3 GHz)	0th derivative	1st derivative
Monopole antenna 1.39 cm	0.67	0.86
Monopole antenna 7 cm	0.84	0.83
Conical antenna	0.84	**0.92**
Discone antenna	**0.91**	**0.91**
Damped sinusoidal pulse (center frequency 150 MHz)	**0th derivative**	**1st derivative**
Monopole antenna 1.39 cm	0.51	0.44
Monopole antenna 7 cm	0.76	0.67
Conical antenna	0.81	0.72
Discone antenna	**0.91**	0.79

the total SFF, as displayed in Table 1, is calculated from the arithmetic mean of these 24 values. For comparison, also a monopole antenna of length 7 cm is included in the analysis.

It can be seen from Table 1 that the discone antenna exhibits a satisfactory SFF with respect to both broadband pulses. The conical antenna performs less advantageous in this respect but, as expected, outperforms the narrowband monopole antennas.

4 Conclusions

In this paper two UWB antenna designs have been analyzed in view of EMC measurement setups that require the coupling of transient electromagnetic fields into interior regions. While the antenna matching has been investigated in a standard way, also the concept of system fidelity factor has been used to gain insight into the transmit behavior of the proposed antennas. The proposed antennas are limited towards low frequencies, making them not suitable for the transmission of double exponential pulses with large low frequency content. However, other standard broadband pulses, such as Gaussian pulses or damped sinusoidal pulses of less low frequency content, can be transmitted in a satisfactory way.

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