URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

A numerical study of HPEM coupling to a nonlinearly loaded cavity subject to an electric energy storage effect

R. Michels[1], M. Schaarschmidt [2], and F. Gronwald[1]
(1) University of Siegen, Reliability of Technical Systems and Electrical Measurement, HÃűlderlinstr. 3, 57076 Siegen, Germany
(2) Bundeswehr Research Institute for Protective Technologies and CBRN Protection, Humboldstr, 100, 29663, Munster, Germany

Abstract

In this contribution we numerically analyze the behavior of a nonlinearly loaded loop antenna inside a resonating environment. As shown by previous research, a transient HPEM excitation can lead to a DC-component in the response of a nonlinearly receiving structure which is attributed to electric energy that is stored during rather long time scales. Oscillations caused by the resonating environment overlap with this DC-component, leading to an overall increased effect.

1 Introduction

The presence of components with nonlinear current voltage characteristics in receiving structures and scatterers can significantly alter their behavior due to demodulation and intermodulation effects. The complexity can be increased if such structures are located inside resonating environments that, in practice, often are given by metallic casings with apertures.

In general, analytic approaches to this type of problem are rather involved and limited to canonical configurations. For example, lossless transmission lines with nonlinear loads inside a rectangular cavity resonator have been analytically analyzed in [1], utilizing left- and right-handed Green's function in time domain. An analytic solution that predicts the effects of intermodulation has been proposed. In a different analytic approach, problems that involve nonlinear antennas inside a resonator are reduced to nonlinear circuit problems which can be solved by the method of successive approximation [2]. However, this method is limited to weak nonlinearities.

In a combined semi-analytical and numerical approach, a nonlinearly loaded loop antenna has been considered in [3]. Here, a strongly nonlinear load is given by a diode that is soldered within the loop of the antenna. The structure is excited by a transient pulse. Two simulation methods are applied to the model: First, the response of the structure is calculated in a full wave simulation. Then an equivalent circuit model of the structure is derived in order to perform simulations with an electric circuit simulator. Both methods reveal the same remarkable effect that due to the rectifying property of the diode, a DC-component is present in the antenna response and still remains after the oscillations caused by the transient excitation have completely decayed. This effect was reproduced by measurement [4] in free space and inside a resonator. It represents stored electric energy that is maintained by the presence of the diode. This contribution provides further numerical results to analyze the emerging DC-component in combination with resonance effects within a cavity. It is organized as follows: In Section 2 a nonlinearly loaded loop antenna, a broadband transient excitation and a suitable rectangular cavity resonator are introduced. In Section 3 the nonlinear load is reduced to a linear one to exhibit its response to a broadband transient excitation, both in free space and within a cavity, by numerical simulations. In Section 4, the same simulations are performed for the nonlinearly loaded loop antenna to identify the relevant nonlinear effects.

2 Configuration setup

2.1 Antenna model

To begin with, the considered antenna is shown in Fig. 1. The loop antenna actually is of rectangular form and of dimensions as indicated in the figure. For the definition of an approximate open-circuit voltage a port resistance of $R = 1\text{M}\Omega$ is introduced as well. The antenna is excited by a plane wave, as indicated, modulated by the given signal. The voltage of the antenna response is sampled at the port resistance and denoted by V in the figure. The parameters of the diode used in the simulations are the following:

Table 1. Diode parameters provided by CST Microwave Studio[6]

R (Ω)	190
C_p (F)	0.3e-12
R_R (Ω)	40e6
I_0 (A)	2.5e-7
T (K)	300

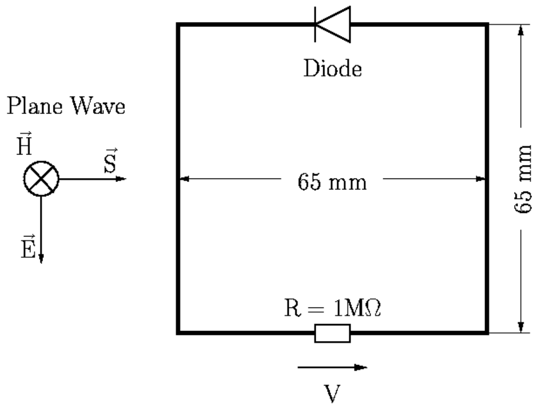

Figure 1. Nonlinearly loaded loop antenna, excited by a signal-modulated plane wave.

In order to compare linear and nonlinear loaded loop antennas, the diode in Fig. 1 is replaced by a parallel circuit with a resistance $R_{\mathrm{R}} = 40\ M\Omega$ which corresponds to the reverse resistance and a capacitor corresponding to the parasitic capacitance of the diode, see Fig. 2.

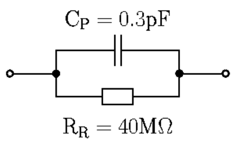

Figure 2. Replacement of the diode by a parallel circuit that includes its reverse resistance R_{R} and parasitic capacitance C_{P}.

2.2 Excitation signal

In order to provide broadband excitations, standard double exponential pulses

$$E(t) = E_0 k \left(e^{-\alpha t} - e^{-\beta t}\right) h(t) \tag{1}$$

are used, see Fig. 3, with parameters $E_0 = 160\ \frac{V}{m}$, $\alpha = \frac{1}{t_{\mathrm{f}}}$ and $\beta = \frac{1}{t_{\mathrm{r}}}$. In addition we use the correction factor k defined by [5]

$$k(\alpha,\beta) = \left[e^{-\alpha \frac{\ln(\alpha/\beta)}{\alpha-\beta}} - e^{-\beta \frac{\ln(\alpha/\beta)}{\alpha-\beta}}\right]^{-1}, \tag{2}$$

and the Heavyside-function h(t).

2.3 Cavity resonator

As cavity resonator, a box with inner dimensions 240 mm x 100 mm x 240 mm made of perfectly conducting material is defined, as indicated in Fig. 4. The resonator has an aperture aiming towards the direction of the incoming wave, given by two slots which intersect at a right angle to form a cross. The slots have a width of 1 mm. The wall thickness of the cavity is set to 1 mm as well.

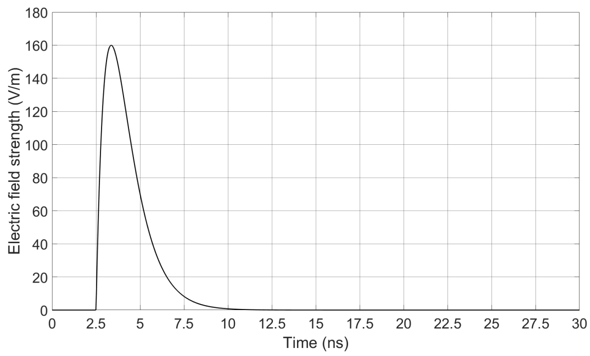

Figure 3. Double exponential pulse used as excitation signal.

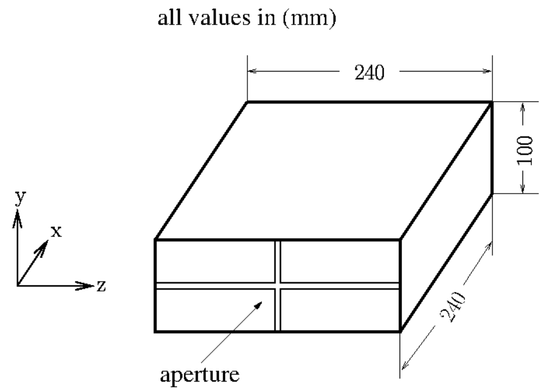

Figure 4. Figure of the resonator with the aperture.

2.4 Location of the antenna inside the cavity

The antenna is oriented inside the cavity as shown in Fig. 5. The area spanned by the loop is parallel to the xy-plane. The origin of the coordinate system denoted in Fig. 4 and Fig. 5 is located at the center of the cavity. The center of the loop is at $x = 40$ mm, $y = 0$ mm, and $z = 40$ mm.

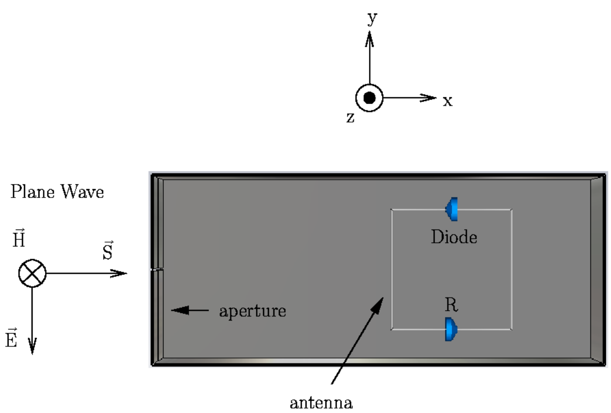

Figure 5. Position of the loop antenna inside the cavity.

3 Coupling of the linearly loaded antenna in free space and inside the cavity

3.1 Natural frequency of the antenna

Simulations with different pulse shapes show that the dominating frequency in the antenna response does not depend on the shape of the exciting pulse but corresponds to the natural frequency of the antenna. We choose a pulse with values $t_\mathrm{r} = 0.75$ ns and $t_\mathrm{f} = 1$ ns. With this excitation, three simulations are performed in free space. The first one includes the complete nonlinearly loaded antenna. In the second simulation, the diode is replaced by the parallel circuit introduced in Fig. 2. Finally, in the last simulation, the parasitic capacitance C_P is removed such that the diode is replaced by the 40 MΩ reverse resistance. In Fig. 6, the numerically calculated spectra of the voltages at the antenna feed are displayed. It is seen that the natural frequency of the nonlinearly loaded antenna is equal to the one of a linear antenna with the diode replaced by the parallel circuit introduced in Fig. 2 and given by 840 MHz.

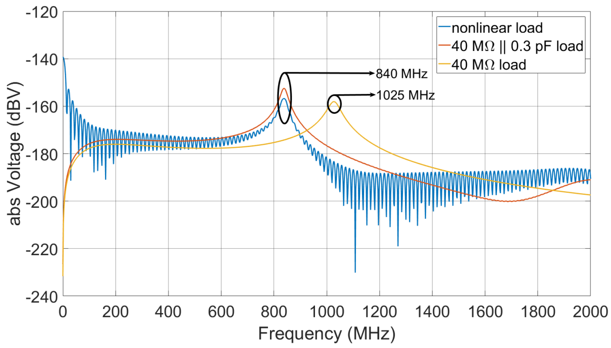

Figure 6. Numerically calculated spectra of the antenna response in free space.

3.2 Electromagnetic coupling between loop antenna and cavity

It was attempted to dimension the cavity such that the main antenna resonance matches one of the cavity resonances. However, this is not trivial if the coupled antenna-cavity system is considered. As can be seen from Fig. 7 an interesting frequency-splitting occurs, even in the linear case. Additionally, to quantitatively describe the aperture coupling, the electric field strength in the cavity at the location of the center of the antenna is measured. While in free space the receiving structure is excited by the electric field strength displayed in Fig. 3, the field strength inside the resonator has the more complicated shape shown in Fig. 8. It turned out that the field strength only has a component in y-direction, compare the axes in Fig. 4 and Fig. 5. If this field strength is compared to the one in free space it is seen that its peak values are smaller by a factor of eight or less. Clearly, the signal is composed of various oscillations that decay rather slowly, due to the perfectly conducting cavity walls.

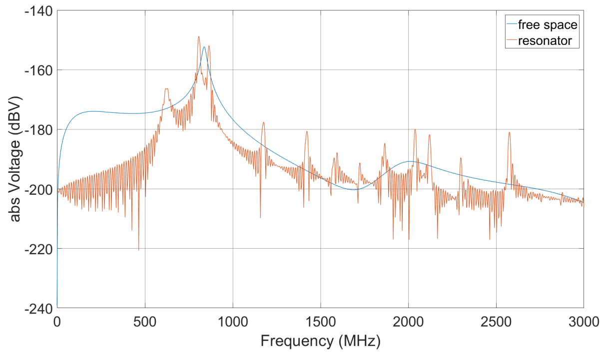

Figure 7. Spectrum of the linear antenna response in free space and inside the cavity resonator.

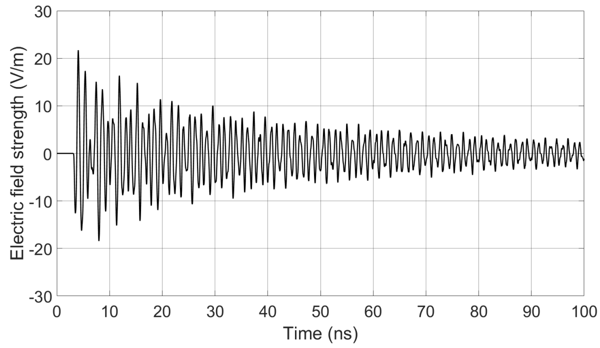

Figure 8. Electric field strength inside the resonator at the location of the antenna center.

3.3 Antenna responses

In the following, the time-domain voltage drop V across the terminating resistance will be referred to as antenna response, compare Fig. 1. The antenna responses are displayed in Fig. 9. Even though the first oscillations in the free space case have higher peak values, the resonating effect of the cavity leads to further oscillations. Next, this is examined for the loop-antenna with nonlinear load.

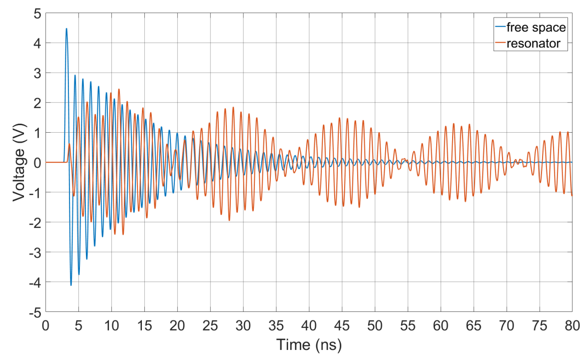

Figure 9. Response of the linearly loaded loop antenna both in free space and inside the resonator.

4 Electromagnetic coupling of the nonlinearly loaded antenna in free space and inside the cavity

Finally, the nonlinearly loaded loop antenna is considered. It is deduced from Fig. 10, that the presence of the nonlinear load has no major effect on the resonance frequencies if compared to the linear case shown in Fig. 7. The response of the nonlinearly loaded antenna in free space and inside the resonator is shown in Fig. 11.

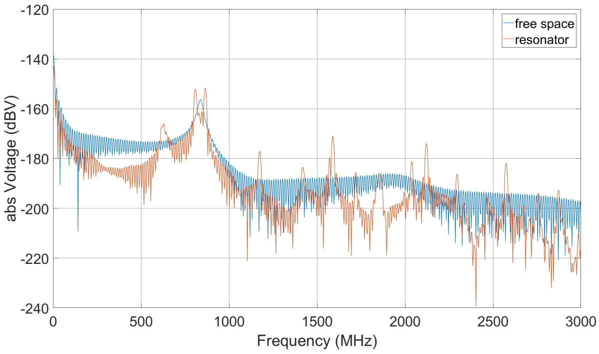

Figure 10. Spectrum of the nonlinear antenna response in free space and inside the cavity resonator.

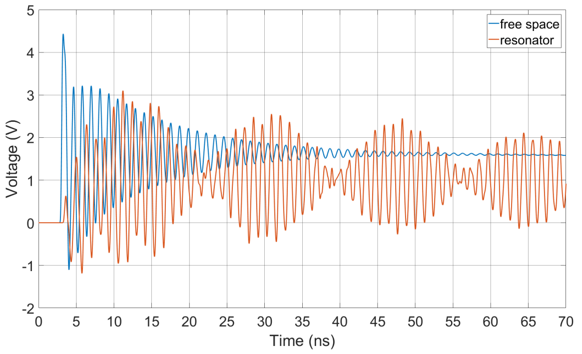

Figure 11. Response of the nonlinearly loaded loop antenna in free space and inside the resonator.

As already noted in the former studies [3], [4], the rectifying effect of the diode leads to a DC-component in the response of the antenna. This can be observed both in free space and inside the cavity. The DC-components are of comparable size, even though the electric field strength within the cavity is smaller by about a factor of eight, indicating that the electric energy storage effect is more pronounced within the cavity. Oscillations caused by the cavity resonances overlap the DC-component, leading to peak values that exceed the DC-component generated in free space.

5 Acknowledgements

This research work was partially funded by the Bundeswehr Research Institute for Protective Technologies and CBRN Protection, Munster, with contract number E/E590/JZ001/HF063.

References

[1] R. Rambousky, S. Tkachenko, and J. Nitsch, “A Novel Solution Algorithm for Nonlinearly Loaded Transmission Lines inside Resonating Enclosures,” *Adv. Radio Sci.*, **12**, 11, November 2014, pp. 135–142, doi: 10.5194/ars-12-135-2014.

[2] F. Gronwald, “Iterative Solution of a Nonlinear Antenna Problem Inside a High-Quality Resonating Chamber,” *Internat. Symp. Electromag. Compat. - EMC EUROPE*, 2012, Rome, Italy, doi: 10.1109/EMCEurope.2012.6396683

[3] M. Kotzev, X. Bi, M. Kreitlow, and F. Gronwald, “Equivalent Circuit Simulation of HPEM-Induced Transient Responses at Nonlinear Loads,” *Adv. Radio Sci.*, **15**, 21, September 2017, pp. 175–180, doi: 10.5194/ars-15-175-2017

[4] R. Michels, M. Kreitlow, A. Bausen, C. Dietrich, and F. Gronwald, “Modeling and Verification of a Parasitic Nonlinear Energy Storage Effect Due to High-Power Elecromagnetic Excitation,” *IEEE Trans. Electromag. Compat.*, **Vol. 62, No.6**, 6, December 2020, pp. 2468–2475, doi: 10.1109/TEMC.2020.2980976

[5] M. Camp and H. Garbe, “Parameter Estimation of Double Exponential Pulses (EMP, UWB) with Least Squares and Nelder Mead Algorithm,” *IEEE Trans. Electromagn. Compat.*, **Vol. 46, No. 4**, 30, November 2004, pp. 675–678, doi: 10.1109/TEMC.2004.838228

[6] Dassault Systems, *CST Microwave Studio Suite 2018*, **online: https://www.3ds.com**