Simulation and modelling of planar EMI/RFI Filters

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ABSTRACT

Electromagnetic interference (EMI) at radio frequencies (RF) in compact integrated power electronic converter modules can be suppressed using lossy transmission line lowpass filters. Structure of such a filter is proposed in [1]. Main application of proposed structure is suppression of RF-EMI (*Radio Frequency ElectroMagnetic Inteneference*) interference in power electronic devices. Paper presents results of numerical simulation and analytical modelling of filter structure. Guidelines for further research are presented and discussed.

Key words: IPEM Modules, EMC, RF-EMI, numerical and analytical modelling

1. INTRODUCTION

In the paper discussion and analysis of the new prototypes of the planar lowpass power filters is presented. Basic structure is shown in Fig. 1 (not in scale). In [2] variations of considered basic structure are proposed and analyzed. Presented in [2] alternative structures were expected to

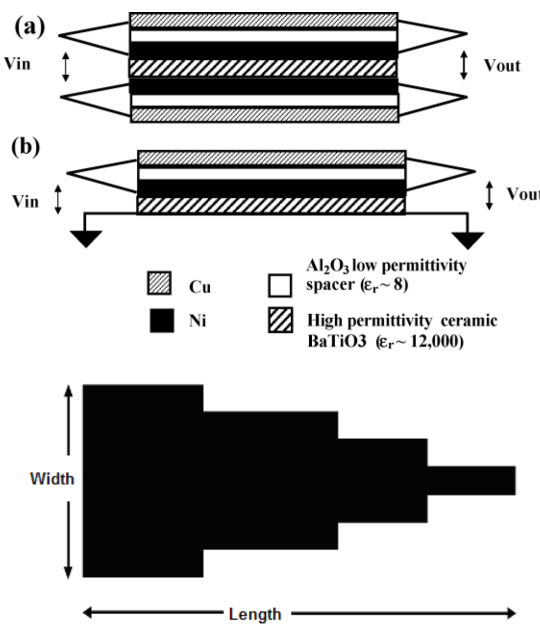

Fig. 1. Cross-section and geometry of analyzed filter structures [1].

provide information needed for accurate and efficient numerical and analytical simulation.
Target application of discussed structures is suppression of RF-EMI interference in power electronic devices. Such interferences are found primarily in integrated high power converters (power densities 13 W/cm^3 and above). Interferences are also induced by electromagnetic coupling between electronic devices during switching and by inductance and capacitance in electronic devices and in module package. Popular technologies used in aerospace industry prefer filters structures that are integrated (for convenience) with coaxial cables. Together with new devices and technologies a need has occur to design new, small, planar lowpass filter for Integrated Power Electronic modules (IPEMs). Such modules with kilowatt powers and high power densities can emit significant RF-EMI interferences. Proposed filters for radio frequency (RF) modules should satisfy three main prerequisites: 1) because structure should be physically small the speed of electromagnetic wave must be reduced to fraction of its free-space velocity value, 2) structure should be electrically and mechanically able to handle power from 1 kW to 10 kW at 300 V to 500 V and 30 A, 3) filter cut-off slope should be as steep as possible (e.g., > 40 dB/decade).

Prototype structure described in [1] satisfies specified above requirements. Manufacturing technology of this kind of filters and experimental measurements of the amplitude characteristics are presented and discussed. Amplitude characteristics are compared with the ones obtained from analytical modeling. Filters in question have different forward and reverse characteristic, what is caused by geometry (as suggested by authors in [1]) and results in non uniform current density and EM field distribution in analyzed structure. As it was mentioned earlier transfer function is derived in forward and reverse direction. Obtained results - amplitude characteristics are different from experimental ones, especially in forward direction.

The goal of the following paper is to further continue the work undertaken in [1], [2], [3] and use a set of numerical, analytical methods and models to define circuit model of considered structures with acceptable accuracy. Simulations results of derived analytical models are presented, potential problems and future guidelines are discussed. In [1], [2], [3] authors investigated simple analytical model and transverse resonance technique. It can deliver accurate model for planar structures, however it did not deliver accurate results for investigated multilayer planar power filter.

2. PARAMETERS OF ANALYZED STRUCTURES

Stepped filter structure [1] is desired because of simple production technology and theoretical analysis. Intention was to use an approximation of exponential shape. Proposed structures are manufactured from several layers Cu - Al_2O_3 - Ni –$BaTiO_3$ - Ni – Al_2O_3 - Cu. Filter cross-section is presented on Fig. 1 (without - a and with - b common ground return). The Ni – $BaTiO_3$ - Ni layers are designed to reduce interferences and its characteristics are main point of interest. Cu layers transfer kW power levels. Unwanted higher order harmonics are diverted into Ni – $BaTiO_3$- Ni layers were are finally suppressed. In [1], [2] the following filter dimensions are considered: length – 100 mm, width of sections – 40 mm, 20 mm, 10 mm and 5 mm. Length of each section – 25 mm. Thickness: Ni – 17 μm, σ = 1,47·107 S/m and μ_r = 100. $BaTiO_3$ layer – 150 μm, tan Δ = $0.0035\sqrt{(f/106)}$ assumed approximation, ε_r = 12000. Structure was simulated in 1 kHz – 100 MHz frequency range. Initial prototype filter structure was fabricated with uniform Ni layer geometry. However non uniform Ni layer shape is characterized by anticipated higher attenuation. Because $BaTiO_3$ ceramic material is untypical in such application its exact material parameters are not known, especially how do this change with temperature and other environmental conditions. Mentioned properties are also result of exact ceramic wafer fabrication technology from powder in sintering process. Proposed structures must accept significant power levels and also thermal properties should be considered.

Further investigation of manufacturing technology, characterization of material parameters and testing of actual filter samples was not conducted. It is beyond the scope of presented paper and could be next step in such filter structures analysis. However, initial research have shown that significant improvement can be achieved and new materials can be applied and tested.

3. NUMERICAL SIMULATIONS

Proposed filter structures were simulated using various 3D fullwave EM software: Zeland IE3D, Ansoft HFSS, QWED Quickwave 3D, CST Microwave Studio, Zeland Fidelity. Chosen software used different numerical techniques (FDTD, MoM, combination of different procedures or techniques) to solve electromagnetic equations in given model. Results have shown difficulties that occur during simulation of such filter structures. Because of untypical filter structure and material parameters (i.e. ε), detailed models in numerical simulation software are required. This results in time demanding, difficult simulations and various parameters in EM software are subject of optimization. Detailed results of numerical simulations are beyond the scope of this paper and can be found in [2]. Numerical experiments delivered valuable data about effects (especially current crowding) that can be observed in filter structure layers. However, the results of simulations differ from measurement in the stop band of the filter.

In an attempt to simplify simulation, model complexity reduction in software was proposed (parameters and segmentation). However it was not possible to replicate with acceptable accuracy all the effects between simulated segments.

Fig. 2 and Fig. 3 show amplitude characteristics from measurements [1] and EM simulations [2].

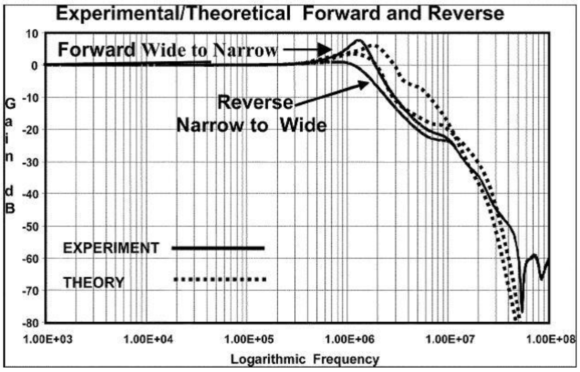

Fig. 2. Amplitude characteristics from measurements and initial analytical modeling [1].

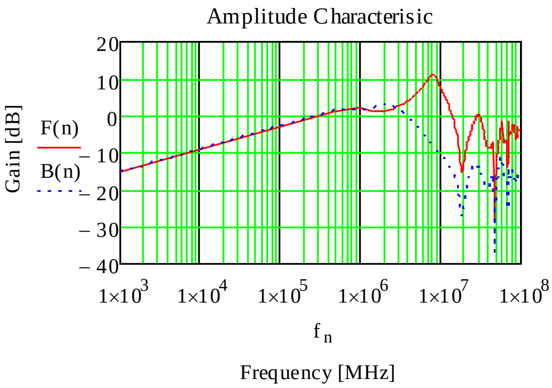

Fig. 3. Amplitude characteristics derived from numerical simulations [2].

4. ANALYTICAL MODELLING

Results of numerical simulations in [2] and [3] were a starting point for authors to further investigate analytical models and develop other set of procedures and techniques. Such approach could deliver simple and scalable analytical models for whole structure that could be used also in filter design and optimization processes (or similar structures). Developed models can be used in circuit simulation software (i.e. SPICE) that is already well optimized and does not require large computing and optimization hardware resources.

One of the possible methods is to combine numerical simulations with analytical modelling. Filter structure can be simulated with reduced physical size or including segmentation. In the subsequent steps, obtained numerical results are used in analytical model. Combined data are used to create analytical model for whole structure with all the details included. However it is still not possible to model complex interactions between/inside each element of the planar structure.

One of the analytical methods which delivered interesting results is Vector Fitting algorithm.

Vector Fitting is a numerical procedure that allows for rational approximation of the transfer, impedance or admittance functions, obtained using measurements or from full wave analysis. In [4] detailed description concerning VF as well as many application examples can be found. The VF output data is in the following form:

$$f(s) = \sum_{m=1}^{N} \frac{r_m}{s-a_m} + d + se \qquad (1)$$

where r_m are residues and a_m poles of the function, d and se are optional and explanation can be found in [4].

During iterative process a set of approximating residues and poles is calculated. Using iterative relocation a set of initial poles and residues is modified. Order of approximation, initial set of poles/residues and other parameters can be specified before optimization. We elaborated approach to use this algorithm for approximation of the transfer function of the filter basing on the amplitude characteristic only. Therefore we used different weights for each frequency range during VF optimization procedure. This technique delivered better overall frequency response approximation. Various other modifications of VF have been also investigated. Those changes were expected to reduce the order of approximation and speed up algorithm convergence. Our simulations have shown that no significant improvement was observed.

Fig. 4 and Fig. 5 present filter frequency response (amplitude and phase) approximated using VF procedure – forward direction. Fig.6 and Fig 7. show approximation for backward direction. VF weights calculation process could be optimized. At the moment it is still a matter of trial and error.

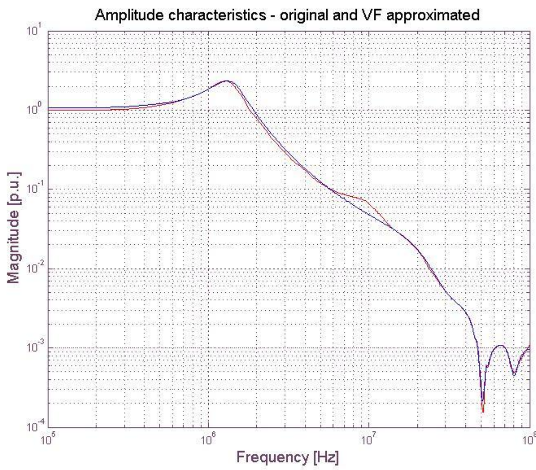

Fig. 4. Amplitude characteristics approximated using VF and weights, forward direction.

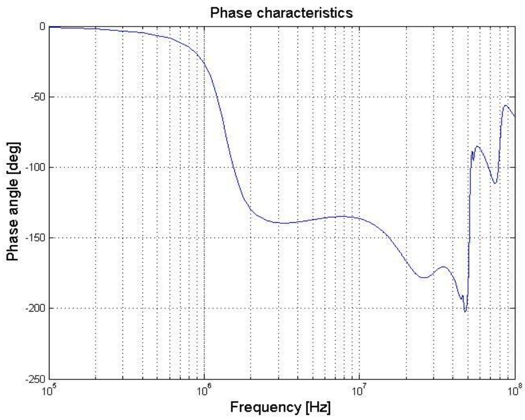

Fig. 5. Phase characteristics approximated using VF and weights, forward direction.

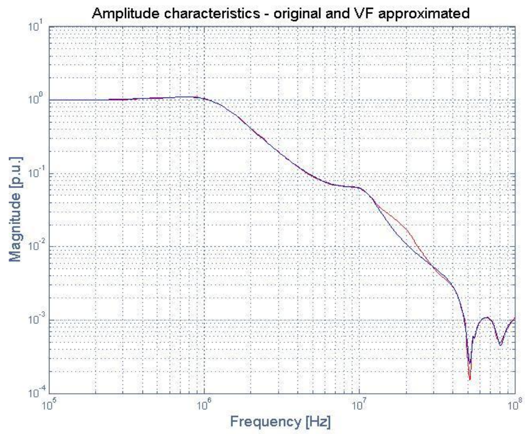

Fig. 6. Amplitude characteristics approximated using VF and weights, backward direction.

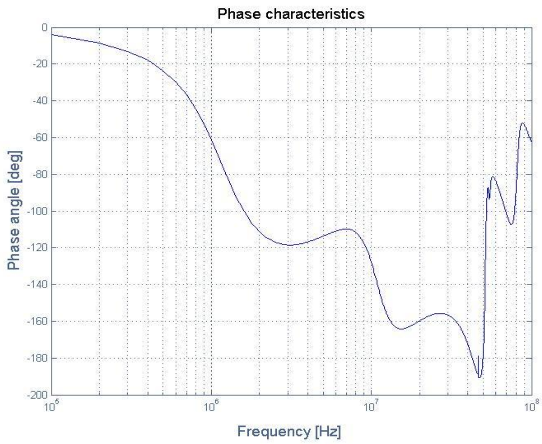

Fig. 7. Phase characteristics approximated using VF and weights, backward direction.

SUMMARY

The paper presents problem of modelling and simulation of the prototype of planar filter structure. Numerical simulations did not deliver accurate results and highlated problems to be solved. Vector Fitting technique delivers valuable and accurate results. It can serve as starting point for further research. The important matter that was not investigated is the passivity of calculated frequency responses with the aim to synthesis of RLC model of the filter.

One of the future points of interest is application of genetic algorithms techniques. It is believed to deliver scalable and accurate circuit model of planar filter structure. Conventional software was not able to calculate accurate wideband equivalent circuit model.

Combination of various analytical techniques also proved to deliver interesting results and is a subject of further research. Main goal of analytical modeling was to deliver a set of procedures that will allow to simulate filter structure with acceptable accuracy compared to actual measurements results (amplitude characteristics).

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