IOSUD - Universitatea Politehnica Timişoa
Şcoala Doctorală de Studii Inginereşti

CONTRIBUTIONS TO THE PROPER DESIGN AND OPTIMIZATION OF ELECTRONIC PRODUCTS IN THE AUTOMOTIVE INDUSTRY FOR ELECTROMAGNETIC COMPATIBILITY THROUGH THE USE OF SIMULATION ENVIRONMENTS

PhD Thesis – Summary

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The doctoral thesis is structured into six chapters: Chapter 1 presents the current context of the accelerated development of electronic systems in the automotive industry and highlights the importance of electromagnetic compatibility, as well as the critical role of signal integrity and power integrity in ensuring the proper operation of modern electronic equipment. Chapter 2 analyzes the relevant standards used in the design and validation of high-speed interfaces, such as OPEN Alliance Automotive Ethernet and PCI Express, emphasizing the strict requirements regarding impedance, jitter, and communication channel integrity. Chapter 3 is dedicated to the use of electromagnetic simulations for the evaluation and optimization of signal integrity, power integrity, and IR drop phenomena, highlighting efficient methods for improving circuit performance from the design phase. Chapter 4 presents the experimental validation of the simulated models by comparing simulation results with measurement data for automotive interfaces, demonstrating the accuracy and applicability of the proposed methodology. Chapter 5 addresses the use of frequency selective surfaces and innovative structures to control electromagnetic wave propagation, including the development of flexible solutions and a thermally tunable water-based polarizer. The conclusions and original contributions of the research are summarized in Chapter 6, highlighting the impact of the proposed solutions on optimizing electromagnetic compatibility and the performance of electronic systems in the automotive industry.

1. Introduction to the Thesis Field

The modern automotive industry is facing a rapid increase in the complexity of electronic systems, driven by the integration of high-speed communications, ADAS (Advanced Driver Assistance Systems), and intelligent functions. In this context, electromagnetic compatibility (EMC) becomes essential for the proper operation of electronic products. This work proposes an integrated optimization methodology based on electromagnetic simulations, with a focus on signal integrity and power integrity. The main objectives are to increase reliability, reduce development costs, and improve EMC performance.

2. Standards Used in the Design of Electronic Devices in the Automotive Field

Chapter 2 presents the regulatory framework and standards used in the design and validation of electronic systems in the automotive industry, playing an essential role in ensuring electromagnetic compatibility and the proper operation of high-speed interfaces. In a field characterized by strict reliability and safety requirements, compliance with international standards is a fundamental condition

for designing modern electronic products.

A first set of analyzed standards refers to the OPEN Alliance Automotive Ethernet specifications [OA, 2020], which define testing and validation methods for 100BASE-T1 and 1000BASE-T1 communication interfaces [IEEE, 2018]. These standards introduce important concepts related to the MDI interface, depicted in Fig.1, differential transmission, and interoperability tests, highlighting the need to control parameters such as jitter, signal distortion, and return loss. By applying these requirements, stable and robust communication between the electronic modules of the vehicle is ensured.

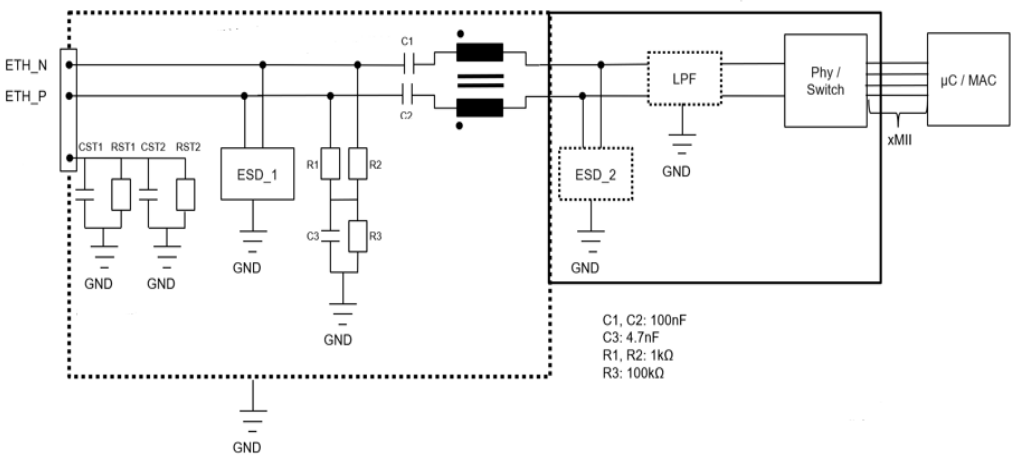


Fig. 1 MDI interface for 100/1000 Base-T1 configuration.

Furthermore, interoperability tests (IOPT) and physical medium attachment (PMA) tests are presented, which verify the physical performance of communication interfaces. These tests include measuring connection establishment time, evaluating signal quality under noise conditions, and analyzing cable behavior in various fault scenarios. Their importance lies in the early identification of signal integrity issues and the prevention of communication errors under real operating conditions.

A second major standard addressed is PCI Express (PCIe) [PCIe, 2017], used for high-speed serial interfaces. In Table 1 the differences between generations are presented. This standard defines essential parameters for communication channel design, such as differential impedance, insertion loss, and compliance with the eye diagram mask.

Table 1. Frequency, period and unit interval for PCIe generations

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Fundamental frequency f (GHz)	1.25	2.5	4	8	16
Time period T (ps)	800	400	250	125	62.5
Unit Interval UI (ps)	400	200	125	62.5	31.25

PCIe also introduces advanced transmission and reception techniques, including signal equalization and the use of SerDes blocks, which enable high data transfer rates. The chapter also details layout recommendations [Nvidia, 2022] for the proper design of printed circuit boards (PCBs), which have a direct impact on signal integrity and electromagnetic compatibility. Aspects such as impedance control, differential pair symmetry, minimization of discontinuities, and avoidance of routing over split ground planes are analyzed. These rules are essential for preventing reflection, crosstalk, and mode conversion phenomena.

Finally, it is emphasized that compliance with the analyzed standards is not merely a formal requirement, but a key element in optimizing the performance of automotive electronic systems. The integration of these standards into the design process, together with the use of electromagnetic simulations, enables the development of reliable, compliant, and competitive products in the current industrial landscape.

3. Evaluation of Signal Integrity through Simulation and Measurement Methods

Chapter 3 is dedicated to the use of electromagnetic simulations for evaluating and optimizing the performance of electronic systems in the automotive industry, with a focus on signal integrity (SI) [Silaghi, 2021, 2], power integrity (PI) [Pescari, 2022, 1], and the analysis of IR drop phenomena [Pescari, 2022, 2]. This chapter highlights the importance of integrating simulations in the early design stages to identify and correct issues before physical prototypes are built, thus contributing to reduced costs and development time [Bogatin, 2018].

In the first part of the chapter, signal integrity is addressed by presenting the main phenomena influencing the propagation of high-speed signals on printed circuit boards (PCBs) [Wang, 2012]. These include reflections, crosstalk, attenuation, and switching noise, all of which have a direct impact on system performance. By using electromagnetic simulation tools, it is possible to analyze signal behavior depending on design parameters such as trace geometry, component values, and PCB stack-up structure. A relevant case study presented in this chapter focuses on the analysis of an RMII Ethernet interface, where simulations were used to identify and correct voltage overshoot at the pins of integrated circuits. Through a parametric study of termination resistor values, it was possible to optimize signal waveforms and eliminate integrity issues, demonstrating the effectiveness of simulation-based approaches in improving system performance. The investigation can be observed in Fig. 2.

The chapter also presents the use of the TDR (Time Domain Reflectometry) technique for evaluating the characteristic impedance of transmission lines. TDR simulations enable the identification of impedance discontinuities caused by layout issues, such as geometric variations of traces or layer transitions, and provide an efficient method for PCB design optimization. By adjusting geometric parameters—such as spacing between traces or via placement—a significant improvement in transmission line behavior was achieved.

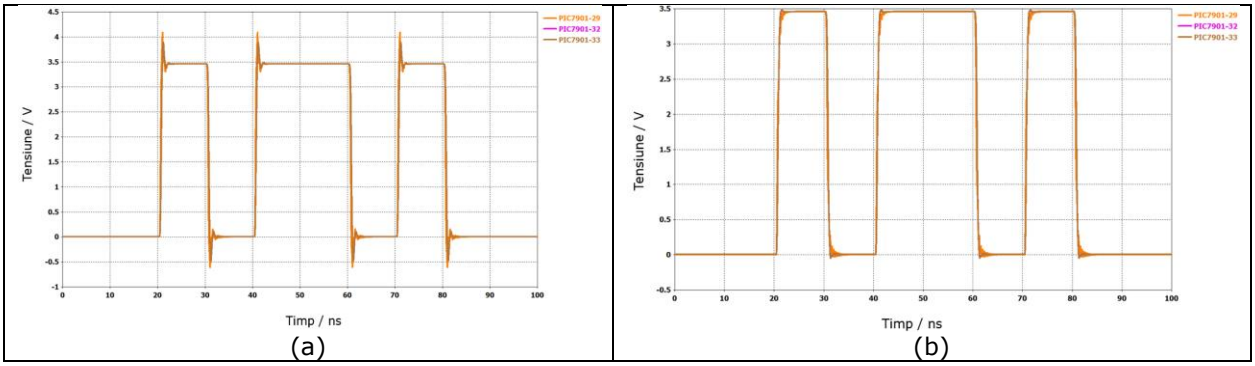


Fig. 2 Voltage results at IC7901. Presence of limit violations (a). Pass result after optimization (b).

Another important component of the chapter is the analysis of power integrity, which focuses on the performance of the power distribution network (PDN) [Sjiariel, 2015]. Methods for evaluating frequency-dependent impedance and techniques for its optimization using decoupling capacitors are presented [Lu, 2017]. The obtained results show that proper PDN design leads to reduced power supply noise and improved stability of high-speed circuits. An example of optimization for 5V rail is depicted in Fig. 3 and in Table 2 the fix number of decoupling capacitors used can be observed.

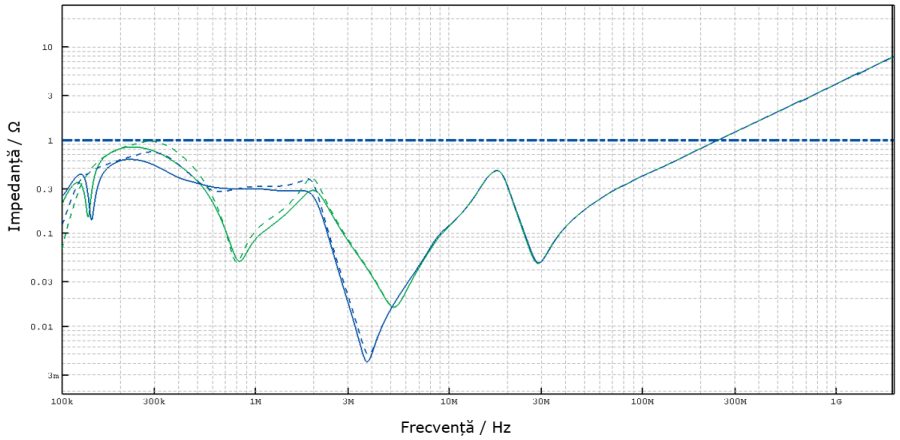


Fig. 3 Optimizing the number of used capacitors.

Table 2. Number of used capacitors.

Initial state		After optimization	
Capacitance value	Number of used capacitors	Capacitance value	Number of used capacitors
47 nF	1	47 nF	1
100 nF	1	100 nF	0
1 µF	1	1 µF	1
10 µF	4	10 µF	1

Furthermore, the chapter addresses the analysis of the IR drop phenomenon, which represents the voltage variation caused by trace resistance and current distribution within the PCB [Xie, 2020]. The simulations allow visualization of voltage distribution (Fig. 4) and identification of critical areas where significant voltage drop or high current densities may occur. By optimizing power routing and current injection points, the impact of this phenomenon on system functionality can be reduced.

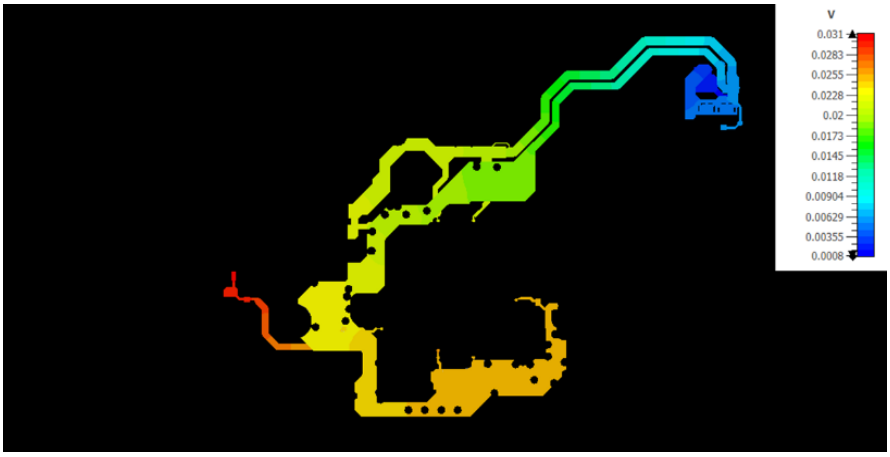


Fig. 4 Voltage drop distribution for 1V8_SMPS.

The chapter emphasizes that an integrated approach combining SI, PI, and IR drop simulations provides a comprehensive understanding of system behavior, enabling the simultaneous optimization of multiple critical parameters. This methodology contributes to the development of robust electronic products compliant with automotive industry standards, while reducing the need for costly design–fabrication–testing iterations.

In conclusion, Chapter 3 demonstrates that electromagnetic simulations are an essential tool

for modern electronic system design, offering both a solid theoretical foundation and practical solutions for improving the performance and reliability of automotive products.

4. Design, Simulation, and Measurement of DPHY, LPDDR4, and Ethernet Interfaces

Chapter 4 is dedicated to the experimental validation of the methodology based on electromagnetic simulations, by comparing results obtained in the virtual environment with measurements performed on real systems. This chapter plays an essential role in confirming the accuracy of the models used and in demonstrating the practical applicability of the proposed approach for optimizing electronic systems in the automotive industry.

In the first part of the chapter, the methodology for correlating simulations with measurements is presented, highlighting the steps required to obtain relevant and comparable results [Pescari, 2024, 1]. These steps include the proper configuration of the test environment, the selection of measured parameters, and ensuring similar conditions between the simulated model and the physical system. The importance of this correlation lies in validating electromagnetic models and increasing confidence in simulation results.

An important case study is the validation of Automotive Ethernet interfaces, where characteristics such as jitter, return loss, and power spectral density (PSD) are analyzed. The conducted measurements confirm the trends observed in simulations, demonstrating that optimizations applied at the layout and component level lead to significant improvements in signal performance. The comparison between simulation and measurement results for mode conversion loss (MCL) is presented in Fig. 5.

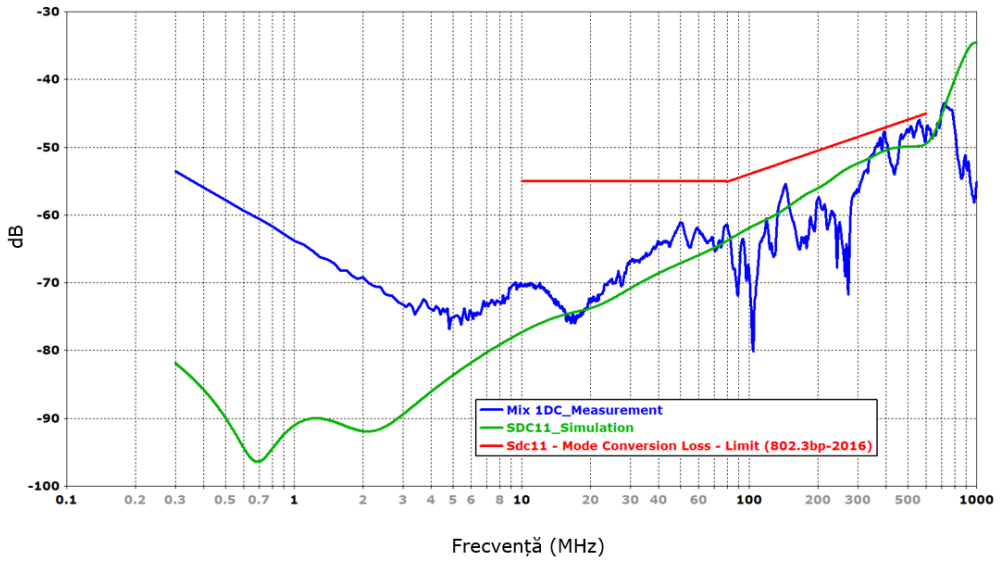


Fig. 5 Measurement and simulation comparison for MCL.

The chapter also includes the analysis of high-speed interfaces used in modern applications, such as D-PHY [Pescari, 2023] and LPDDR4 [Pescari, 2024, 2]. Regarding LPDDR4 [JEDEC, 2018], critical parameters related to timing and eye diagram opening are evaluated, as can be seen in Fig. 6, highlighting the impact of signal integrity on proper memory operation.

For the D-PHY interface [MIPI, 2021], the characteristics of differential signals are analyzed, along with how implemented optimizations contribute to improved transmission performance. In Fig. 7, both differential nets have U-shape sections. Because the distance between parallel sections of the same net is not enough, coupling appeared and the simulation was classified as fail. Layout was changed and the trace geometry was improved to reduce the coupling effect, obviously taking length matching into account.

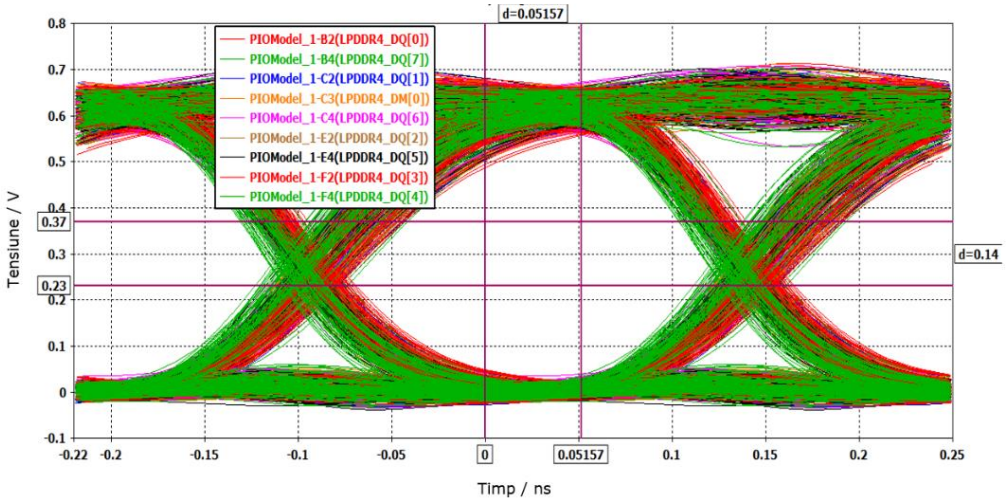


Fig. 6 DQ eye mask. µC is writing.

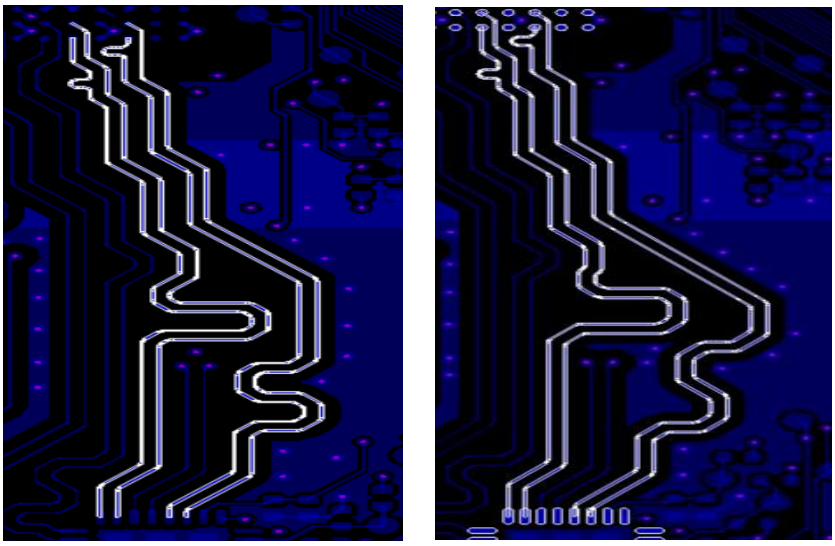


Fig. 7 Layout before (left) and after (right) optimization.

The experimental results obtained are systematically compared with simulation results, showing a very strong correlation between them. The identified differences are analyzed and explained through model limitations or the influence of external factors, such as process variations or environmental conditions. This detailed analysis contributes to refining the methodology and improving simulation accuracy.

The chapter also emphasizes the importance of using appropriate measurement equipment, such as high-speed oscilloscopes and network analyzers, in evaluating electronic system performance. The correct selection and configuration of instrumentation directly influence the quality of the acquired data and the relevance of the conclusions drawn.

In conclusion, Chapter 4 demonstrates that the proposed methodology—based on integrating electromagnetic simulations with experimental validation—represents an effective solution for the development and optimization of automotive electronic systems. The strong correlation between simulations and measurements confirms the effectiveness of the approach and highlights its potential for application in real industrial design processes.

5. Applications of Frequency Selective Surfaces in the Field of Signal Integrity

Chapter 5 addresses the use of Frequency Selective Surfaces (FSS) and advanced metamaterial-based structures for the control and manipulation of electromagnetic waves. These structures represent innovative solutions in the field of electromagnetic compatibility, with applications in filtering, shielding, and polarization control of electromagnetic signals, particularly in the context of modern communication systems [Munk, 2000].

In the first part of the chapter, the fundamental principles of frequency selective surfaces are presented, highlighting how the geometry of their constituent elements influences the electromagnetic response of the structure. Their behavior is analyzed as a function of frequency, wave incidence, and signal polarization, demonstrating the capability of FSS to operate as spatially selective filters.

A particular emphasis is placed on the development of flexible FSS structures, capable of maintaining their performance even under mechanical deformation [Silaghi, 2023]. These structures are of increasing interest in automotive applications and modern electronics, where flexibility and integration in complex environments are becoming more important requirements. The conducted studies on the structure depicted in Fig. 8 highlight the influence of curvature on frequency response and how the design can be optimized to minimize performance degradation. Transmittance behavior for various bending angles is illustrated in Fig. 9.

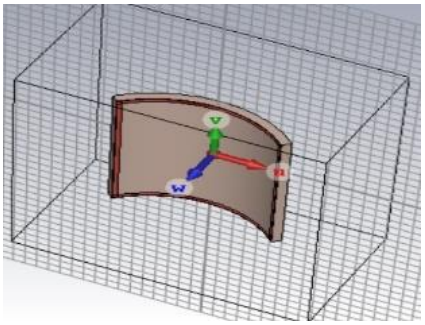


Fig. 8 Bending of the unit cell at 90°

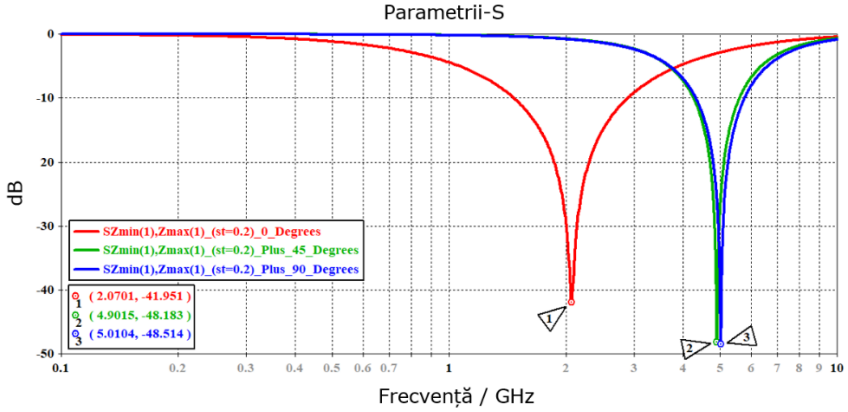


Fig. 9 Comparison between transmittance for various bending angles.

The chapter also introduces an innovative electromagnetic polarizer structure, based on the use of water as an active medium (Fig. 10) [De Sabata, 2026]. This approach enables the realization of a thermally tunable device capable of modifying the polarization properties of electromagnetic waves depending on temperature variations. The proposed solution stands out due to its low cost, structural simplicity, and adaptability, offering a viable alternative to conventional technologies used in polarization control.

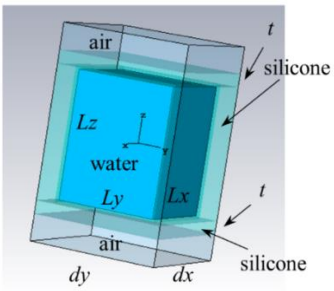


Fig. 10 Structure of the unit cell.

The results of the simulations and analyses demonstrate the high performance of the proposed structures, both in terms of frequency selectivity (Fig. 11) and adaptability to varying operating conditions (Fig. 12). The advantages of using such structures in reducing electromagnetic interference and improving communication system performance are emphasized.

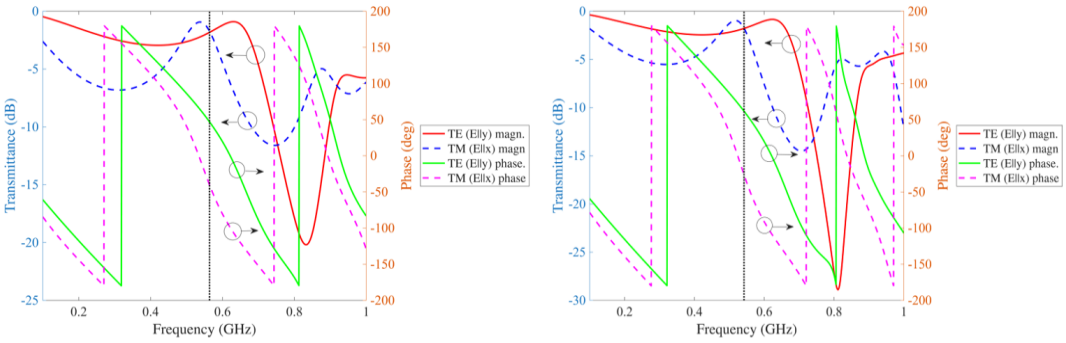


Fig. 11 . Frequency response in transmission, in normal incidence (magnitude and phase): (a) Polarizer 1; (b) Polarizer 2. The vertical lines are drawn at the operation frequencies

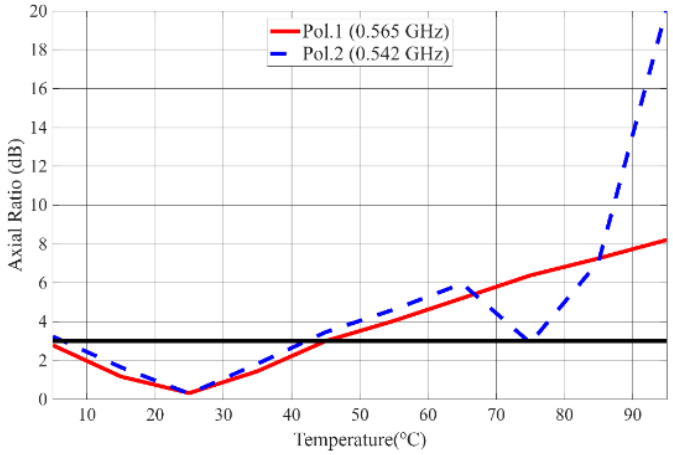


Fig. 12 Axial ratio vs. temperature at the initial operation frequency of the polarizers.

Finally, Chapter 5 highlights the original contribution of this research in the field of advanced electromagnetic structures, demonstrating that integrating frequency selective surfaces into the design of electronic systems provides new opportunities for optimizing electromagnetic compatibility. The proposed solutions open promising directions for future applications, both in the automotive industry and in other technological domains.

6. Conclusions and Original Contributions

Chapter 6 summarizes the main conclusions of the research and highlights the original contributions of the thesis in the field of electromagnetic compatibility applied to electronic systems in the automotive industry. The results obtained confirm that the use of electromagnetic simulations in the design process represents an effective method for optimizing performance and increasing the reliability of modern electronic systems.

An important result is the development of an integrated analysis and optimization methodology based on the simultaneous evaluation of signal integrity (SI), power integrity (PI), and IR drop phenomena. This approach enables the early identification of critical issues and the implementation of effective solutions from the design phase, contributing to a reduction in the number of iterations required during product development.

The experimental validation carried out in the previous chapters demonstrates the accuracy of the models used and the relevance of electromagnetic simulations in real-world applications. The strong correlation between simulated and measured results confirms that the proposed methodology can be successfully applied in industrial processes, providing significant benefits in terms of cost and development time reduction. Another important aspect of the thesis is represented by the contributions in the field of advanced electromagnetic structures, through the development and analysis of Frequency Selective Surfaces (FSS) and innovative polarization control solutions. These structures demonstrate the ability to control electromagnetic wave propagation and open new research directions and applications in areas such as electromagnetic shielding and high-speed communications.

The original contributions of the work can be summarized as follows:

- development of an integrated EMC optimization methodology based on electromagnetic simulations;
- analysis and optimization of high-speed interfaces from the perspective of signal and power integrity;
- implementation and validation of simulation models correlated with experimental measurements;
- proposal and characterization of innovative FSS structures, including flexible and thermally tunable solutions.

In conclusion, the thesis demonstrates that integrating electromagnetic simulations into the design workflow represents an indispensable approach for the development of modern electronic systems. The obtained results contribute both to advancing knowledge in the field and to improving industrial practices, providing concrete solutions for optimizing electromagnetic compatibility in the automotive industry.

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