The Scientific Temper (2024) Vol. 15 (3): 2502-2506
Doi: 10.58414/SCIENTIFICTEMPER.2024.15.3.15

E-ISSN: 2231-6396, ISSN: 0976-8653
https://scientifictemper.com/

RESEARCH ARTICLE

Analysis of substrate materials for flexible and wearable MIMO antenna for wireless communication

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Abstract

In recent years, flexible and portable antenna technologies have become critical to the development of next-generation wireless communication technologies such as fifth generation (5G) and beyond. The purpose of this study is to evaluate the performance of three basic materials (Flame Retardant 4) FR4, polyvinyl chloride (PVC) and liquid crystal polymer (LCP) used in the design of flexible and portable antennas. The methodology involves studying the resonant frequency ranges, return losses, bandwidth, gain and antenna radiation efficiency of each material. The results show that LCP has the widest bandwidth of 3.19 GHz and the highest radiation efficiency of 90%, making it suitable for high-frequency applications. The substrate PVC, while achieving a significant bandwidth, has a limitation at high-frequency accuracy due to its higher dielectric constant. Although FR4 is cost-effective, its effectiveness is limited in high-frequency applications due to its narrower bandwidth and higher loss coefficient. These results indicate that LCP is an optimal choice for advanced radio frequency (RF)applications, especially in next-generation wireless communication technologies. Future research should focus on improving the properties of these materials and study the characterization of composite materials to further improve their suitability for flexible and portable antennas.

Keywords: Flexible antenna, Flame Retardant4, LCP-Liquid crystal polymer, Multiple input multiple output, PVC-Polyvinyl chloride, Resonant frequency.

Introduction

The introduction of 5G technology marks a substantial advancement in wireless communication, offering faster data speeds, lower latency, and better connectivity. The development of high-performance antennas is necessary to fully reap these benefits. The development of multiple input multiple output (MIMO) antennas that are portable and adaptable is essential to 5G systems, particularly when integration with portable devices and mobility are required. Optimizing the efficiency, flexibility, durability, and overall performance of these antennas requires careful substrate material selection. Bending and stretching are just two of the many situations in which these antennas must continue to operate at their best. To ensure the stability and efficacy of the antenna's operations, it is imperative to select a suitable substrate material. For the substrate material to meet the strict requirements of 5G frequencies, a precise combination of electrical, mechanical, and thermal properties must be verified.

This study aims to examine the electromagnetic and mechanical characteristics of different substrate materials employed in adaptable and wearable MIMO antennas. Its objective is to appraise the effectiveness of these materials in 5G applications and identify the most suitable substrate materials for producing high-performance, flexible, and portable MIMO antennas. Additionally, it aims to achieve a thorough examination of substrate materials suitable for adaptable and wearable MIMO antennas in the context of 5G applications.

Review of Literature

Recent studies highlight the significance of flexible and wearable antennas in enhancing the user experience within 5G systems. Investigation has been directed toward materials capable of delivering the required flexibility while upholding antenna functionality.

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How to cite this article: Patil, S. N., Kagalkar, R. M. (2024). Analysis of substrate materials for flexible and wearable MIMO antenna for wireless communication. The Scientific Temper, **15**(3):2502-2506.

Doi: 10.58414/SCIENTIFICTEMPER.2024.15.3.15

Source of support: Nil

Conflict of interest: None.

Received: 24/04/2024 **Accepted:** 28/05/2024 **Published** : 30-05-2024

Various rigid and non-flexible substrate materials such as FR4, alumina, polytetrafluoroethylene (PTFE) and RTDuroid 5880 using rectangular microstrip patch antenna as a reference design antenna was designed for 2.45 GHz low power applications for substrate thickness values of 1.6 and 0.8 mm (Ramasamy, K., & Krishnan, T. 2023).

The substrate effectiveness is impacted by dielectric constant, loss tangent, flexibility, and mechanical robustness. The potential application of polyimide, polyethylene terephthalate (PET), and polydimethylsiloxane (PDMS) have been extensively explored for design of flexible antennas (Liu, X., *et al*. 2020; Chen, S., *et al*. 2019; Islam, M. R., *et al*. 2019).

Polyimide is a a favored option for wearable antennas due to its exceptional thermal stability and mechanical durability, and sustained high- frequency operations along with flexibility (Wang, H., *et al*. 2020; Park, J. Y., *et al*. 2019).

PET is preferred due to its cost- effectiveness, flexibility, and ease of manufacturing. Nevertheless, the performance at higher frequencies is affected by relatively high dielectric constant and loss tangent encouraging tradeoffs in design (Zhang, Y., *et al*. 2020; Wong, K. L., *et al*. 2020).

PDMS is suitable for wearable purposes due to its flexibility and biocompatibility. Despite these benefits, its high loss tangent presents challenges for high-frequency uses (Singh, P. K., *et al*. (2020); Tang, M. C., *et al*. 2019).

Liquid crystal polymer (LCP) is also preferred in flexible antennas due to its low dielectric constant, low loss tangent, and exceptional mechanical properties. Its potential for wearable antenna has been underscored in many studies (Liu, J., *et al*. 2020; Wang, Z. Q., *et al*. 2019).

Comparative analyses have weighed diverse flexible substrate materials, taking into account their electromagnetic and mechanical characteristics. These evaluations offer insights into the trade-offs and appropriateness of various materials for specific uses (Mousavi, S. M., *et al*. 2020; Zhang, L., *et al*. 2020; Singh, R., *et al*. 2020).

Novel materials such as graphene, MXenes, and conductive polymers have emerged due to advancements in material science. These emerging materials showcase specific qualities that offer the possibility of notably boosting the effectiveness of flexible and wearable antennas. Integrating flexible antennas into wearable gadgets necessitates surmounting challenges like maintaining performance during deformation and ensuring user comfort (Liu, P. J., *et al*. 2020; Lee, J. S., *et al*. 2020).

The HFSS allows parameterization of the model geometry and material properties. This feature, along with built-in optimization algorithms, helps the designers to arrive at optimized design performance against multiple criteria. This feature is used to achieve the desired optimization of the antenna (Joe D, A., & Krishnan, T. 2023).

Continuing research concentrates on innovative designs and manufacturing strategies aimed at addressing these constraints. The following Table 1 provides a comparison of different flexible substrates commonly used in antenna design, highlighting their relative permittivity, loss tangent, and typical thickness range.

Table 1: Comparison of industry standard substrate materials for antenna

Material	*Relative permittivity (εr)*	*Loss tangent (tanδ)*	*Thickness (mm)*	*Reference*
FR4	4.4	0.02	1.6	Wang *et al*. (2015)
PVC	3.2	0.002	0.1	Wang *et al*. (2018)
LCP	2.9	0.002	0.1-0.3	Su *et al*. (2020).
PDMS	2.7	0.02	0.5-1.0	Chou *et al*. (2017).

In this paper, a compact planar printed MIMO antenna, using flexible substrates having a good isolation between antenna elements in MIMO structure over a broad range of frequencies, is evaluated and presented. The initial design of a single element includes a printed monopole antenna with a improved slotted feed line. The collinear arrangement of elements forms a dual port element antenna and ensures low correlation. The performance of the MIMO antenna is investigated with three substrate materials for optimal selection of substrate suitable over the wide bandwidth, making it appropriate for practical MIMO systems for Wireless communication systems.

Proposed System

The ANSYS® high-frequency structure simulator (HFSS) software was used to simulate the designs of the antennas. ANSYS high-frequency structure simulator (HFSS) is a proprietary modeling tool used for designing and simulating high-frequency electronic components such as antennas, RF or microwave components, high-speed interconnects, filters, etc.

The following are the key features of ANSYS HFSS,

3D Electromagnetic Field Simulation

HFSS simulates 3D full-wave electromagnetic radiating fields for accurate and fast design of high-frequency structures.

Adaptive Meshing

HFSS automatically refine the solution with integrated advanced adaptive meshing techniques. This is done by meshing adjustments until the solution converges, ensuring that the results are accurate.

Multi-physics Simulation

It also supports united simulations including thermo-mechanical effects for comprehensive performance analysis of devices under real-world test case conditions.

High-Performance Computing

HFSS utilizes multi-core computing resources to handle complex and large-scale simulations, reducing the time required for simulations.

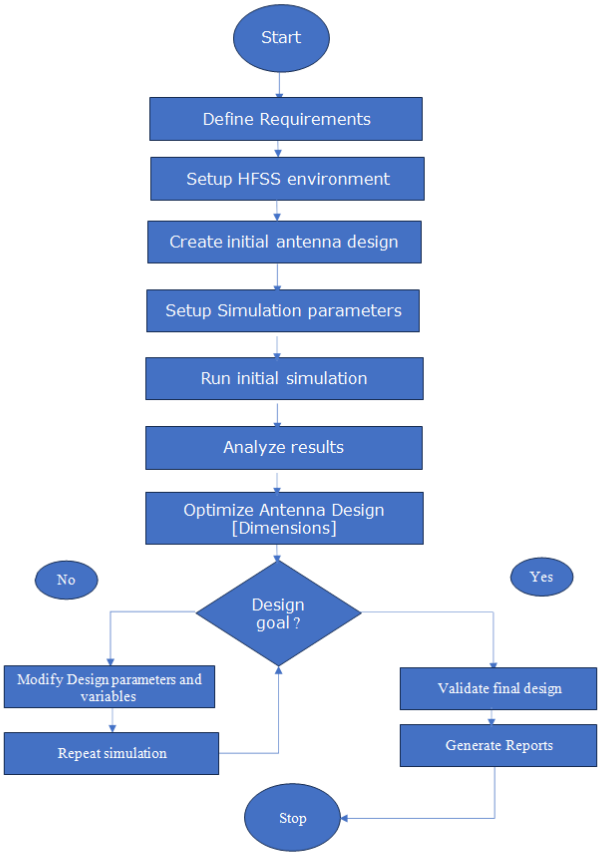

Figure 1: Generic flow of the MIMO antenna using ANSYS HFSS

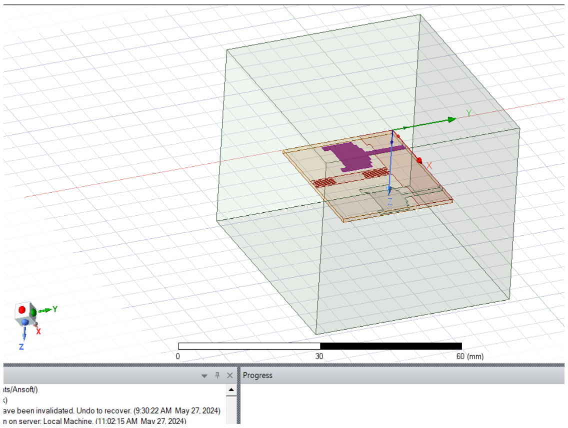

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Figure 2: The entity of the proposed MIMO antenna

Table 2: Specifications about the geometry of the prototype architecture

Dimensions	*Values (mm)*	*Dimensions*	*Values (mm)*	*Dimensions*	*Values (mm)*
Length	26.05	Length g	8.05	Width fs	0.85
Length fs	4.05	Length s	7.05	Width f	1.45
Length f	9.05	Distance s	6.00	Width 1	11.05
Length 1	8.05	Width f	1.45	Width 2	8.05
Length 2	1.55	Width	31.05	Width 3	5.05
Length 3	0.55	Length s1	5.05	Width 4	8.05
Width s	3.05	Ground width	0.30	Width fs	0.85

Integration with Circuit and System Simulation

HFSS integrates seamlessly with ANSYS circuit and system simulation tools to perform co-simulation and verify the performance of the complete system, from component to system level ANSYS. (2024).

Different substrates, including LCP, PVC, and FR4, were employed in the models due to their elasticity and high-frequency performance characteristics. Each design was optimized to achieve the desired resonant frequencies by determining the optimal dimensions. Flexible substrates like LCP, POLYAMIDE, and PVC were chosen for their flexibility, while FR4 was selected for its durability and high efficacy

The design steps for a MIMO antenna are illustrated in the Figure 1.

In order to reduce the correlation among the antennas within a MIMO system, it is imperative to uphold appropriate separation between them. It is crucial to adhere to the principle that the antenna separation should be at least half of the wavelength (λ/2) corresponding to the operational frequency. The wavelength (λ) can be determined through the utilization of the following formula.

$\lambda = c/f$ --(1)

where c is the speed of light ($3*10^8$ m/s) and f is the frequency in Hz.

For each antenna in the MIMO system, you need to compute the return loss (RL) and voltage standing wave ratio (VSWR) to evaluate how well the antenna matches the transmission line is given by

$RL(\text{in dB}) = -20\log10(|S11|)$ -- (2)

where S11 is the reflection coefficient. VSWR is associated to S11 by $VSWR=1-|S11|/1+|S11|$ -- (3)

Figure 2 illustrates the configuration of an antenna element used in the proposed MIMO design. The radiating element is placed on a FR4 epoxy substrate with dimensions of 38 × 30 × 1.6 mm^3. Both the radiating component and ground plane are made of uniform copper with a conductivity of 5.8×10^7 S/m.

The dimensions of the antenna are summarized in Table 2. The antenna consists of a U-shaped radiator and a ground plane as its only components. HFSS-Optometrics was used to optimize the dimensions of both the radiating elements and the ground plane to achieve an optimal size for the antenna element. To assess impedance matching and bandwidth, the return loss (S11) was measured. Extensive measurements were taken across various frequencies to ensure accurate characterization of each antenna's performance.

The return loss S11 in dB is shown in Figure 3 for the reference FR4 based substrate antenna. The resonant

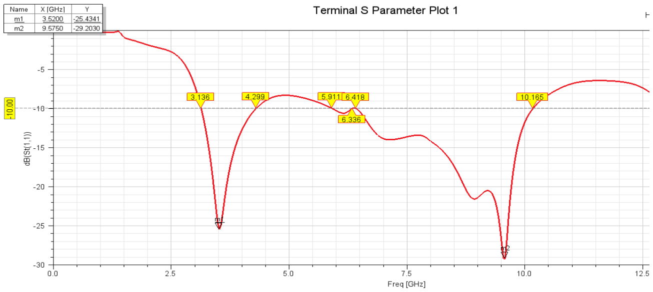

Figure 3: |S11| Response of the FR4 based reference substrate

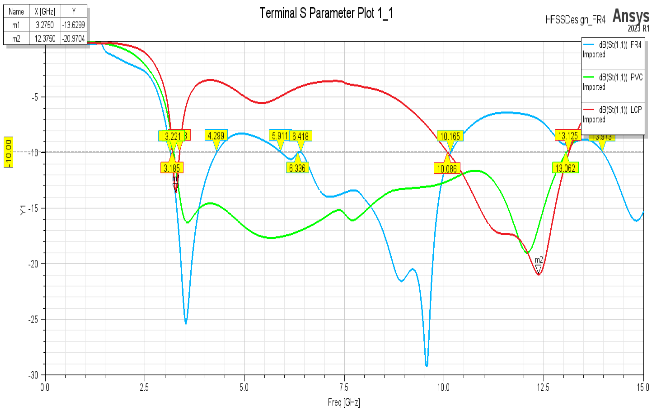

Figure 4: Comparative analysis diagram of return loss S11 in dB

frequencies are measured using fast Sweep analysis in HFSS. The antenna exhibits a dual band resonant frequency.

Three distinct antenna prototypes (LCP, FR4, and PVC) have been developed and simulated in order to investigate the performance of different substrate materials in wearable and flexible antennas. The reference antenna is made of FR4 material. These materials were selected on the basis of their compatibility with high-frequency applications, flexibility, and dielectric characteristics. The most recent research results on flexible and wearable antennas were compared with the design specifications and performance evaluations of these antennas. Each antenna's dimensions were established to ensure peak performance at its particular resonance frequency. We simulated the LCP, FR4, PVC, and antennas. The design of MPA for the 5G frequency spectrum effectively makes use of the dielectric characteristics of LCP, POLYAMIDE, PVC, and PET.

Results and Discussion

Comparative analysis of designs often involves examining the performance metrics, such as return loss and the frequency range over which these metrics are achieved. Here's a comparative analysis of the presented designs.

The return loss diagram S11 (in dB) *versus* frequency in GHz for all the substrate materials LCP, FR4, PVC, was obtained and compared as shown in Figure 4.

The comparative evaluation of FR4, PVC, and LCP materials based on their resonant frequency ranges, return loss, bandwidth, gain, and antenna radiation efficiency offers valuable insights into their appropriateness for various RF and microwave applications. Table 3 provides comparative performance metrics of the MIMO antenna with different substrates. The various parameters of resonant frequency, bandwidth, gain, and Antenna radiation efficiency was obtained from simulation studies.

FR4, a commonly used substrate material in printed circuit boards, displays resonant frequency ranges at 3.185 to 3.590 GHz and 12.375 to 13.125 GHz. The return loss values of -16.2660 and -20.9704 dB at these frequencies indicate significant signal attenuation, a crucial aspect for RF applications. The calculated bandwidths for these ranges are 0.405 and 0.750 GHz, respectively. While FR4's gain of 2.5 dBi and antenna radiation efficiency of 70% is moderate, its high loss tangent may restrict its performance in high-frequency applications, especially those necessitating high precision and low loss.

PVC displays potential with resonant frequency ranges spanning from 4.299 to 6.336 GHz and 10.086 to 13.125 GHz. The material showcases remarkable return loss values of -20.9704 and -10.0860 dB, respectively. PVC's substantial bandwidths of 2.037 and 3.039 GHz position it as a feasible option for applications that demand wide frequency ranges. Moreover, boasting a gain of 3.0 dBi and an antenna radiation efficiency of 85%, PVC delivers a well-rounded performance, although its higher dielectric constant may limit its usage in specific high-frequency scenarios.

With resonant frequency ranges of 10.165 to 13.062 GHz and 3.221 to 6.418 GHz, LCP is unique. The vast bandwidths of 3.197 GHz and 2.897 GHz, along with the return loss values

Table 3: Comparative performance of different substrates

Material	*Resonant requency range (GHz)*	*Return loss (dB)*	*Bandwidth (GHz)*	*Gain (dBi)*	*Antenna radiation efficiency (%)*	*Reference*	*Compared parameter*
FR4	3.185–3.590	-16.26	0.405	2.5	70	[Wang *et al.*, 2015]	Return Loss, Bandwidth
FR4	12.375–13.125	-20.97	0.750	2.5	70	[Wang *et al.*, 2015]	Return Loss, Bandwidth
PVC	4.299–6.336	-20.97	2.037	3.0	85	[Wang *et al.*, 2018]	Gain, Efficiency
PVC	10.086–13.125	-10.08	3.039	3.0	85	[Wang *et al.*, 2018]	Bandwidth, efficiency
LCP	3.221–6.418	- 10.0860	3.197	3.5	90	[Su *et al.*, 2020]	Bandwidth, gain
LCP	10.165–13.062	- 10.1650	2.897	3.5	90	[Su *et al.*, 2020]	Bandwidth, Gain

of -10.0860 and -10.1650 dB, highlight LCP's applicability for high-frequency and broadband applications. The 3.5 dBi gain and 90% higher antenna radiation efficiency of LCP demonstrate its latent applications in innovative RF and microwave systems.

Conclusion

This study employed ANSYS HFSS software to assess the efficiency of antennas fabricated from LCP, PVC, and FR4 substrates, with an emphasis on resonant frequency spectrum, return loss, bandwidth, gain, and radiation efficiency as vital parameters in RF and microwave technologies. FR4 substrates showed resonance within the range of 3.185 to 13.125 GHz, achieving return losses of up to -20.9704 dB and bandwidths extending to 0.750 GHz. However, its modest 2.5 dBi gain and 70% radiation efficiency, along with a high loss tangent, might hinder its relevance in precision-driven contexts. PVC substrates showcased a broader frequency range from 4.299 to 13.125 GHz, accompanied by noteworthy bandwidths of up to 3.039 GHz; however, its elevated dielectric constant might constrain its utility in certain high-frequency scenarios despite a gain of 3.0 dBi and 85% efficiency. LCP demonstrated greater performance characteristics with frequency ranges spanning 3.221 to 13.062 GHz, bandwidths reaching up to 3.197 GHz, and a minimal return loss of -10.086 dB. LCP emerges as a suitable option with the highest gain of 3.5 dBi and an efficiency of 90% for innovative wideband RF applications, particularly in 5G-based flexible and wearable technologies.

In conclusion, LCP emerges as the most appropriate substrate for cutting-edge RF applications, highlighting the importance of substrate selection in advanced antenna design and suggesting further research on optimizing substrates to improve telecommunications systems.

Acknowledgment

The Authors would like to thank the Department of Technical Education, Karnataka and Nagarjuna College of Engineering for their support.

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