COmparing T-Shape Isotropic Antennas on Kevlar and FR4 Substrates for Enhanced Gain

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Keywords: Innovative Isotropic T-Shape Antenna, Gain Enhancement, Kevlar Substrate, FR4 Substrate, ISM Band, HFSS, Return Loss, Technology.

Abstract: To compare and analyse the innovative isotropic T-shaped antenna's enhancement of gain through the use of a Kevlar substrate with an FR4 substrate. Materials and Methods: This paper conducts a correlational analysis of two methods: the innovative isotropic T-shaped antenna utilizing a Kevlar substrate and the FR4 substrate, both employed for designing the innovative isotropic T-shaped antenna. Two groups have been considered for comparative analysis, with the calculation of the sample size facilitated by the G-power application. One group pertains to the Kevlar substrate, and the other group involves the FR4 substrate. Each group consists of 10 samples, resulting in a total sample size of 20. The alpha error threshold is set at 0.05, accompanied by a 95% confidence interval and 80% power. The outcomes have been derived using HFSS software. The gain achieved by the innovative isotropic T-shaped antenna utilizing a Kevlar substrate, intended for aerospace applications, is 9.4 dB. This performance is significantly better than that of the T-shaped antenna employing the FR4 substrate, which attains a gain of 2.8 dB at a frequency of 2.4 GHz. Notably, a significant gain disparity exists between the two substrates, with a two-tailed significance value of 0.001 ($p<0.05$) as established by independent samples t-tests. The innovative isotropic T-shaped antenna, utilizing a Kevlar substrate, achieves a gain of 9.4 dB at 2.4 GHz, featuring an index of 2.2 and a thickness of 1.6 mm. This performance surpasses that of the T-shaped antenna using the FR4 substrate.

1 INTRODUCTION

In the aerospace sector, composites with commendable functionality find utility as substrates in antennas, serving as constituents to enhance the overall gain and efficiency of the system (Zhang et al., 2021). In pursuit of this commendable functionality, a multitude of techniques have been introduced to incorporate the novel isotropic T-shaped antenna using Kevlar substrate (Lv et al., 2017), thereby crafting component structures of the system that concurrently facilitate signal transmission and mechanical performance (Singh and Singh, 2022). The innovative isotropic T-shaped antenna, employing a Kevlar substrate, has been developed to seamlessly integrate both antenna and component structures, featuring a multi-layered arrangement (VanBlaricum, n.d.), with the intent of enduring and excelling in demanding conditions such as mechanical vibrations, aerodynamic resistance, and variations in temperature (Simons, 2021). The applications of these innovative isotropic T-shaped antennas, employing Kevlar substrates, span a broad spectrum, finding extensive usage in wireless communication technologies such as 4G networks and within the aviation industry for communication purposes (Avşar Aydın, 2021).

In the last five years, a total of 1675 articles have been documented in Google Scholar, while 196 articles have been recorded in IEEE Xplore. To enhance antenna gain, methodologies such as employing substrates, integrating electromagnetic bandgap (EBG) structures, and adjusting impedance through parasitic elements have been introduced (Caizzone et al., 2021). Given the dynamic pace of technological progress, there is a growing trend towards the adoption of more environmentally sustainable materials in the design of novel isotropic T-shaped antennas (Zhou et al., 2020). Among the range of substrates employed, Kevlar exhibits transversely isotropic characteristics when subjected

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to minor strains (Bhattacharya et al., 2018) (S.K et al., 2021). The proposed design is executed using HFSS software, facilitating the measurement of gain enhancement (Daniel et al., 2021).

The prevailing research on the isotropic T-shaped antenna using the FR4 substrate highlights a deficiency in gain. The approach of incorporating the Kevlar substrate in the innovative isotropic T-shaped antenna yields a notable enhancement in gain, surpassing the performance of the isotropic T-shaped antenna that relies on the FR4 substrate (Liu et al., 2022) (A.G et al., 2022). To mitigate impedance concerns, the size of the Kevlar substrate's ground plane is kept minimal. This strategy prevents interference with the isotropic dimensions beneath the T-shaped antenna and helps maintain an impedance of 40 ohms. This careful sizing prevents the ground plane from compromising gain performance and minimizes capacitive coupling between the microstrip patch thickness and the ground plane (M. K. Khan and Feng, 2022). A Defected Ground Structure (DGS) is strategically applied at the end of the ground plane to ensure efficiency. This is particularly important as the separation between the end of the T-shaped isotropic element and the FR4 ground plane increases. The presence of dielectric loss tangent deterioration at the edges of dimensions can lead to an undesirable concentration of the electric field, ultimately impacting performance (Yang et al., 2016). The central objective of this study is to design, compare, and analyse an innovative isotropic T-shaped antenna employing both Kevlar and FR4 substrates, all aimed at achieving gain enhancement.

2 MATERIALS AND METHODS

The investigation was conducted at the Antenna Laboratory within the Department of Electronics and Communication Engineering at Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences. This study encompasses two distinct approaches to antenna design: one employing the Kevlar substrate (Group 1) and the other using the FR4 substrate (Group 2). Each approach includes a sample size of 10, and these samples were utilized for the study with G-power set at 80% and an alpha of 0.05.

The radiation characteristics of the isotropic T-shaped antenna with a Kevlar substrate are grounded in the phenomenon of fringing fields, which emerge at the ends of the patches. To achieve a broader bandwidth, it is imperative for the dielectric constant value to remain modest. In the creation of the T-shaped isotropic antenna design, a solitary slot was fashioned using Kevlar material, employed as the substrate with a specific thickness, and the patch was integrated as the grounding electrode. The chosen dielectric material features a dielectric constant of 4.4, a quality that allows the substrate to maintain mechanical integrity effectively, even in challenging conditions encompassing both dry and humid environments.

The interpretation of the isotropic T-shaped antenna, which features a Kevlar substrate and a square-shaped patch, suggests an issue with the grounding structure. Apart from enhancing parameters such as return loss and Voltage Standing Wave Ratio (VSWR), the incorporation of the isotropic Kevlar substrate within the T-shaped antenna design also leads to improvements in bandwidth within the ISM (Industrial, Scientific, and Medical) band, as well as gains in terms of antenna gain and efficiency. These enhancements stem from the strategic implementation of slots and defects. Notably, the antenna demonstrates resonance at three specific frequencies: 2.80 GHz, 6.00 GHz, and 8.80 GHz.

In the context of technology, WLAN (Wireless Local Area Network) operates within a frequency range spanning from 2.40 GHz to 5.80 GHz.

The dimensions of the T-shaped antenna with a Kevlar substrate are 15mm in height and 90mm in width. This antenna is designed for operation within the frequency spectrum of 1 to 10 GHz and serves as the input for the testing phase. The collected frequency range data for the gain of the isotropic T-shaped antenna with a Kevlar substrate, as well as the one with an FR4 substrate, falls between 4.86 dB and 3.54 dB. The gain of the T-shaped isotropic antenna using an FR4 substrate exhibits variability ranging from -0.08 dB to -0.51 dB, contingent upon the type of substrate utilized.

The design of the isotropic T-shaped antenna with a Kevlar substrate involves operation at 10 GHz as its primary frequency, and a secondary frequency shift from 5 GHz to 7 GHz. To further minimize the return loss within the ISM band, a slot antenna is integrated. This antenna element is positioned on the Kevlar substrate to facilitate signal transmission and reception, situated on the outer surface of a ground waveguide structure. The isotropic antenna element comprises a transmitter embedded within the FR4 substrate, intentionally designed to reduce the gain, while an antenna isolated on the substrate is meant to induce excitation of a slot located on the outer surface of the device. This slot can be activated by means of techniques like applying an electric current across it, generating an electromagnetic field emanating from the slot.

The feeding technique for the T-shaped antenna is derived from WLAN applications. The isotropic T-shaped antenna employing a Kevlar substrate is experimented with varying substrate widths to assess its impact on the return loss at both 5.8 GHz and 10 GHz frequencies. The structured Kevlar substrate confers the benefit of concurrently diminishing the overall dimensions of the substrate-based T-shaped antenna while simultaneously amplifying its gain.

The T-shaped isotropic antenna with an FR4 substrate utilises a printed patch design to achieve a lower gain across multiple frequency bands. Conversely, for the T-shaped isotropic antenna employing a Kevlar substrate, a patch structure is implemented atop a minimal thickness ground plane. The primary objective of designing a Kevlar substrate T-shaped antenna is to suppress the antenna mode at 2.4 GHz, as well as to encompass the upper ISM band at 5 GHz. The illustrated figure displays the design of the Kevlar substrate T-shaped antenna, showcasing its ability for broadband operation, spanning a frequency range from 4.30 to 2.07 GHz. Moreover, this design exhibits a transmission range of 10 dB, substantiating its potential and versatility.

3 STATISTICAL ANALYSIS

SPSS has been utilised for analysis (McCormick and Salcedo, 2017) to evaluate the enhanced gain achieved through the implementation of Kevlar substrate and FR4 substrate in the creation of innovative isotropic T-shaped antennas. The independent variable in this context is frequency, whereas the dependent variable pertains to bandwidth. To compare the means, an independent samples t-test was conducted.

4 RESULTS

The conceptualization of the T-shaped isotropic antenna with an ISM band Kevlar substrate emerged at a frequency of 10GHz, accompanied by a secondary frequency (shifting from 5GHz to 7GHz). In the context of the FR4 substrate T-shaped antenna, a strategic approach was employed to further diminish the return loss within the proposed Kevlar substrate T-shaped antenna's impedance. Through optimization, the feeding technique for the resultant antenna was honed, tailored to the dual ISM band frequencies of 5.8GHz and 10GHz. The methodology involved shaping the Kevlar substrate T-shaped antenna, utilising the typical T-shaped FR4 substrate as a benchmark. Instead of complete removal, varied slot widths were employed to investigate their impact on the antenna's return loss. The structured Kevlar substrate T-shaped isotropic antenna introduces a dual benefit. It manages to reduce the antenna's overall dimensions while simultaneously amplifying its gain.

Table 1: Data are categorized into three different groups based on Frequency (GHz), Gain for the Kevlar and FR4 Substrate based T shape Antenna. The samples taken are 10. The total sample size is 20.

Frequency (KHz)	Gain for Kevlar Substrate (db)	Gain for FR4 Substrate (db)
1.00	4.86	3.09
1.80	2.65	4.28
2.00	1.95	2.79
5.40	2.32	1.83
6.00	1.39	2.27
7.40	3.98	1.05
7.88	2.98	1.16
8.00	3.01	2.19
8.80	2.19	3.10
10.00	1.54	4.51

The Kevlar substrate model of T shape antenna created with the HFSS tool and antenna return loss with ideal isotropic T shape antenna characteristic the appropriate frequencies were produced with a wide impedance matching conditions in the lowest (2.3-3.55) and highest (4.1-5.9) bands respectively. The mean gain of the Kevlar substrate (James and Tour 2013) T shape antenna is higher than the FR4 substrate T shape isotropic antenna at 2.4 GHz value is 2.8dB.

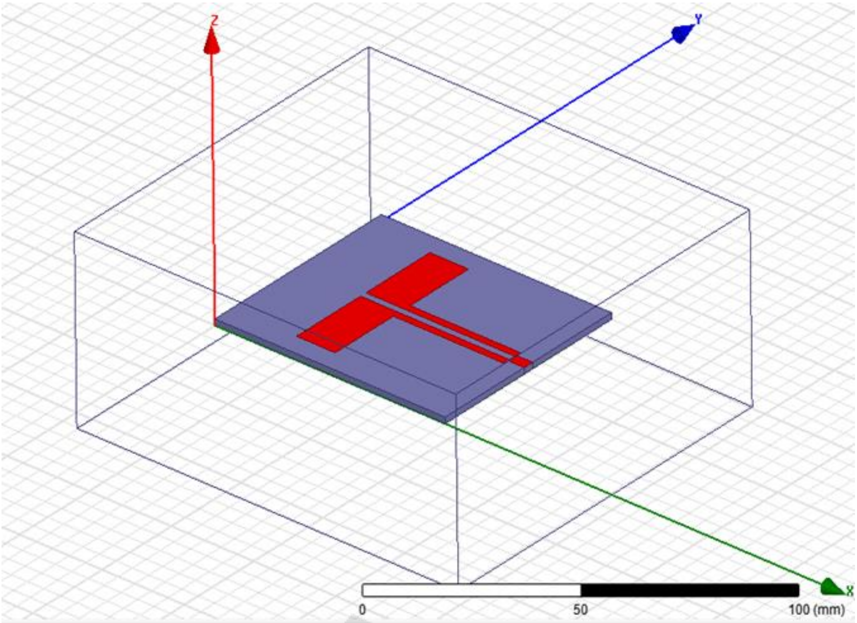

Figure 1: Design of the Innovative isotropic T shape Antenna using HFSS software and the Side view is shown (X-axis: Length of the patch, substrate, ground; Y-axis: Width of the patch, substrate, ground).

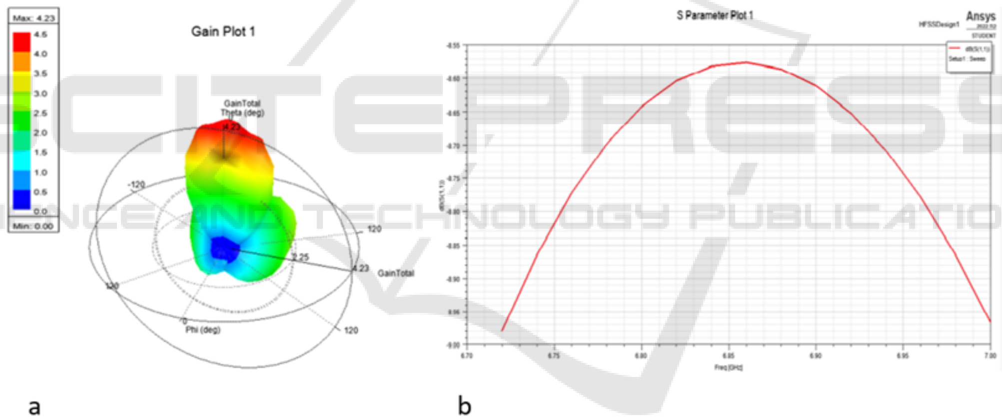

Figure 2: (a) Representation of the Gain performance of Innovative T shape Antenna with the gain of kevlar substrate shaped antenna is 2.4 GHz value is 2.8dB. The minimum to the maximum color bar point scale is used for measuring the gain value (b) Representation of the return loss performance Innovative T shape Antenna with kevlar substrate has a return loss of 5.8 GHz and 10 GHz. The minimum to the maximum color bar point scale is used for measuring the return loss.

In Table 1, the data are classified into three distinct groups according to the Frequency (GHz), Impedance, and Gain values for both the Kevlar substrate and FR4 substrate of the innovative isotropic T-shaped antenna, which was designed using HFSS.

In Table 2, the group-level statistical analysis showcases the mean, standard deviation, and standard error for the Gain of the Isotropic T-shaped antenna when employing Kevlar substrate and FR4 substrate. Notably, a statistically significant variance in bandwidth is observed between the two methods. Specifically, the Isotropic T-shaped antenna utilising the Kevlar substrate exhibits the highest Gain (2.68), while the Isotropic T-shaped antenna with the FR4 substrate presents the lowest Gain (2.62).

In Table 3, the SPSS statistics indicate the improved Gain of the Isotropic T-shaped antenna when employing Kevlar substrate and FR4 substrate, as determined by the independent sample t-test. The analysis reveals a significant disparity in radiation performance between the two substrates, with two-tailed significance values of 0.001 ($p<0.05$) achieved through independent samples t-tests. The Innovative isotropic T-shaped antenna employing Kevlar substrate notably exhibits superior Gain and achieves statistically significant superiority over the Innovative isotropic T-shaped antenna utilising the FR4 substrate.

In Fig. 1, the Innovative isotropic T-shaped Antenna design, created using HFSS software, is presented alongside its side view.

Fig. 2 showcases the Innovative isotropic T-shaped Antenna's HFSS software-based design, also displaying a side view. The X-axis delineates the Length of the patch, substrate, and ground, while the Y-axis represents the Width of the patch, substrate, and ground.

Fig. 3 exhibits the Gain performance of the Innovative T-shaped Antenna. The gain of the Kevlar substrate antenna at 2.4 GHz is measured at 2.8 dB. A colour bar point scale spanning from minimum to maximum is employed to denote gain values.

Fig. 4 portrays the return loss performance of the Innovative T-shaped Antenna. The Kevlar substrate-based antenna displays a return loss of 5.8 GHz and 10 GHz. Similar to the previous figure, a colour bar point scale spanning from minimum to maximum is utilised for return loss measurement.

Fig. 5 is a Bar Chart comparison of Gain between Kevlar and FR4 substrates. It is apparent that the gain of the innovative isotropic T-shaped antenna using the Kevlar substrate outperforms that of the FR4 substrate-based T-shaped antenna. The X-axis depicts Kevlar vs. FR4 substrate, while the Y-axis represents Mean Accuracy ±1 SD.

Table 2: Group statistical analysis of mean, standard deviation, and standard error of Gain of Isotropic T Shaped antenna using Kevlar Substrate and FR4 substrate is represented. There is a statistically significant difference in accuracy between the methods. The Isotropic T Shaped antenna using Kevlar Substrate has the highest Gain (2.68) and the Isotropic T Shaped antenna using FR4 substrate has the least Gain (2.62).

	Group	N	Mean	Std.Deviation	Std.Error mean
Gain	Isotropic T Shaped antenna using Kevlar Substrate	10	2.68	1.08	0.34
Gain	Isotropic T Shaped antenna using FR4 substrate	10	2.62	1.17	0.37

Table 3: SPSS statistics depict an improved Gain for Kevlar substrate and FR4 substrate by independent sample t-test. Significance value is found to be 0.01 (p<0.05) is assumed equal variances and not assumed equal variances.

	Levene's Test for equality of variances		T-test for Equality of means						
								95% confidence Interval of the difference	
	F	Sig	t	df	Sig. (2-tailed)	Mean diff.	Std. Error Diff	Lower	Upper Upper
Equal variances assumed	10	0.001	7.864	9	<0.01	2.687	0.34	1.914	3.460
Equal variances not assumed	10	0.001	7.096	9	<0.01	2.627	0.37	1.789	3.464

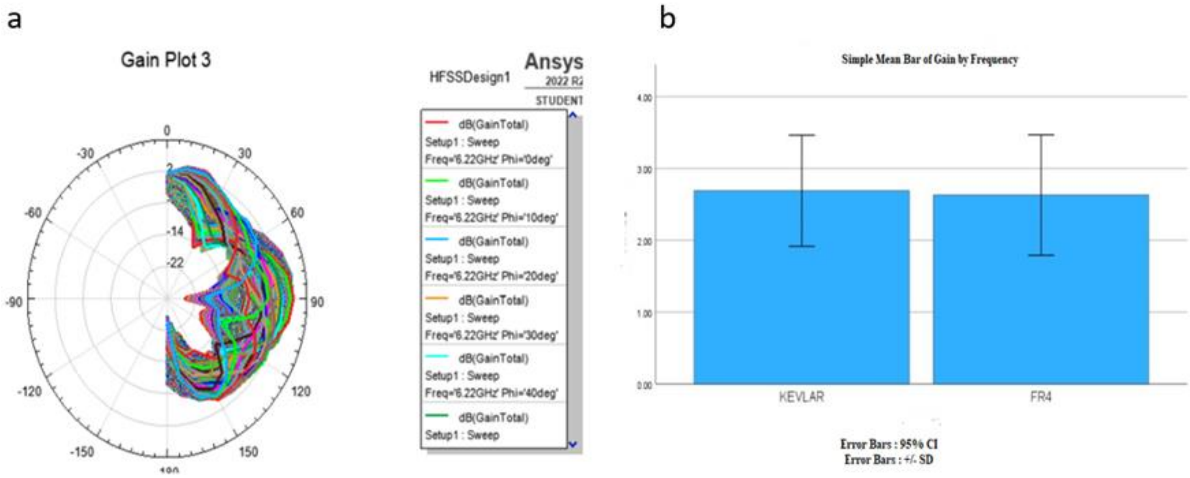

Figure 3: (a) Representation of the Gain performance of Innovative T shape Antenna. The mean gain of the Kevlar substrate T shape antenna is higher than the FR4 substrate T shape isotropic antenna at 2.4 GHz value is 2.8dB. (b) Bar Chart comparison of Gain Enhancement using Kevlar Substrate and FR4 substrate based Isotropic T shaped Antenna. Gain of the innovative isotropic T shape Antenna using Kevlar appears to be better than the FR4 substrate based Isotropic T shaped Antenna. X Axis: Kevlar Substrate vs FR4 substrate. Y Axis: Mean Accuracy ±1 SD.

5 DISCUSSION

The antenna's return loss is influenced by the integration of an isotropic T-shaped antenna with a Kevlar substrate, featuring a triangular cut that imparts dual-band characteristics. This modification renders the antenna with the aforementioned traits. Employing a triangular defect along one of the parallel arms of a dual-band FR4 substrate T-shaped isotropic antenna yields the desired frequencies, supported by a comprehensive range of impedance characteristics (Miligy, Morsy, and Soliman, 2021).

The innovative isotropic T-shaped antenna, when utilizing the FR4 substrate, demonstrates higher energy absorption in comparison to the T-shaped antenna employing a Kevlar substrate. Therefore, as an alternative, the substrate material selection has been influenced by previous research findings (Finocchio, Prasad, and Ruggieri, 2022). Kevlar substrates offer superior attributes in terms of high modulus and tensile strength, outperforming other materials such as FR4 substrate, glass fiber, and carbon. Kevlar is specifically chosen due to its pronounced wear and tensile resistance properties (Hehenberger, Elmarissi, and Caizzone, 2022). The incorporation of nano alumina serves to potentially enhance the transfer current formation and present favourable scattering parameter performance. The substrate's permittivity is set at 9.9, and it is geared for use within the C band frequency range (Yuan et al., 2022).

A significant portion of the radiation loss fields from the isotropic antenna embedded in the Kevlar substrate are emitted towards the same direction within the antenna structure. Consequently, the proximity of the FR4 substrate has a notable influence on the antenna's Gain characteristics (P. A. Khan, Afrid Khan, and Raja, 2022). This observation signifies that WLAN technology applications induce two resonances in microstrip patch antennas, and the triangular cut significantly advances the matching conditions in the lowest (2.2775-2.553) and highest (5.144 GHz-5.90 GHz) ISM bands, respectively (Iqbal et al., 2018).

The resonance peak of the FR4 substrate antenna shifts towards lower frequencies when positioned on copper. However, the ground surface cavity maintains a relatively consistent state. This distinct behaviour presents a limitation during the antenna's design process. In terms of future prospects, the same antenna design could be elevated by incorporating an alternative substrate, aiming to achieve enhanced performance in aspects such as gain, directivity, and return loss.

6 CONCLUSION

The innovative isotropic T-shaped antenna employing a Kevlar substrate attains a gain of 9.4 dB at a frequency of 2.4 GHz, boasting an index of 2.2 and a thickness of 1.6 mm. This performance notably surpasses that of the T-shaped antenna using an FR4 substrate, which also features an index of 2.2 and a thickness of 1.6 mm, but operates at 2.4 GHz. The outcomes distinctly highlight the superiority of the innovative isotropic T-shaped antenna utilising the Kevlar substrate. This antenna design exhibits promising outcomes, suggesting its suitability for widespread applications within wireless communication contexts.

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