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INVESTIGATION OF BROADER BANDWIDTH ELLIPTICAL DIPOLE ANTENNA PERFORMANCE PARAMETERS FOR 5G, KU AND KA-BAND APPLICATIONS: DIELECTRIC CONSTANT EFFECTS

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Abstract

This study presents an examination of the design and evaluation process of an elliptical dipole antenna operating at the design frequency of 5 GHz. Initially based on conventional dipole antenna principles, the antenna's design is iteratively refined through bandwidth enhancement techniques, resulting in the emergence of ultra-wideband characteristics. Notably, the modified antenna design features a distinctive notch band spanning from 4.21 to 10.06 GHz, positioning it as a versatile solution suitable for applications across the mid-band of 5G, as well as the full Ku and partial Ka bands, encompassing frequencies from 27 GHz to 31 GHz. Furthermore, this study investigates the impact of varying dielectric constants on antenna parameters, shedding light on a critical aspect often overlooked in conventional dipole antenna calculations. Through systematic analysis, it is revealed that a dielectric constant of 4.3, aligned with the commonly used low-cost epoxy-based FR-4 material, yields optimal performance. While higher dielectric constants broaden the antenna's characteristics, lower values are found to enhance communication efficiency, thus offering potential benefits in terms of power consumption and cost savings. The detailed examination and findings presented in this study enrich the understanding of antenna design principles and provide valuable guidance for future research and practical applications in the field of wireless communication and antenna engineering.
Keywords: Antenna, Dielectric Constant, 5G, Ka Band, Ku Band

5G, KU VE KA-BANT UYGULAMALARI İÇİN GENİŞ BANT GENİŞLİĞİNE SAHİP ELİPTİK DİPOL ANTEN PERFORMANS PARAMETRELERİNİN İNCELENMESİ: DİELEKTRİK SABİT ETKİLERİ

Özet

Bu çalışmada, 5 GHz tasarım frekansında çalışan bir eliptik dipol antenin tasarım ve değerlendirme süreci incelenmektedir. Başlangıçta geleneksel dipol anten prensiplerine dayanan anten tasarımı, bant genişliği artırma teknikleri ile yinelemeli olarak iyileştirilmiş ve ultra geniş bant özelliklerinin ortaya çıkmasıyla sonuçlanmıştır. Özellikle, modifiye edilmiş anten tasarımı 4,21 ila 10,06 GHz arasında uzanan belirgin bir çentik bandına sahiptir ve bu da onu 5G'nin orta bandının yanı sıra 27 GHz ila 31 GHz frekanslarını kapsayan tam Ku ve kısmi Ka bantlarındaki uygulamalar için uygun çok yönlü bir çözüm olarak konumlandırmaktadır. Ayrıca bu çalışma, değişen dielektrik sabitlerinin anten parametreleri üzerindeki etkisini araştırarak, geleneksel dipol anten hesaplamalarında genellikle göz ardı edilen kritik bir konuya ışık tutuyor. Sistematik analizler sonucunda, yaygın olarak kullanılan düşük maliyetli epoksi bazlı FR-4 malzemesi ile uyumlu olan 4,3 dielektrik sabitinin en iyi performansı verdiği ortaya çıkmıştır. Daha yüksek dielektrik sabitleri antenin özelliklerini genişletirken, daha düşük değerlerin iletişim verimliliğini artırdığı ve böylece güç tüketimi ve maliyet tasarrufu açısından potansiyel faydalar sunduğu bulunmuştur. Bu çalışmada sunulan ayrıntılı inceleme ve bulgular, anten tasarım ilkelerinin anlaşılmasını zenginleştirmekte ve kablosuz iletişim ve anten mühendisliği alanında gelecekteki araştırmalar ve pratik uygulamalar için değerli bir rehberlik sağlamaktadır.
Anahtar Kelimeler: Anten, Dielektrik Sabiti, 5G, Ka Bandı, Ku Bandı

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1. Introduction

The demand for antennas, which operate in wide frequency ranges [1–11], especially in the Ku (12–18 GHz) and Ka (26.5–40 GHz) bands, is becoming increasingly important in modern wireless communications and satellites technology [12]. It is deduced from literature analysis that antennas are key devices to transmit and receive of the electromagnetic signals. Among a myriad of antenna configurations, the dipole antenna and its variants like the elliptical dipole antenna play also important role in supporting communication in different frequency bands. Among the countless antenna configurations, the dipole antenna and its variants like the elliptical dipole antenna play a critical role in communication systems for different frequency ranges. Especially, elliptical dipole antenna is a main component to achieve higher bandwidth since it demonstrates an asymmetry shape and provides the antenna to radiate effectively through broader frequency range than traditional dipole shapes [10]. Thus, the elliptical dipole antenna structure points out the challenge of limited band coverage of conventional dipole antennas in the different band ranges Ku and Ka bands [12-14]. The geometric variation of the elliptical dipole antenna provides better radiation patterns and wider bandwidth, making it suitable for broadband radar, ultra-wideband (UWB) wireless communication and other wireless communication applications [13-16].

Ku and Ka bands have also paramount effect on various applications in the field of telecommunications and satellite communications due to the higher transfer rates and employment of the larger channel capacity. The Ku band spectrum is covered from 12 to 18 GHz. [17, 18]. Additionally, the Ku band is utilized for satellite-earth data transmission, which requires higher traffic capacity, making it an essential component for satellite applications [19]. On the other hand, the Ka band operates at higher frequencies from 26.5 to 40 GHz to be required high-speed applications such as earth observations, satellite communications, radar applications, and broadband communication networks [19, 20]. In [19, 20] also contribute to the significance of antenna designs for Ku and Ka band applications. Various studies have focused on developing dual-band antennas for Ku and Ka bands, aiming to achieve wide bandwidth, improved gain, and radiation characteristics suitable for satellite and radar applications [12, 21-23].

As of 5G mid-band applications, 3.5 GHz frequency can empower the effective signal transmission and reception [24]. The main constrain of designing devices is specifically about space-constrained applications of 5G integrated into small devices namely smartphones and IoT devices [24]. Appropriate designed dipole antennas also provide broadband performance given the diversity of spectrum used in 5G networks [24]. Elliptical dipole antennas can be designed to have circular or elliptical polarization to prevail over problems such as signal attenuation and multipath propagation in urban environments, where 5G networks are commonly deployed [24, 25]. In addition, dipole antennas can be easily integrated into MIMO systems to provide spatial diversity and increase the overall performance of the communication link for the technology in 5G networks [26-29].

The purpose of this study is to delve into the relationship between constants and substrate materials to analyze their effect on the antenna performance parameters. The initial antenna designed is proposed for the mid-band application of 5G, Ka and Ku bands with a notched band covering 4.21 to 10.06 GHz. Then, the dielectric constant (Eps, εr) is altered along with the different values including 1.6, 2.2, 3.8, 4.3, and 12, respectively. The parametric study reveals that dielectric constant of 4.3 is employed via cost-effective and epoxy-based FR-4 material, which makes the available to the optimal performance. This study also ensures some insights about trade-off related with the dielectric constants since higher constants promote the effective communication, power loss diminution, low-cost. On the other hand, antenna designing with the dielectric constant of 4.3 underpins a nuanced sense on VSWR, group delay and radiation efficiency, respectively. In essence, this study carries out as a guidance for the antenna designers and researchers to emphasize and highlight the role of dielectric constants with several demands for diverse applications.

2. Antenna Design

2.1. Theoretical Background

The theoretical background of the proposed elliptical dipole antenna bears from the fundamentals of the dipole antenna theory and the principles of antenna design to achieve specific performance goals such as improved bandwidth [30-38]. The general overview of the theoretical background for this study is considered as:

A) Dipole Antenna Theory:

A dipole antenna is one of the simplest forms of antenna, which consists of two conductive elements (arms) that are fed at the center [34-36, 38, 39]. It operates by generating electromagnetic fields when an alternating current flows through it [40]. The length of the arms generally determines the resonant frequency and operating frequency [34-36, 38].

The conventional dipole antenna dimension (L_{all}: the overall length of the radiating antenna) is generally calculated at the desired frequency range by using the following Equations 1-2:

$$\lambda = \frac{c}{f} \tag{1}$$

$$L_{all} = \lambda/2 \tag{2}$$

Where λ stands for wavelength, c is speed of light, and f depicts the resonance frequency of the dipole antenna.

B) Bandwidth Improvement:

Traditional dipole antennas generally have limited inherent bandwidth, which shrinks their utilization in multi-purpose applications. There are several techniques employed for the improvement of the bandwidth. One common method is to modify the geometry of the antenna radiating elements. In this study, the conventional dipole antenna is modified in the form of elliptical patches to enhance the bandwidth and operating frequency as well [41].

C) Geometry Optimization:

The proposed antenna structure is also designed to offer advantageous in terms of bandwidth, resonance frequency, and impedance matching since the elliptical shapes generally yields broader impedance bandwidth as compared to straight elements [42-44].

D) *Material Selection and Substrate Design:*

The choice of the substrate material and its properties (dielectric constant, permittivity, thickness, loss tangent etc.) play an important role in defining the antenna performance parameters. The substrate properties affect parameters such as impedance matching, efficiency, and radiation characteristics [45-48].

Based on the above theoretical background of the antenna design and the effect on the antenna performance parameters, the dipole antenna is initially designed at the design frequency of 5 GHz. Then, the dipole antenna structure is modified with respect to the bandwidth improvement methods, geometry optimization with parametric studies. Finally, the effect of the dielectric constant on the antenna performance parameters is investigated.

2.2. Mathematical Calculations for Conventional Dipole Antenna

The radiating part length of the conventional dipole antenna is calculated as 30 mm by using above Equations1-2 and detailed as follows:

$$\lambda = \frac{c}{f} = \frac{3\times 10^8}{5\times 10^9} = 0.06\, meter = 60\, mm \qquad (1)$$

$$L_{all} = \lambda/_2 = 60/_2 = 30\, mm \qquad (2)$$

The dipole antenna is simulated with respect to the above dimension calculations via CST MWS program as depicted in Figure 1. Discrete port is attained to excite the antenna with the 50Ω impedances. It is also deduced from Figure 1 that the feed gap is defined as 1.81 mm.

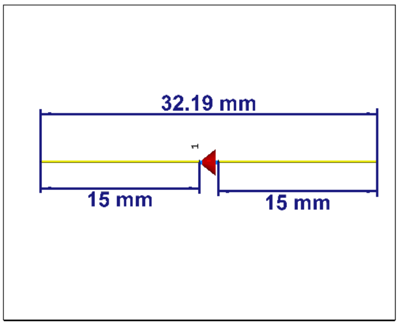


Figure 1. The conventional dipole antenna at the resonance frequency of 5 GHz.

2.3. Evaluation and Numerical Modelling of the Proposed Antenna

The proposed antenna structure is modified and designed as given in Figure 2. The detailed physical antenna parameters are labelled in Figure 2a-2b [49]. Then designed antenna designed via CST MWS environment is depicted along with the substrate width and length in Figure 1c and elliptical patches & feed gap in Figure 2d, respectively. Initially, the dielectric permittivity is selected as 2.2, which belongs to the Rogers RT5880 substrate material with the thermal conductivity of 0.2, the loss tangent of 0.0009, the thickness of 0.284 mm. Other physical antenna parameters are calculated as given in Table-1. The theoretical background of the proposed elliptical dipole antenna relies on the dipole antenna structure by changed the arm shaped and improved the bandwidth [50, 51].

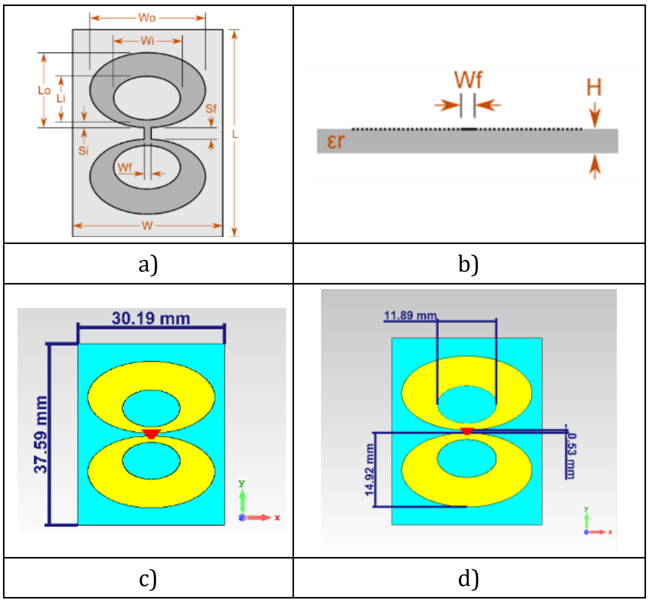


Figure 2. Different views of the proposed elliptical dipole antenna.

Table 1. The physical parameters of the proposed elliptical dipole antenna structure.

Physical Parameters	Value	Label

Outer Ellipse Length	14.92 mm	Lo
Outer Ellipse Width	26.25 mm	Wo
Feed Gap	0.532 mm	Wf
Feed Line Width	0.532 mm	Sf
Substrate Height	0.284 mm	H
Relative Permittivity	2.2	εr
Dielectric Width	30.19 mm	W
Dielectric Length	37.6 mm	L
Inner Ellipse Length	7.64 mm	Li
Inner Ellipse Width	11.9 mm	Wi
Inner Ellipse Offset	1.35 mm	Si

3. Results and Discussion

3.1. Initial Proposed Antenna Structure

First of all, the antenna performance parameters are simulated and analyzed with respect to the initial proposed antenna structure dimensions. Figure 3 depicts the reflection coefficient of the initial design with the desired frequency ranging from 1.5 GHz to 31 GHz. It is deduced from Figure 3 that the proposed antenna structure has notch band characteristic from 4.21 to 10.06 GHz. In other words, the proposed antenna structure radiated at broadband frequency spectrum covering 5G(mid-band), entire Ku band, and Ka band including from 27 GHz to 31 GHz, respectively. Secondly, Voltage Standing Wave Ratio (VSWR) parameter is simulated and investigated in Figure 4. It is also confirmed from Figure 4 that the initial antenna structure radiates with the lower VSWR at desired frequency ranges.

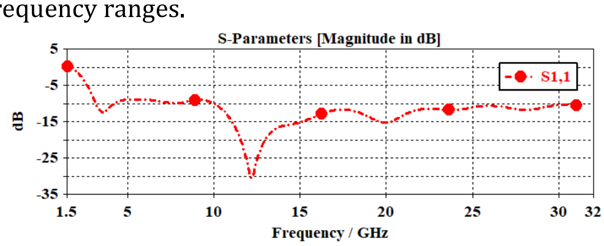


Figure 3. The reflection coefficient characteristic of the initial proposed antenna structure.

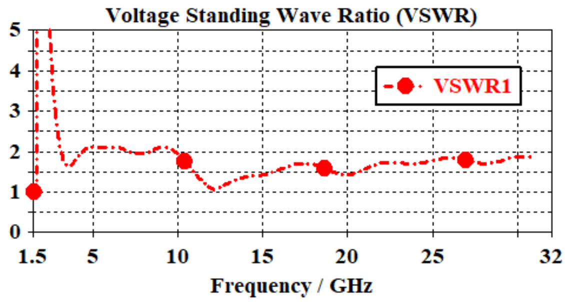


Figure 4. VSWR characteristic of the initial proposed antenna structure.

The initial designed antenna has a notch band characteristic from 4.21 to 10.06 GHz. Then, when group delay parameter is investigated as seen from Figure 5, there are two pulses with the 0.44 ns at 3.479 GHz and -0.69 ns at 12.167 GHz, respectively. Except this range, group delay is almost stable entire in the frequency range of interest. It is also important to deduce from the initial antenna performance parameter about stable group delay, which prevents the pulse distortion and ensures the accurate target range. Total efficiency is also another utmost performance parameter to analyze the initial antenna structure depicted in Figure 6. It is clear from Figure 6 that the radiation efficiency of the initial proposed antenna is also acceptable for the proposed frequency ranges.

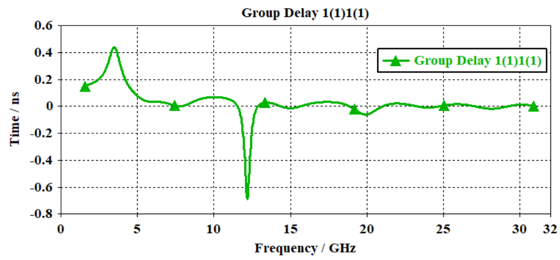


Figure 5. Group delay characteristic of the initial proposed antenna structure.

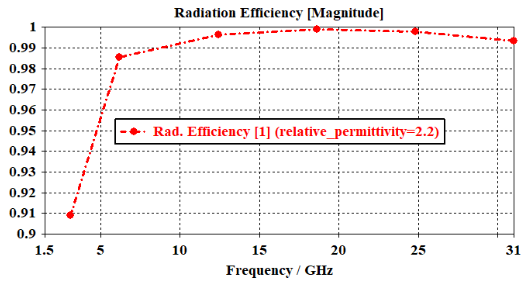
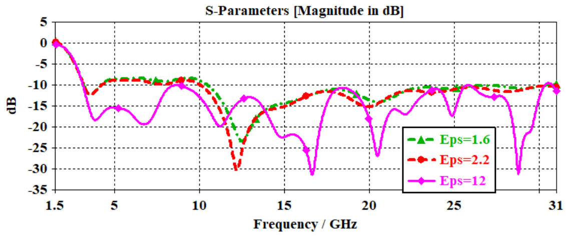


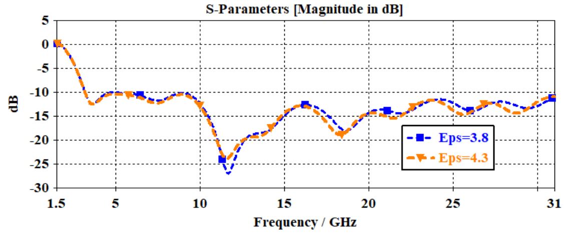
Figure 6. Radiation efficiency characteristic of the initial proposed antenna structure.

3.2. Parametric study for the antenna substrate dielectric constant

The dielectric constant of the substrate material has effects on the antenna performance parameters. Thus, the dielectric constant is parametrized as 1.6, 2.2, 3.8, 4.3, and 12, respectively. These corresponding values are related with the commonly used substrate material in the existing literature. It is clear from Figure 7 that increasing dielectric constant changes the antenna from band-pass to broader characteristic. Thus, application area is crucial requirements to determine the usage of the proposed antenna structure. However, the designing antenna structure with the dielectric constant of substrate material is generally considered as 4.3 since it is corresponded with low-cost epoxy-based FR-4 material.



a)



b)

Figure 7. The parametric analysis of the various dielectric constants along with the reflection coefficients.

VSWR parameters is analyzed with respect to different dielectric constants in the desired frequency range. It is also deduced from VSWR characteristic in Figure 8 that increasing the dielectric constant makes the proposed antenna broader than the initial structure. On the other hand, group delay parameter is also investigated by changing the dielectric constants in Figure 9. It is clear from group delay parameter visualized in Figure 9 that lower dielectric constants have lower phase distortion and stable phase characteristic as compared to the dielectric constant of 12. That is, the optimum dielectric constant was again determined to be 4.3 regarding the low-cost epoxy-based FR-4 by observing the group delay parameter and comparing it with other parameters such as S_{11} and VSWR.

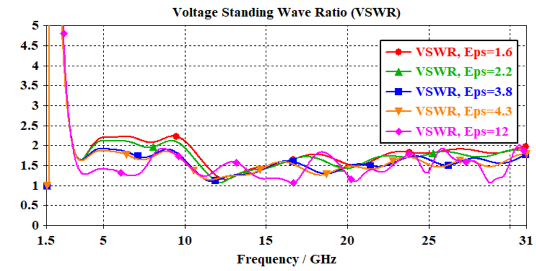


Figure 8. The parametric analysis of the various dielectric constants along with VSWR.

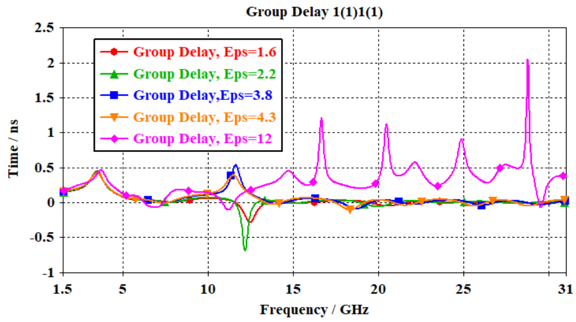


Figure 9. The parametric analysis of the various dielectric constants along with the group delay.

In this section, to last but not least, the radiation efficiency of the proposed antenna structure with different dielectric constants is investigated in the related frequency spectrum. It is outlined from Figure 10 that the proposed antenna with lower dielectric constants contributes to more effective communication and mitigate the power. This also results in cost savings in terms of substrate material namely FR-4 in the desired applications.

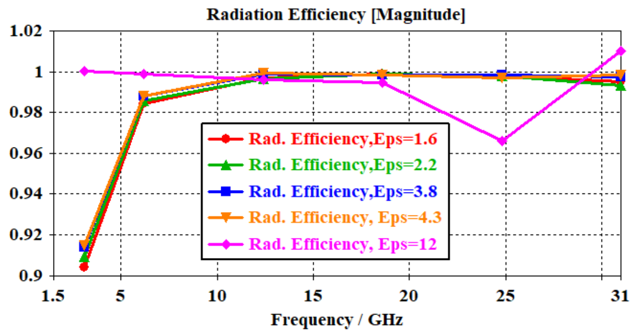


Figure 10. The parametric analysis of the various dielectric constants along with the radiation efficiency.

4. Conclusion

In summary, this study comprehensively investigated the performance parameters of the proposed antenna design through a broad frequency spectrum from 1.5 GHz to 31 GHz. The foremost antenna design featured peculiar 4.21-notch bandwidth characteristics at 10.06 GHz, making it suitable for 5G mid-band, Ku-band and Ka-band applications, including frequencies from 27 GHz to 31 GHz. Further testing included varying the dielectric constant of the substrate material from 1.6 to 12. Results showed that a dielectric constant of 4.3, equivalent to the commonly used low-cost epoxy-based FR-4 material, provided optimal performance. Increasing the dielectric constant expanded the characteristics of the antenna, but it was observed that a lower dielectric constant resulted in more efficient communication performance, thus helping to reduce power consumption and save costs. The study enhances the existing literature by offering a comprehensive analysis of antenna performance under varying dielectric constants and underscores the importance of considering application-specific requirements in the design process.

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