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Potential of Commercial Titanium in Electromagnetic Shielding for 5G Frequency Domain

5G Frekans Bölgesi için Ticari Titanyumun Elektromanyetik Ekranlama Potansiyeli

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ABSTRACT

The rapid advancements in telecommunications, medicine, military systems, and electronic devices have led to significant public health concerns regarding electromagnetic pollution. This issue is complex due to the potential for electromagnetic interference (EMI) to cause malfunctions or reduced performance in various electronic devices and systems. Electromagnetic shielding materials are essential for reducing pollution and protecting individuals, devices, and systems. Titanium, with its unique attributes, including enhanced electrical conductivity, durability, environmental sustainability, chemical stability, and superior mechanical properties, is an effective defense against electromagnetic pollution. This study utilizes commercially pure titanium grade 4 (CP Ti Grade 4) due to the complex processes involved in obtaining pure titanium. The study investigates the electromagnetic shielding efficacy of titanium in the 5G frequency bands using a Vector Network Analyzer (VNA), waveguides, and coaxial cables, demonstrating an impressive shielding effectiveness (SE) of approximately 70 dB within the 3.3–6 GHz frequency range.

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ÖZET

Telekomünikasyon, tıp, askeri sistemler ve elektronik cihazlardaki hızlı ilerlemeler, elektromanyetik kirlilik konusunda önemli bir halk sağlığı endişesine yol açmıştır. Bu sorun, elektromanyetik girişimin (EMI) çeşitli elektronik cihaz ve sistemlerde arızalara veya performans düşüşlerine neden olma potansiyeli nedeniyle karmaşıktır. Elektromanyetik koruyucu malzemeler, kirliliği azaltmak ve bireyleri, cihazları ve sistemleri korumak için gereklidir. Titanyum, gelişmiş elektrik iletkenliği, dayanıklılık, çevresel sürdürülebilirlik, kimyasal kararlılık ve üstün mekanik özellikler gibi benzersiz nitelikleri ile elektromanyetik kirliliğe karşı etkili bir savunmadır. Bu çalışma, saf titanyum elde etme sürecinin karmaşıklığı nedeniyle ticari olarak saf titanyum grade 4 (CP Ti Grade 4) kullanmaktadır. Çalışma, titanyumun 5G frekans bantlarındaki elektromanyetik koruma etkinliğini bir Vektör Ağ Analizörü (VNA), dalga kılavuzları ve koaksiyel kablolar kullanarak araştırmakta ve 3,3–6 GHz frekans aralığında yaklaşık 70 dB'lik etkileyici bir koruma etkinliği (SE) göstermektedir.

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1. INTRODUCTION

EMI shielding describes the use of a material shield capable of absorbing and/or reflecting electromagnetic radiation, particularly in the radio wave and microwave range. This shielding is essential for protecting electronic devices, as the electric fields within electromagnetic radiation can interact with electrons within these devices. Additionally, shielding is necessary to reduce the tendency of devices that emit this type of radiation to contaminate the environment with radiation. Electromagnetic pollution can pose a health hazard. For instance, EMI can cause medical devices such as pacemakers to malfunction [1]. Therefore, electronic devices and sources of radiation require shielding. It is important to distinguish EMI shielding from shielding against gamma rays or neutrons, which is critical for nuclear reactors [2].

To ensure device performance and keep potential adverse effects on human health within controllable limits and realistic targets, metallic materials are used for their structural advantages. Electromagnetic theory suggests that high conductivity enhances SE by promoting both the absorption and reflection of radiation. This is the reason for the recent trend in the literature towards metallic additive composites and polymer matrices [3]. In fact, studies on electromagnetic shielding show that new materials with appropriate modifications are more emphasized than traditional materials. With advancing technology, applications that utilize multiple regions of the spectrum simultaneously have become possible. In addition, previously unused frequency bands have begun to be actively used. Although 5G technology was not discussed at the end of the 20th century, it is now widely used in all areas of life. Consequently, effective new device and material design for 5G frequencies has become critical. As demonstrated in the given example, new material and device design are directly related to the requirements of the current era.

When designing materials for electromagnetic fields or searching for materials suitable for a related problem, two fundamental aspects are considered: minimizing radiation emission and minimizing susceptibility to external sources. In this context, according to electromagnetic theory, magnetic materials are effective in low frequency bands, while materials with high conductivity are effective for shielding against high-frequency electromagnetic radiation [3]. This information provides a foundational starting point for operations related to the frequency range of interest.

Magnetic materials are useful for shielding against radiation by absorbing it. This absorption is due to the interaction between the AC magnetic field in electromagnetic radiation and the magnetic dipoles present within the material [2]. Mumetal, a nickel-iron ferromagnetic alloy, is a well-known material with exceptionally high magnetic permeability. Mu-metal has been shown to be effective in shielding. A composite with a polymer matrix was used to demonstrate this [4]. Iron oxide ($Fe3O4$), also known as magnetite, is ferromagnetic, while nickel is ferromagnetic. Carbon, on the other hand, is not magnetic and is diamagnetic in graphite. Iron oxide nanoparticles are not conductive, but they are effective for shielding even without a conductive additive in a cement-based material [5]. Copper slag is also somewhat effective due to its limited magnetic character [6].

Materials with high electrical conductivity play an essential role in blocking and absorbing radiation. For instance, conductive carbon black is widely used for electromagnetic absorption applications due to its high electrical conductivity, which enhances the dispersion of electromagnetic waves [7]. Conductive materials are typically used to shield high-frequency electromagnetic fields, while magnetic materials with high permeability are used to protect against low-frequency magnetic fields [8]. Electrical conductive materials absorb and reflect radiation due to the interaction mechanisms of electromagnetic waves. When exposed to an electric field, the free carrier electrons in these materials move, resulting in the absorption (dissipation) of energy and a reduction in radiation. In addition, materials with high conductivity are known for their ability to reflect (scatter) electromagnetic waves back from their surfaces. This is because they prevent the propagation of radiation by reflecting it back with the free electrons on the material's surface, thus reducing unwanted interactions. Metals, particularly those with high electrical conductivity, are frequently used in radiation shielding [9]. Similarly, conductive metals like aluminum, copper, steel, and silver are widely used for EMI shielding due to their effectiveness, which is closely tied to the conductivity of materials [10]. These materials are often used in industrial applications, electronic devices, and space technology to control radiation effectively. Additionally, carbon-based materials [11], such as graphene [12] and carbon nanotubes [13], are gaining attention in electromagnetic shielding applications due to their high conductivity and durability. Electromagnetic shielding is used to protect spacecraft and electronic devices from radiation effects, prevent interference in communication systems, and in medical and military applications that require precise operation, as well as in the automotive industry [14].

In modern technology and industrial applications, it is crucial to ensure the structural requirements and achieve the desired quality of electromagnetic shielding performance. At this point, the concept of skin depth emerges. Skin depth is the depth at which the electric field intensity decreases to 1/e of its value at the surface of a material [15]. It plays a major role in determining the ability of a material to absorb or reflect electromagnetic waves. The penetration depth of electromagnetic waves into the material's surface, expressed as skin depth [16], is especially critical for electromagnetic waves operating at high frequencies. The depth at which electromagnetic waves penetrate into a material is determined by the material's electrical conductivity and frequency. This depth is commonly referred to as the 'skin depth'. As the skin depth increases, the amount of electromagnetic energy that penetrates the material decreases. In electromagnetic shielding, materials with high conductivity are typically preferred because they result in a smaller skin depth [17]. This allows for more effective absorption or reflection of electromagnetic waves at the material's surface. Therefore, to enhance shielding performance, particularly for electromagnetic waves operating at high frequencies, it is desirable for materials to possess high conductivity properties, resulting in a smaller skin depth. Consequently, this study investigates the electromagnetic shielding performance of titanium in this context.

In recent years, the use of commercial pure titanium or titanium alloys has become popular in the medical field and other sectors where excellent mechanical properties, low weight, and high corrosion resistance are essential [18]. CP Ti Grade 4 was chosen to assess its electromagnetic shielding performance in this study due to titanium's unique physical and chemical properties. Titanium has a broad range of industrial applications due to its low density and high strength. Over the last decade, its cost has significantly reduced [19].

The objective of this article is to highlight the role of CP Ti Grade 4 in industrial applications by quantifying its electromagnetic shielding potential. This will facilitate a deeper understanding of the benefits that titanium offers in the field of electromagnetic shielding. It should be noted that there are different forms of titanium [20], CP Ti Grade 4, which is characterized by its purity levels of 98-99%, stands out as one of the most accessible forms in the market. This research, using an accessible form of titanium, provides insights that can be used to evaluate other forms, thus providing a comprehensive view of the usefulness and benefits of titanium in electromagnetic shielding.

Titanium's effectiveness in electromagnetic interference (EMI) shielding is not solely contingent upon its conductivity; rather, it is also a consequence of its distinctive combination of low density and high mechanical strength [21,22]. These properties render it especially appealing for applications where weight is a critical factor, such as in the aerospace, automotive, and portable electronic devices industries. Furthermore, titanium's inherent corrosion resistance guarantees that it will retain its structural integrity and shielding effectiveness over time, even in harsh environmental conditions. This durability, in conjunction with its biocompatibility, has also resulted in an increasing utilization of titanium in medical devices, where both mechanical strength and reliable shielding from EMI are of paramount importance.

Furthermore, titanium's compatibility with a diverse array of other materials, including polymers and other metals, presents opportunities for the development of composite materials that integrate the advantages of multiple components. These composites can be engineered to optimize specific properties, such as conductivity, mechanical strength, and flexibility, thereby rendering them suitable for a broader range of EMI shielding applications [23]. For instance, titanium-based composites could be engineered to provide enhanced shielding in the high-frequency ranges utilized by contemporary communication technologies while simultaneously exhibiting lightweight and durable characteristics suitable for incorporation into portable devices.

Moreover, the advent of advanced manufacturing techniques, such as additive manufacturing (3D printing), has further expanded the potential applications of titanium in EMI shielding. These techniques permit the precise manipulation of material properties and the fabrication of intricate geometries that are challenging to attain through conventional manufacturing processes. This capability is particularly valuable for the customization of EMI shielding solutions in order to meet the specific needs of different applications, ranging from small-scale electronic components to large aerospace structures.

The potential of titanium in EMI shielding remains a topic of ongoing investigation, with new avenues for optimization being continually identified through research [24]. For example, surface treatments and coatings can be applied to titanium in order to enhance its electromagnetic properties while maintaining its other advantageous characteristics [25]. Moreover, research is underway to ascertain the long-term efficacy of titanium-based shielding materials in diverse settings, thus guaranteeing their dependability and efficacy throughout the operational lifetime of the devices they safeguard.

In summary, the distinctive combination of characteristics exhibited by titanium, including its mechanical strength, low weight, corrosion resistance, and biocompatibility, renders it an exceptionally promising material for electromagnetic interference (EMI) shielding applications. As technology continues to evolve and the demands on shielding materials become more complex, titanium and its alloys are likely to play an increasingly important role in ensuring the reliability and safety of electronic devices across a wide range of industries. This investigation aims to contribute to the growing body of knowledge on titanium's electromagnetic shielding performance, providing valuable insights for future research and application.

2. ELECTROMAGNETIC SHIELD MEASUREMENTS

The rise in electromagnetic radiation due to the increasing prevalence of electronic devices in daily life has led to concerns over EMI and the need for effective protective mechanisms. This article provides an in-depth examination of the mechanisms employed in electromagnetic shielding, offering significant experimental insight into the principles governing the interaction between materials and electromagnetic fields. The discussion covers different shielding materials, their properties, and the underlying physical phenomena. It is important to present the theoretical and mathematical foundation to clarify the complexities of SE.

Electromagnetic shielding is the process of blocking or reducing electromagnetic fields by using materials to prevent their entry into sensitive electronic components. The effectiveness of shielding materials is commonly measured using a metric called SE, which is expressed in decibels (dB) and indicates the material's ability to reduce the intensity of electromagnetic radiation. The principles of electromagnetic shielding are easier to understand

when explained using Maxwell's equations and the principles of electromagnetism. Shielding effectiveness (SE) is determined by a combination of factors, including the material's ability to absorb, reflect, and transmit electromagnetic fields. To explain these factors, mathematical expressions are used.
The reflection, transmission, and absorption coefficients (denoted as R, T, and A, respectively) define the impact of a material on electromagnetic waves. The reflection coefficient quantifies the amount of energy reflected by the material, typically ranging between 0 and 1. Similarly, the transmission coefficient indicates the extent to which electromagnetic waves pass through the material, also taking values between 0 and 1. These coefficients are related to the frequency (f), wavelength (λ), and the material's specific conductivity (σ).

$$R = \frac{(Z2 + Z1)^2}{(Z2 - Z1)^2} \tag{1}$$

$$T = 1 - R \tag{2}$$

$$A = 1 - R - T \tag{3}$$

Here, Z1 and Z2 represent the characteristic impedances of the material and the surrounding medium, respectively [26]. Another significant parameter frequently mentioned in the literature is the skin depth. The skin depth (δ) is a measure determined by the penetration of the electromagnetic wave into the material, and its formula is presented in Eq. 4

$$\delta = \left(\frac{2}{\omega\mu\sigma}\right)^{1/2} \tag{4}$$

Here, ω denotes the angular frequency, μ represents the magnetic permeability and σ signifies the electrical conductivity.
Electromagnetic shielding requires careful selection of appropriate materials. The introduction section mentions that conductive materials, such as metals, are widely used because of their ability to absorb and reflect electromagnetic radiation. Copper, aluminum, and titanium are among the most commonly employed metals in this context. Relevant studies on these materials can be found in the literature [27-29].
Although the interactions between electromagnetic fields and materials have been mathematically explained above, these phenomena are graphically illustrated in Figure 1, where the resulting effect of each component varies. A fundamental mechanism of electromagnetic shielding is reflection, whereby the shielding material deflects incoming electromagnetic waves away from the protected area. This process involves a higher potential for reflection in conductive materials with high conductivity [30]. Unlike traditional EMI protective materials, where reflection is predominant, materials where absorption is dominant prevent electromagnetic wave pollution caused by the reflection and scattering of incoming waves. The absorption-dominant materials usually have a higher absorption coefficient (A) than the reflection coefficient (R), which significantly reduces secondary electromagnetic pollution. These materials can also be used in military camouflage applications as EM wave absorbing materials [31]. Absorption is the process of converting electromagnetic energy into heat within the shielding material. Materials with a high absorption coefficient contribute to the overall shielding effectiveness by dissipating absorbed energy as heat. The absorption performance of composites is assessed by determining the return loss in decibels, which provides an insight into the amount of EMI that can be absorbed by the shielding material. Scientific studies have shown that materials with a return loss of -10 dB can absorb 90-95% of EMI, while materials with a return loss of -20 dB can absorb approximately 99% of electromagnetic radiation [32]. The third mechanism of EMI protection involves multiple reflections and internal scattering. In the multiple reflection mechanism (shown in Figure 1), incoming waves reflect off the back surface and return to the first surface [33]. The electromagnetic interference (EMI) shielding effectiveness (SE) is dependent on the frequency of the waves [34]. It is important to have a comprehensive understanding of frequency-dependent shielding mechanisms as different shielding materials may exhibit varying SE values at different frequencies. For instance, a magnetic composite may have a high EMI SE in the X-band while having relatively lower values in other bands [35].
Electromagnetic shielding is designed to protect against the harmful effects of electromagnetic fields. Research in this area suggests that the shielding performance of titanium can vary depending on the frequency of electromagnetic waves, as well as the material's thickness and geometry. The objective of this study is to assess the efficacy of titanium's electromagnetic shielding in diverse scenarios and to identify the benefits derived from its intrinsic characteristics. As an initial step, SEM analysis was conducted to identify the structural characteristics of the titanium sample used in this study. The results of the SEM analysis are presented in Figure 2.
The scanning electron microscope (SEM) image of CP Titanium Grade 4 clearly displays the material's surface and microstructure, including the grain structure, grain boundaries, and porosities. The grain structure is a critical factor in determining the material's mechanical properties, with smaller grain sizes generally resulting in higher strength and hardness [36]. CP Titanium Grade 4 has a relatively fine grain structure, which contributes to its high strength and hardness. The image displays a uniform grain structure, indicating consistent processing and the absence of weak points. The grain boundaries of titanium are critical for its corrosion resistance. Materials with fewer grain boundaries typically exhibit higher corrosion resistance. CP Ti Grade 4 has relatively few grain boundaries, which enhances its corrosion resistance. The grain boundaries in the image appear smooth and clean, suggesting well-processed material without impurities. The SEM image of commercial grade 4 titanium shows

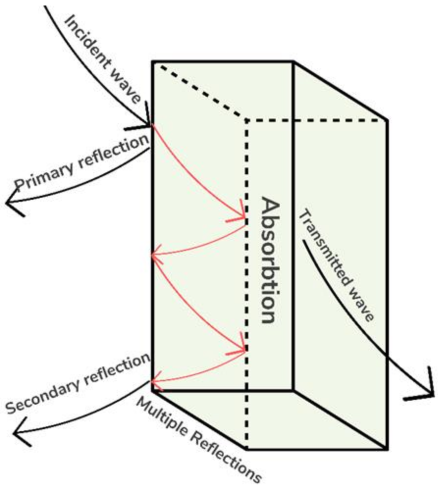

Figure 1. Interaction of incoming EM radiation with the shield.

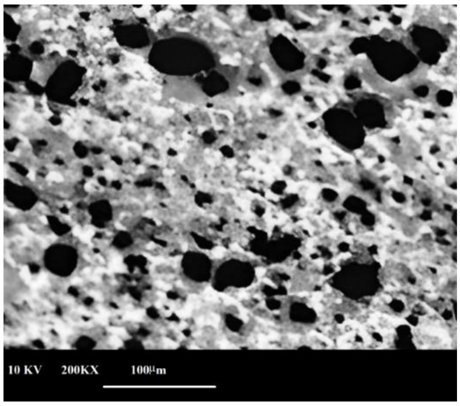

Figure 2. SEM image of titanium.

that the material has high strength, hardness, and corrosion resistance. However, porosities on the material's surface can negatively affect its mechanical properties and corrosion resistance. Therefore, it is crucial to maintain a clean and smooth surface to preserve its integrity.
CP TI is available in four grades, ranging from 1 to 4, which are categorized according to their respective purity and oxygen content levels. The highest oxygen content (approximately 0.4%) and the strongest mechanical properties are observed in Grade 4. The alloy Ti-6Al-4V, also known as grade 5 titanium [37], is also available. CP TI Grade 4 is widely used in various sectors due to its high strength, hardness, and corrosion resistance. This makes it an ideal choice for numerous applications, such as implants [37]. The decision to use titanium grade 4 in this study is based on its mechanical and structural properties, which make it useful in various fields. Additionally, titanium has advantages over other materials used in electromagnetic shielding. Our study aims to demonstrate the superiority of titanium in electromagnetic shielding compared to other materials.
CP Ti Grade 4 is a commercially pure titanium grade that contains a minimum of 99% titanium element. It is designated as 3.7065 according to the EN standard and R50700 in the UNS standard. This grade is known for its strength, good ductility, and moderate formability. Additionally, it exhibits superior corrosion and fatigue resistance in seawater environments. Commercial pure titanium is known for its high strength and excellent corrosion resistance, making it a competitive alternative to steels and nickel alloys in various applications [38]. The iron content in titanium increases with the grade number (grades 1 to 4) and helps control grain size during recrystallization [20]. No changes in content have been made, as per the instructions provided. The iron content in titanium increases with the grade number (grades 1 to 4) and helps control grain size during recrystallization [20]. The iron content in CP Ti increases with the grade level, which improves grain size control during recrystallization. CP Ti is particularly suitable for applications that require both strength and corrosion resistance, with a minimum yield strength of 480 MPa (70 ksi) and service temperatures up to 400°F (204°C) [38]. Table 1 presents the details of the titanium sample used in this article.

2.1. Shielding Performance measurements

A variety of techniques are employed to assess electromagnetic shielding, with the objective of analyzing the absorption, reflection, or transmission of electromagnetic fields by materials. These measurements are crucial for determining the electromagnetic compatibility of materials and optimizing their performance during design stages. The American Society for Testing and Materials (ASTM) publishes relevant test methods, specifications, practices, guides, and classifications [39].
There are a number of methods for measuring shielding, including conductivity measurements, SE measurements, RF (Radio Frequency) permeability measurements, SWR (Standing Wave Ratio) measurements, TEM (Transverse Electromagnetic) Cell measurements, and Faraday Cage measurements. The details of each of these methods will be discussed below.
Conductivity measurements often assess electromagnetic shielding based on material conductivity. ASTM D4935 provides a standard method for the measurement of the radio frequency (RF) conductivity of flat sheet materials [40], which determines the surface resistivity and the surface conductivity. Electromagnetic shielding effectiveness is a critical parameter in assessing a material's ability to absorb or reflect electromagnetic waves. ASTM D4935 is a standard used to measure Shielding Effectiveness (SE) by testing a material's ability to absorb electromagnetic energy. It also measures RF permeability, which is the ability of electromagnetic waves to pass through a material. The Standing Wave Ratio (SWR) quantifies the ratio of standing waves created by a material reflecting electromagnetic waves internally. ASTM D4935 provides a standard method for measuring electromagnetic

radiation, ensuring consistency across laboratories. The technical scope of this method is limited to frequencies ranging from 30 MHz to 1.0 GHz [41].

Table 1. Type analyses of Ti Grade 4 (UNSR50700) [38].

Material	%
Carbon (Maximum)	0.08
Titanium (Nominal)	Balance
Iron (Nominal)	0.5
Nitrogen (Maximum)	0.05
Hydrogen (Maximum)	0.015
Oxygen (Maximum)	0.4

Figure 3. Shielding performance measurement mechanism.

The Transverse Electromagnetic (TEM) cell, as specified by ASTM D4935 and ASTM D6090, is used to evaluate the electromagnetic properties of a material in a controlled environment. Furthermore, the TEM cell serves as a shielded enclosure for RF plane-wave fields, characterized by simple construction and portability in smaller versions. The field within is well-characterized, facilitating the calibration of electromagnetic field probes and sensitivity measurements. A smaller cell can achieve higher frequency operations [42]. To protect electronic devices and circuits from incoming EMI, a widely used method is to enclose them in a Faraday cage. Faraday cage measurements provide an isolated environment from electromagnetic fields, allowing for the direct assessment of electromagnetic shielding performance. ASTM D4935 includes such measurements [43]. In the ASTM measurement method, the transmission, reflection, and absorption of a given material are calculated based on the values of S parameters. In addition to the equations presented in the previous section (equation 1,2,3), the shielding effectiveness of a material is expressed as a logarithmic value which is expressed in the following equation [44].

$$SE = 10\,log(\frac{1}{R+T})dB \qquad (5)$$

In this study, as shown in Figure 3, shielding performance was measured using a VNA, coaxial cables and waveguides. The methodology offers several advantages, including the ability to conduct measurements over a wide frequency range, to obtain accurate and precise measurements, to perform repeatable experiments and to implement rapid experimental procedures. CP Ti Grade 4 samples were placed between the relevant waveguides to assess their shielding performance. Switching the waveguides allowed measurements to be taken over different frequency bands. The waveguides used in this study allowed measurements in the frequency range of 3.3-6 GHz. The results of the measurements are shown in Figures 4 and 5.

3. RESULTS

The shielding performance of titanium in the frequency range from 3.3 GHz to 4.9 GHz has been extensively studied, as shown in Figure 4, which provides a graphical representation of the shielding efficiency with frequency on the horizontal axis and shielding power on the vertical axis. The red line indicates the reflection component, which varies with surface properties, internal structure, and the wave's angle of incidence. It is evident that reflection typically plays a more dominant role in the shielding effectiveness of high conductivity materials [45]. The lower effectiveness of titanium in reflection can be attributed to its low conductivity, which is only 3.1% of aluminum's electrical conductivity [46]. The total shielding effectiveness, shown by the yellow line, accounts for both reflection and absorption effects and indicates that titanium provides effective electromagnetic shielding over the frequency band examined, though its performance varies, highlighting its complexity and selective response to electromagnetic waves. These variabilities suggest that the effectiveness of titanium in providing electromagnetic shielding over a wide frequency band may differ depending on the frequency, indicating potential advantages or disadvantages in specific applications. It is critical to note the performance of up to 70dB at 4.3GHz. Figure 5 shows the shielding performance of titanium against electromagnetic fields in the frequency bands of 4.9-6 GHz. The blue line indicates the ability of the material to absorb electromagnetic waves, which generally depends on its ability to internalize these waves and convert the energy into heat, often related to the internal structure and electrical properties of the material. The reflection capacity of a material is indicated by the red line, which shows how much incoming electromagnetic waves are reflected off its surface. This characteristic is mainly related to the electrical conductivity and surface properties of the material. The yellow line represents the total shielding effectiveness, which is the combination of both reflection and absorption.

In the frequency band of 5.6-5.9 GHz, there is an increase in the reflectivity of titanium, as shown by the red line. Concurrently, the absorption characteristics show a decrease, particularly after 5.6 GHz, so that the overall

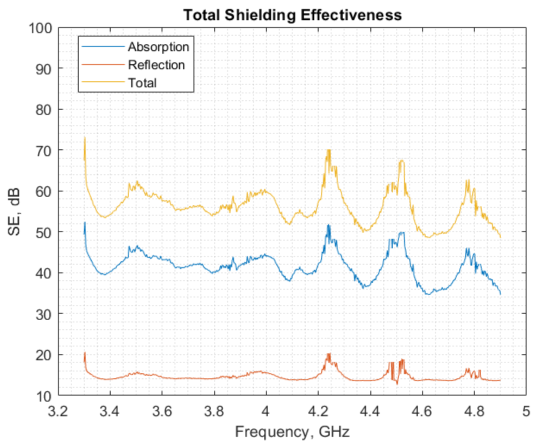

Figure 4. Electromagnetic shielding performance of titanium (3.3-4.9 GHz).

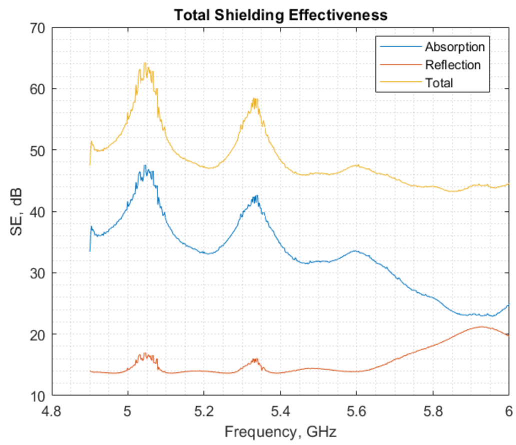

Figure 5. Electromagnetic shielding performance of titanium (4.9-6 GHz).

shielding performance in the 5.4-6 GHz frequency band remains in the 45-50 dB range. Whereas any performance above 40 dB is generally interpreted as effective shielding, it is clear that titanium alone may not be suitable for medical and military applications beyond 5.4 GHz. Nevertheless, the evidence of shielding effectiveness of up to 62 dB in the vicinity of 5 GHz points to its potential applicability in frequency selective scenarios.

4. DISCUSSION

There are studies in the literature on the shielding effectiveness (SE) of titanium against electromagnetic interference (EMI), particularly true in foam and composite forms. For instance, Ti3C2, a 2D material, can function as a protective coating or layer in electronic devices to mitigate EMI due to its excellent electrical conductivity and large surface area of the two-dimensional structure. Liu et al. [47] used TI3C2 layers obtained from Ti3AlC2 powders through HF etching to produce Ti3C2/paraffin composites with varying Ti3C2 content. Electromagnetic interference shielding effectiveness (EMI SE) measurements carried out over 2.0-18.0 GHz showed an increase in EMI SE with higher Ti3C2 content, peaking at 39.1 dB for composites containing 60% Ti3C2 at a thickness of 2.0 mm. This finding demonstrates the potential of the material used for EMI SE [47]. Two-dimensional titanium carbides (Mxenes) display significant properties, including high conductivity and EMI SE, which are crucial for applications in printed and flexible electronics. The study by Vural et al. [48] demonstrated that inkjet printing of 2D Mxenes, supported by tandem repeat proteins, enables the production of highly conductive electrodes on various substrates such as cellulose paper, glass, PET, and PMMA, achieving a conductivity of 1080 ± 175 S cm^–1 at a thickness of 2.25 µm. These Mxene-based electrodes are suitable for flexible electronics as they maintain their conductivity even when bent. In addition, they exhibit effective EMI shielding properties comparable to the latest material technologies, with a shielding effectiveness of 50 dB for films of 1.35 µm thickness. The electrodes also respond to changes in humidity, expanding their potential applications.

In a related study [49], the manufacturing of foamed titanium carbonitride (Ti3CNTX) films for EMI protection was investigated by comparing hydrazine and thermal reduction methods. The study achieved an EMI SE value of 118.4 dB at a working frequency of 14.3 GHz, demonstrating promising approaches for high-performance non-metallic EMI shielding materials.

The study by Han et al [50] demonstrates the fabrication of sandwich-structured composites based on Ti3C2 MXene with tunable electromagnetic absorption and shielding behavior. The composites are produced through RF etching and annealing processes, preserving the original layered morphology and enhancing the electromagnetic absorption capacity in the X-band region. The composite, which contains 50% annealed MXenes by weight, achieves a minimum reflection loss of -48.4 dB at 11.6 GHz. This is due to the formation of TiO2 nanocrystals and amorphous carbon, which makes it suitable for use in electromagnetic absorption and protection applications.

Titanium foams are a preferred material for EMI SE applications due to their advantageous mechanical properties. In their study, Liu et al [51] obtained results indicating that a porous titanium foam with interconnected pores, manufactured via polymer foam, has effective electromagnetic shielding at low frequencies ranging from 0.3 to 3000 MHz. The shielding effectiveness decreases as the frequency increases. However, at higher frequencies, a fluctuating region emerges where the effectiveness stabilizes around an average value. This observation suggests potential applications in electromagnetic radiation protection across a range of frequencies.

The studies discussed illustrate a growing interest in the use of titanium-based materials for electromagnetic interference (EMI) shielding, particularly in advanced forms such as foams, composites, and two-dimensional (2D) materials like MXenes [52-54]. These materials demonstrate considerable promise in terms of shielding effectiveness (SE), largely due to their distinctive structural and electrical properties. It is noteworthy that the flexibility of MXene-based electrodes, as demonstrated by Vural et al., highlights their potential for use in the next generation of flexible and printed electronics [48]. The combination of high electrical conductivity and robust EMI shielding at minimal thicknesses renders these materials particularly attractive for lightweight and adaptable electronic applications. Moreover, the work of Guo et al. on sandwich-structured composites with tunable electromagnetic absorption and shielding behavior paves the way for new avenues of tailored EMI protection solutions, where specific frequency bands can be targeted for optimal performance [55].

Furthermore, the utilization of foamed titanium materials, as investigated by Verma et al., demonstrates the significance of structural design in attaining effective EMI shielding across a broad frequency range [56]. The interconnected pore structure of titanium foams not only contributes to mechanical robustness but also impacts the SE by creating pathways that enhance electromagnetic wave attenuation. These findings collectively suggest that titanium-based materials, particularly when engineered at the nano- and micro-scale, hold significant promise for future developments in EMI shielding technologies, catering to both traditional and emerging high-frequency applications.

The following table (Table 2) lists some of the current studies in the literature on the measurement of SE performance.

Tablo 2. EMI shielding performance of different shielding materials.

Frequency (GHz)	Material Used	SE (dB)	Ref
X band 8-12 GHz	c-MWCNT/AgNWs/PANFs hybrid film	40.59	[57]
	Ti3C2Tx/bacterial cellulose	43.7	[58]
	Ti3C2Tx/bacterial cellulose	41	[59]
	CNF/MXene/FeCo composite	58	[60]
	SiTiOC ceramic nanocomposites	27.85	[61]
5G	Aluminium	45-90	[28]
	Ti3C2Tx MXene	65.25	[62]
	CP Ti Grade 4	**50-70**	**This work**

5. CONCLUSION

This study investigates the electromagnetic shielding effectiveness of titanium in the context of 5G applications (sub 6 GHz). The findings contribute significantly to the existing literature on titanium's electromagnetic shielding capabilities. The analysis covers a wide spectrum ranging from 3.3 to 6 GHz, providing a comprehensive understanding of its performance in specific frequency bands. Throughout the research process, Titanium has demonstrated a remarkable shielding effectiveness in the band of 50 to 70 dB, acting as an effective electromagnetic shield in the 5G frequency range. The shielding performance of titanium decreases as the frequency increases, indicating its frequency-dependent behavior. However, this decrease is not linear, as titanium can exhibit higher shielding effectiveness at certain frequencies compared to lower ones. Titanium has demonstrated particularly effective shielding effectiveness values within the 4.5 and 5.1 GHz frequency bands, making it suitable for use in certain 5G spectrum bands.

The use of the physical advantages of titanium, such as its durability and mechanical properties, makes it a suitable material for 5G applications within the specified frequency bands. In the sub-6 GHz 5G frequency spectrum, titanium exhibits an absorption-dominant characteristic, with an average absorption of 20 to 50 dB, and a reflection characteristic typically falling within the band of 10 to 20 dB.

Focusing on 5G frequencies, this study provides insights for future studies on electromagnetic compatibility (EMC) properties of different metals and layer configurations. The findings suggest that titanium provides a potential advantage for effective electromagnetic shielding in wireless communication technologies. It is important to underline that this study only deals with the EMI shielding behavior. Therefore, future investigations are advised to include the electrical resistance and mechanical properties associated with titanium materials.

Author Contribution

U.S is responsible for entire paper.

Conflict of Interest

The author declares that he has no conflict of interest.

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