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Towards a miniaturized microstrip attenuator with the composite material film

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Abstract. In this study, A microstrip attenuator made of a graphite, silicon carbide (SiC), graphite and silicon carbide (GSC) thin film is designed, fabricated, and tested. The attenuator was tested in the frequency found from 1 to 10 GHz using the PCB technology and implemented on an FR4 substrate. Using the HFSS software and based on experimental results, the attenuation characteristics and performance of various materials are investigated. The HFSS simulations considered the key parameters, such as the material conductivity, dielectric constant, film thickness, and examined their impact on the electromagnetic field distribution,. A considerable attenuation is observed in these materials, albeit with variations across the tested frequencies. The paper highlights the potential of the composite materials, such as GSC, in advancing the attenuator technology, particularly for applications requiring compact, efficient, and broadband solutions. It is shown that integrating composite films into microstrip attenuators significantly improves their performance. The final results, corroborated by both simulations and practical experiments, confirm that these materials are viable for the RF and microwave applications.

Keywords: microstrip, microwave attenuator, Graphite/SiC, S-parameters, HFSS simulation

Miniaturiziran mikrotrakasti atenuator s kompozitnim filmom

Prispevek opisuje razvoj in testiranje mikrovalovnih atenuatorjev iz grafita, silicijevega karbida (SiC) ter tankih plasti grafita in silicijevega karbida (GSC). Tiskana vezja na podlagi FR4 smo testirali v frekvenčnem območju od 1 do 10 GHz. Z uporabo programske opreme HFSS in eksperimentalnih rezultatov smo preučili karakteristike atenuacije in zmogljivosti različnih materialov. Simulacije HFSS so upoštevale ključne parametre, kot so prevodnost materiala, dielektrična konstanta, debelina filma ter njihov vpliv na porazdelitev elektromagnetnega polja. Rezultati so pokazali znatno atenuacijo teh materialov, čeprav so se pojavile nekatere variacije pri preizkušenih frekvencah. Raziskava poudarja potencial kompozitnih materialov, kot je GSC, pri razvoju tehnologije atenuatorjev, zlasti za aplikacije, ki zahtevajo kompaktne, učinkovite in širokopasovne rešitve. Rezultati nakazujejo, da lahko integracija kompozitnih filmov v mikrovalovne atenuatorje prinese pomembne izboljšave zmogljivosti. Zaključki raziskave, potrjeni z eksperimentalnimi in simulacijskimi rezultati, poudarjajo izvedljivost teh materialov za prihodnje RF in mikrovalovne aplikacije.

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1 INTRODUCTION

With the increased of the demand for high-frequency and microwave communication systems, researchers began to develop microstrip attenuators in the 1960s and 1970s [1], [2]. Researchers designed they to provide a controlled signal attenuation, minimize losses, and ensure a good impedance matching.

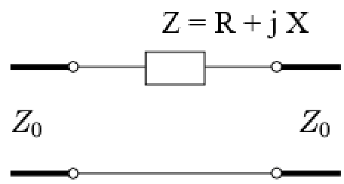

Figure 1. Attenuator equivalent circuit model.

The attenuator shown in Fig. 1 is a π attenuator, where Z0 is the system impedance on the left and right. It is characterized by a zero-reflection coefficient when viewed from the left relative to Z0, as well as from the right relative to Z0. Attenuation factor K is defined as the value that determines the signal attenuation through the attenuator [3].

$$K = \frac{Power_{in}}{Power_{out}} \quad (1)$$

Fig. 2 shows balanced resistive attenuators, with their corresponding design equations.

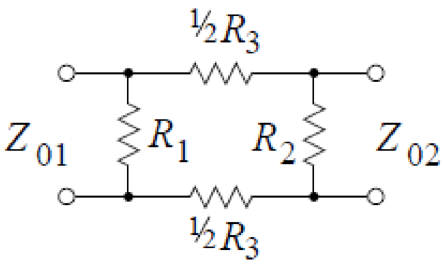

Figure 2. Balanced pi attenuator [3].

If $Z_{01} = Z_{02} = Z_0$, then $R_1 = R_2 = Z_0 = \left(\frac{\sqrt{K}+1}{\sqrt{K}-1}\right)$ (2)

and $R_3 = \frac{Z_0}{2\sqrt{K}}(K-1)$ (3)

Fig. 3 shows the implementation of the attenuators by incorporating a lossy section of the transmission line.
The formerly used substrates initial substrates often included ceramics or microwave-compatible composites. The introduction of FR4 marked a turning point in the microstrip attenuator design [4], [5]. The epoxy glass composite widely used in the electronics industry enabled more cost-effective manufacturing and adaptability on standard printed circuit boards.
Over the decades, the microstrip attenuator manufacturing techniques have advanced from the manual methods to the automated and precise methods. This change which considerably improved the attenuation and the impedance adaptation properties, is needed by the modern communication systems [6].
The attenuators decrease the amplitude of the basic signal travelling through a transmission line. The fundamental approach is to introduce a loss into the line while maintaining a characteristic impedance similar to that of the connecting lines to minimise reflections. Figs. 1. a and 1. b demonstrate the process of applying resistive material to a microstrip line in wireless circuits to make it lossy [1].

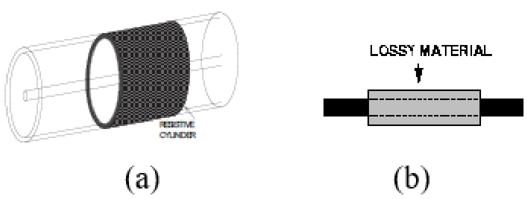

Figure 3. Various attenuators: (a) coaxial and (b) microstrip configurations.

The microstrip attenuators can be optimised using a variety of materials, such as the graphene, to adjust their performance in terms of the insertion loss, bandwidth and frequency response.
The objective of the paper is to evaluate the performance of the microstrip attenuators using various materials to adjust their attenuation characteristics; i.e. the bandwidth and frequency response and to design attenuators capable of maintaining low and stable attenuation levels over a wide frequency band while optimising their miniaturisation without compromising their efficiencies.

2 Description of Materials

2.1 *Presentation of the materials investigated*

The graphite/SiC composite (GSiC) combines the distinctive properties of the graphite [7], [8], [9] and silicon carbide (SiC) [10] and [11] to create a composite material with significantly improved performance.
Table 1 lists the properties of the graphite, a material widely recognized for its lightweight nature and high thermal and electric conductivity. Because of them, it serves as the main matrix in the composite.
Silicon carbide (SiC), a relatively recent semiconductor material, plays a crucial role as a reinforcing material. Its key physical properties, (see Table 1), including a high hardness, remarkable abrasion resistance, and exceptional thermal stability, provide the composite with an stable robustness and reliability under varied thermal conditions.

2.2 *Basic properties and reasons for the use*

The main matrix choice of the graphite is based on its ability to provide an efficient thermal and electric conduction while maintaining a low weight, which is essential for applications requiring lightweight yet high-performance materials.
We use SiC as a reinforcement materiel due to its superior mechanical properties, including the hardness and abrasion resistance. Furthermore, its thermal stability allows the composite to maintain performance under high-temperature states, thereby expanding the potential applications of the GSC composite.
The complementary properties of the graphite and SiC enable the GSC composite to excel in demanding environments, ensuring a reliable performance and increased durability.

Table 1:Characteristics of the graphite/SiC composite materials

Graphite Powder

Carbon content (%)	98
Humidity (%)	< 0.5
Conductivity (S/m)	70000 S/m
Mass density (kg/m^3)	2250
Silicon carbide « SiC »	
Thermal conductivity ($W/m.k$)	120-200
Mohs hardness	9
Mass density (g/cm^3)	3.21

2.3 *Material synthesis*

The manufacturing process of the graphite/SiC (GSC) thin film composite starts with the mechanical grinding of the silicon and graphite powders, resulting in particles smaller than 20 µm. We are then dispersed these powders in a high-temperature polyethylene glycol (PEG) solution to dispers and disaggregat the aggregates. Adding, a concentrated nitric acid removes the metallic impurities. The solution is then filtered to get a pure graphite-silicon carbide mix.
The silicon substrates, we proposed by ultrasonicating them in acetone and then rinsing them with deionized water. The Hydrofluoric acid then treats them to etch the surface oxide layer. After drying, we are heated up the substrates to 350 °C and a silicon carbide solution deposited between them. Preheating distributes the solution uniformly over the substrate surface. Finally, the samples are annealed at 1200 °C in a controlled atmosphere, thereby stabilising the composite structure.

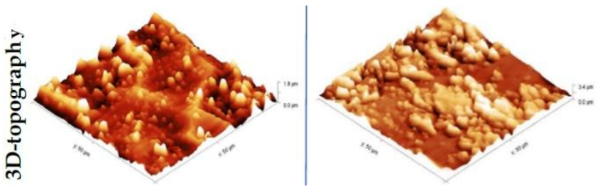

Figure 4. AFM image of the topography.

The AFM analysis of the graphite/SiC (GSC) composite surface shows that the different crystalline grains are initially spread out randomly. Because of the thermal treatment, the crystalline grains aggregate to form larger clusters, significantly altering the material's microstructure. On a 10x10 µm scale, this change is very clear. The importance of annealing in changing the grain size and its distribution, which provides an important information about how the GSC properties change over time.

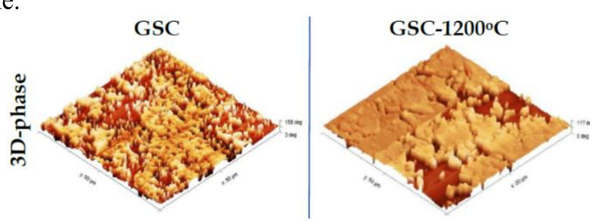

Figure 5. AFM phase analysis.

The AFM phase analysis shows that the surface of the graphite/SiC (GSC) composite has two separate phases demonstrated by the big differences in the colour. The areas of the low contrast indicate the minimal interaction between the probe and the surface. The high-contrast areas reveal denote a stronger interaction. The dark color shows the graphite-rich areas confirming the non-uniform distribution and highlighting similarities with the previous graphite island distribution observations.

An X-ray diffraction (XRD) is used to illustrate the crystalline structure of the synthesised materials. The results confirm the formation of the desired phases and identify the impurities present in the composite. The interpretation of the XRD peaks demonstrates the materials purity and phases, thereby validating the quality of the graphite/SiC composite and the success of the synthesis process, (see Fig. 3).

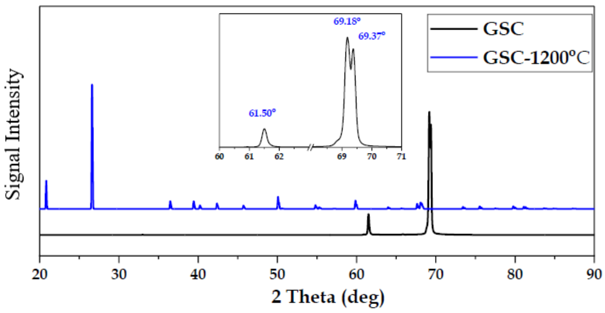

Figure 6. X-ray diffraction (XRD) spectrum of GSC film.

3 Numerical Study of the Microstrip Attenuators

3.1 *Design and structure*

The presented microstrip attenuators are different because they are built using the PCB technology, given in [11] and [12] and include both SiC and the graphite and a composite made of the graphite and silicon.

The attenuators consist of a main copper line, with various materials deposited in its centre to evaluate their ability to introduce an attenuation. Fig. 4 shows the design of the configurations using the Ansys HFSS software.

To have the characteristic impedance of 50 ohms on the microstrip line of width W, the attenuators use an FR4 substrate of a thickness of 1.6 mm. The dimensions are: L = 4 mm, L1 = 8 mm, L2 = 2.8 mm, Len = 21 mm, and Wid = 24.1 mm. The material dimensions are S1 = 3 mm and S2 = 0.8 mm. The access line for ports 1 and 2 is 3 mm wide.

The losses in the microstrip line lower the signal. They are caused by the conductor, dielectric, and radiation losses. The radiation losses affect only the magnetic substrates like YIG. [13] describes a simple formula to measure the attenuation due to the conductor losses.

$$\alpha_c = \frac{8.686\sqrt{\frac{\omega\mu_0}{2\sigma}}}{Z_0 W} \tag{4}$$

where σ is the conductivity, μ_0 is the permeability of the free space, and ω is the angular frequency.

3.2 Characterization and morphological analysis

The AFM topographical analysis shows that heating the graphite/SiC (GSC) composite changes the grains arrangement to the changing them from the being randomly spread out to becoming more organised and larger groups, which consequently changes the microstructure of the material.

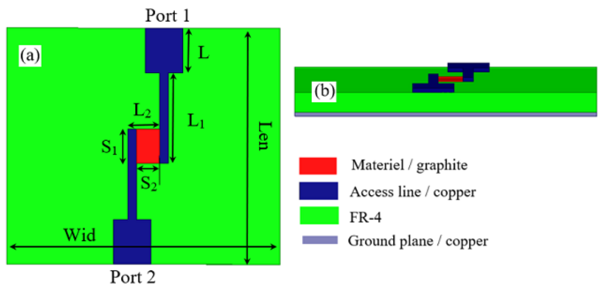

Figure 7. Configuration of the proposed graphite-based microstrip attenuator: (a) top-layer view, (b) side view.

Fig. 8 shows the evolution of the S parameters [14], obtained with the 3D electromagnetic simulation as a function of the frequency, for an optimised graphite-based attenuator. The S parameters show optimal results. The insertion losses (S21) are -3 dB and the reflection coefficient is -20 dB in the frequency band of 2 to 18 GHz.

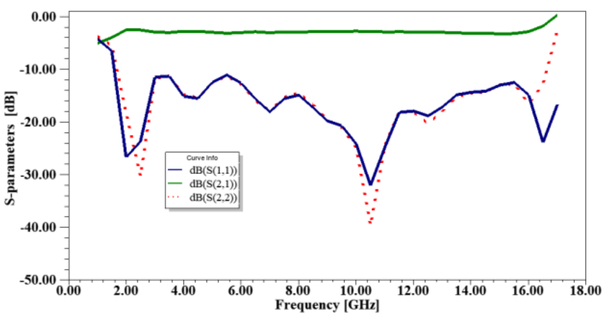

Figure 8. Simulation of the graphite-based microstrip attenuator performance.

4 Experimental of the Presented Attenuator Results

Various methods are used to manufacture the microstrip attenuators [15], we propose an based on the PCB technology with simplified material deposition stands out for its simplicity.

The realization of the proposed attenuator forms the basis for a detailed presentation of the experimental results, providing a comprehensive and coherent representation of their performance.

For the microwave power attenuation applications, our microstrip attenuator is designed, fabricated, and tested for the frequency band of 1 to 10 GHz.

The materials performance is evaluated in terms of the attenuation (S21 parameter) and reflection (S11 parameter) over the frequency band from 1 to 10 GHz. A detailed comparison is made between the simulation results and experimental measurements. A network analyzer E5071C is used for the S-parameters measurements. Table 1 summarizes the attenuation levels and reflection coefficients calculated for the various materials used. The comparison helps select the optimal attenuator configuration for specific applications.

To characterize the performance of each studied material, the S parameters are measured at various frequencies.

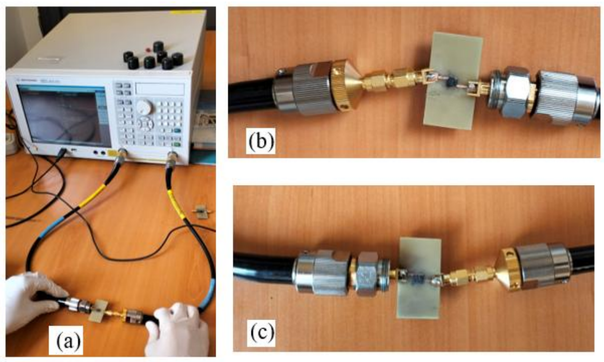

Figure 9. Proposed; (a) attenuator under test, (b) attenuator with a graphite powder, and (c) attenuator with a SiC powder.

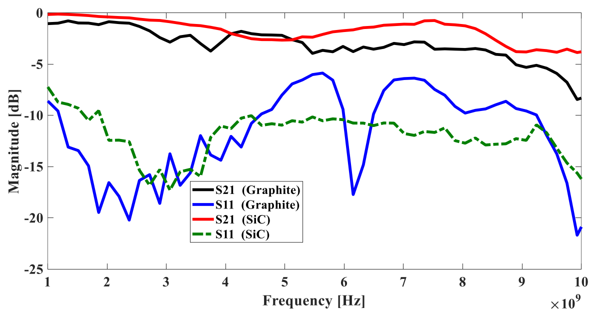

Figure 10. Transmission and reflection response of the attenuator based on graphite and SiC powder.

Fig. 10 shows that graphite adds some losses, with the insertion losses of up to 3.45 dB are likely to be due to the low resistance at the frequencies below 3 to 6 GHz. However, at higher frequencies, the graphite significantly increases the attenuation due to the increased skin effect losses and enhanced signal absorption. This property suggests that the graphite is effective in attenuating high-frequency signals.

Oppositely, SiC exhibits the relatively high attenuation around 4.60 dB in the 1 to 10 GHz band for beign made of crystals and for its natural absorbtion and release of the energy from the microwave signals. This can be helpful when the consistent attenuation is needed over a wide frequency band and good isolation (S11 = 28.69 dB).

For the graphite, the minimal reflection occurs in the 1.5 to 2.98 GHz frequency band; and for SiC, it occurs in the 2.5 to 3.5 GHz.

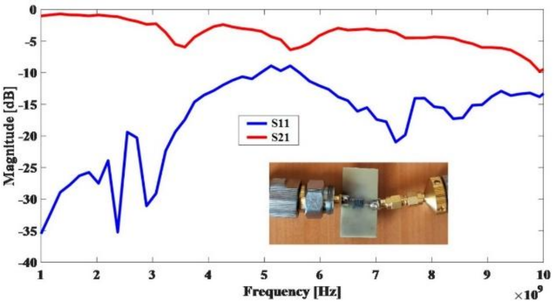

Figure 11. Transmission and reflection response of an attenuator based on the GSC/Si powder.

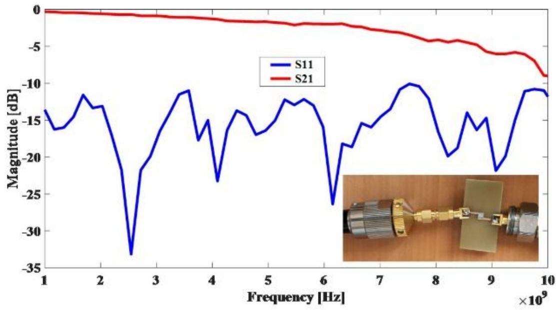

Figure 12. Transmission and reflection Response of the attenuator based on the GSC/Si thin film.

The used GSC/Si powder material presents the S parameters shown in Fig. 11. It indicates the optimal results with the insertion losses of -5 dB and reflection of -35 dB in the frequency band from 1 to 3.5 GHz, and -20 dB at 7.5 GHz.

Fig. 12 shows that the GSC/Si thin film exhibits a significant attenuation with the good isolation of -34.69 dB at 2.80 GHz, suggesting a stable and effective performance over a wide frequency band.

The materials used offer an intermediate performance with a moderate attenuation across the tested frequencies. The GSC (Graphite-Silicon Carbide) and SiC (Silicon Carbide) layers stand out for their stability in the attenuation, effectively achieving the goals of 3 dB to 5 dB over a wide frequency band. The GSC/Si thin film and powder show considerable reflection losses compared to the graphite and Si over the different tested frequencies.

The paper provides an in-depth analysis of the experimental results shown in Table 2. It offers an optimal selection of the attenuator materials. For the applications requiring the stable attenuation over a wide frequency band, the GSC/Si thin films prove to be particularly promising.

Table 2: Results

Config	Reflec [dB]	Attenu [dB]	Center Freq [GHz]	Pass Band	Band width
SiC	-28,69	-4.60	2.83	1 — 5	4
GSC/Si (poweder)	-35	-5	2.50	1 — 3.5	2.5
	-20	-7	7.50	6 —10	4
GSC/Si (thin film)	-34.69	-2.78	2.80	2 —3.5	1.5
	-25	-4.92	4	3.80 —5	2.80
	-29.42	-5.43	6	5.50 —7	2.50
	-22.78	-8	8 / 9	7.8— 9.50	1.70
Graphite Sim	> ∣ -20 ∣	-3	2.50	2 —10	8
Graphite Meas	20	-3.45	2.5	1.5 —2,98	1.48

Table 3: Performance comparison: proposed attenuator and alternatives

Reference	Ref [16]	Ref [17]	Ref [18]	This work
Working band (GHz)	3.5-8.2 / 8-18	0-5	3.5-6.5	2 — 9.5
Reflection (dB)	< -10	25	<-10	-34.69
Attenuation (dB)	2.5-14	0.3/15	1-13	3
Material used	Graphene Nanoplates	Graphene Flakes	Graphene	GSC/Si
Fabrication process	PCB	PCB	CVD	PCB

Table 3 compares the performance of the proposed attenuator with the attenuators of the reference publications. Our design outperforms them with a significantly minimised the reflection coefficient and a larger operational frequency band, while maintaining a comparable level of attenuation. Moreover, our fabrication process is mush simpler compared to the others.

5 Conclusions

A complete presentation is given of a PCB-based attenuator performance works on an FR4 substrate using different materials to lower the frequency from 1 to 10 GHz. The S-parameter measurements of the studied materials are analysed to evaluate their attenuation characteristics.

The critical importance is shown of the numerical modelling using the HFSS software to accurately predict the circuit characteristics and the effectiveness of experimental measurements in validating the predictions through a methodical approach.

It is shown that the studied materials exhibit an adequate performance and effective impedance matching. The GSC and SiC layers are paid particular attention due to their significant attenuation capacity, albeit varying across the tested frequencies, making them particularly promising.

Recommendations are given for the future optimisation of the RF attenuators, highlighting the importance of integrating the composite materials in designing miniaturised and high-performance components. The presented advancements contribute to meeting the increasing demands of the modern telecommunication and RF technology applications, paving the way for further innovations in the field.

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