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Tunable and Input-Matched Attenuator Based on Few-Layer Graphene

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***Abstract*—This paper presents a novel tunable microstrip attenuator, based on few-layer graphene flakes. The attenuator consists of a microstrip line with two pairs of graphene pads located between the microstrip line and metal vias, positioned at the two sides of the microstrip line. In the proposed device, the insertion loss can be changed electronically by varying the applied control voltage. The structure is designed in such a way, that the attenuation is mainly due to dissipation, while minimizing the reflection contribution. A prototype of the proposed structure has been fabricated and experimentally verified. It operates in a frequency band of DC to 10 GHz, with 25 dB tunability and minimum insertion loss of 1.5 dB.**

***Keywords*—Graphene, tunable microwave devices, voltage-controlled attenuators.**

I. INTRODUCTION

The use of nanomaterials, and in particular graphene, has received significant attention in the last years for applications at microwave frequencies, thanks to its unique features and especially its tunability properties [1]-[4]. More specifically, the tunability of graphene can be exploited to modify its conductivity from very low values to fairly high ones, thus allowing the implementation of innovative components and systems at microwaves and millimeter waves [3], [4].

While graphene has been used in different forms, the technology based on few-layer graphene (FLG) appears particularly interesting, due to the simple and cost effective manufacturing process [5], [6]. In addition, this form of graphene preserves the major properties, and in particular the tenability due to electrostatic doping [7].

Among several other microwave applications, the tunability of graphene conductivity has been exploited for the implementation of voltage-controlled microwave attenuators. A graphene-based tunable microstrip attenuator was presented in [7]: it is based on a microstrip line with a gap midway through the line, which is filled with FLG flakes. By applying an external bias voltage, the conductivity of FLG changes, and this in turn modifies the insertion loss of the attenuator. When zero bias voltage is applied, the insertion loss is large, whereas the insertion loss decreases when increasing the control bias voltage.

Subsequently, another microstrip attenuator was proposed in [8], which consists of a microstrip line with two FLG pads

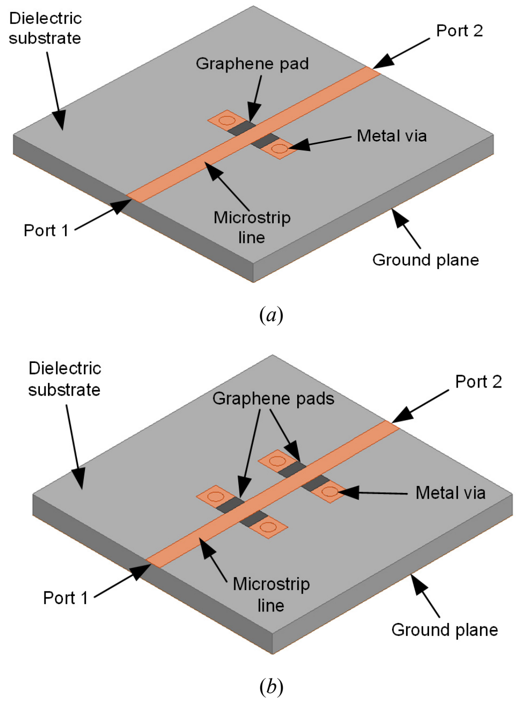


Fig 1. Geometry of the graphene-based tunable microstrip attenuators: (*a*) Microstrip attenuator with one pair of symmetrical graphene pads, located between the microstrip line and grounded vias; (*b*) Microstrip attenuator with two pairs of graphene pads, spaced by a microstrip line section.

symmetrically located on either sides of a microstrip line, between grounded metal vias and the microstrip itself (Fig. 1*a*). Varying the bias voltage modifies the resistance of the FLG. This varies the transmission scattering parameters, resulting in a electronically-controlled variable insertion loss. In this structure, the insertion loss is low when the bias voltage is zero, and it increases by increasing the bias voltage. The main drawback of this solution is that the insertion loss is due both to power dissipation in the graphene and to reflection.

This paper presents an improvement of the tunable attenuator proposed in [8], and consists of two pairs of FLG pads, separated by a short microstrip section (Fig. 1*b*). This solution allows for two major advantages: the tunability range is largely extended, and the input matching is significantly improved, in such a way that the insertion loss is mainly due to power dissipation rather than reflection.

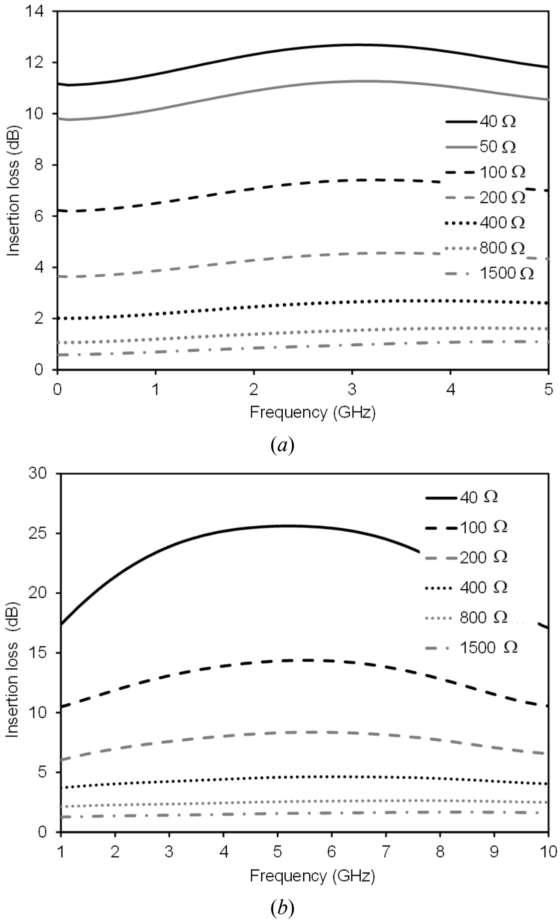


Fig. 2. Insertion loss vs. frequency: (*a*) simulated results for different values of graphene resistance in the 2-post design; (*b*) simulation results for different values of graphene resistance in the 4-post design.

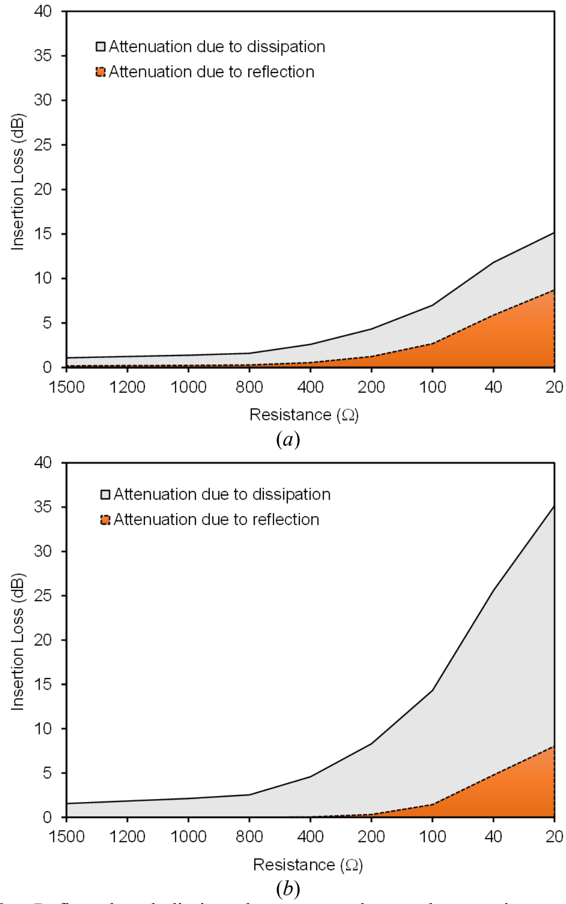


Fig. 3. Reflected and dissipated power vs the graphene resistance at the frequency of 5 GHz: (*a*) simulated results for the 2-post design; (*b*) simulation results for the 4-post design.

II. Design of the Attenuator

The proposed attenuator is an improved version of the attenuator in [8]. Fig 1*a* shows the structure originally proposed in [8], which incorporates graphene flakes deposited between two symmetrically placed vias and a microstrip line. Fig 1*b* shows the new proposed design, which consists of an attenuator with four FLG pads (two on each side of the microstrip line with graphene depositions in between the microstrip line and the vias). Transmission through the microstrip line is controlled by the applied bias voltage on the graphene flakes. The applied bias voltage reduces the resistance of the graphene flakes, increasing the current passing through it. This, in turn, attenuates the signal propagating along the microstrip line.

The microstrip attenuator based on two posts [8] was designed on CER-10 Taconic laminated dielectric substrate. The substrate has a thickness h=1.27 mm with ε_r=10, and loss tangent, tanδ=0.0035. The line in this case has a thickness of 1.17 mm resulting in 50-Ω characteristic impedance. The graphene pads have length 1.40 mm and width 0.66 mm, and the metal via has a radius of 0.4 mm.

In the case of the 2-post design, the insertion loss of the attenuator ranges from 1 dB for a maximum graphene resistance of 1500 Ω to 12 dB at graphene resistance of 40 Ω, as shown in the Fig. 2*a*. This gives 11-dB tunability in the frequency band from DC to 5 GHz.

In the 4-post attenuator proposed in this work, simulations were performed using Ansys HFSS. FLG flakes were modelled as infinitely thin resistive sheet with assigned values of resistances in the range of the expected graphene resistance.

The design was based on Taconic RF-60 substrate. It has a thickness of h=0.64 mm with ε_r=6.15 and loss tangent, tanδ=0.0028. The graphene pads have length 1.40 mm and width 0.66 mm. The metal vias as in the case of the 2-post have a radius of 0.4 mm. The microstrip line in this case has a width of 0.94 mm, in order to get a characteristic impedance of 50 Ω. There is a microstrip section with a length of 5 mm between each pair of posts, in order to ensure maximum tunability range and wide-band operation.

Simulations show that the 4-post design exhibits better performance under all features of the attenuator, namely broader operation bandwidth and larger tunability range. In fact, Fig. 2*b* shows the simulation of insertion loss versus frequency, for different values of the graphene resistance. The minimum attenuation in the simulated results shows a value of 1.5 dB for a value of graphene resistance equivalent to 1500 Ω, while the maximum attenuation at a graphene resistance of

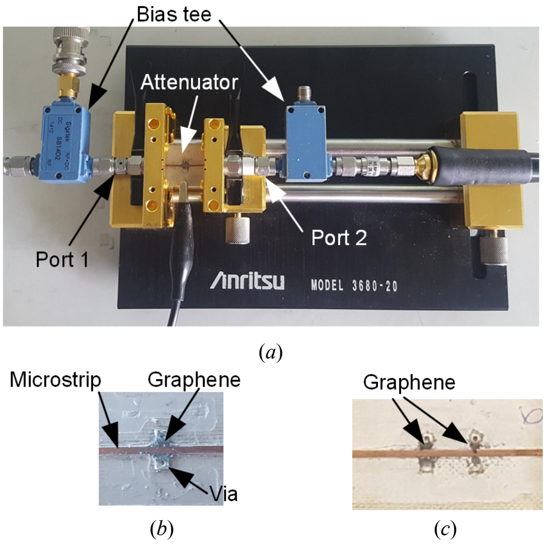


Fig. 4. Prototype of the graphene-based microstrip attenuators: (*a*) The measurement setup: (*b*) Structure with one pair of graphene pads (two-post device); (*c*) Structure with two pairs of graphene pads (four-post device).

40 Ω is 25 dB. Hence, the total tunability in this case, as demonstrated by the simulations results in 23.5 dB. In this case, the frequency response is fairly constant from DC to 10 GHz, which is twice as that of the previous 2-post design.

An even more relevant advantage of the new design is related to the individual contributions of (large) dissipation and (small) reflection in the determination of the insertion loss.

Fig. 3*a* shows the contributions of reflected and dissipated power versus the graphene resistance, in the case of the 2-post design. The contribution of the reflection is shown by the orange region whereas the contribution of the dissipation towards the total attenuation can be seen in the gray region. At lower resistance of 20 Ω (where the insertion loss is maximum), the total attenuation is 14 dB, with 6 dB dissipation and 8 dB reflection.

In the novel 4-post design, the contribution of the dissipation towards the total attenuation in this case is very high with lower reflection values, as shown in the Fig. 3*b*. More specifically, a total attenuation of 14 dB is achieved with a resistance of 100 Ω: in this condition, the contribution of dissipation is 12.6 dB and the contribution of reflection is only 1.4 dB. Moreover, the total attenuation can be further increased by further reducing the value of graphene resistance to 20 Ω: in this case the total attenuation is 35 dB, with 27 dB dissipation and 8 dB reflection.

III. Measured Results Comparison

Prototypes of the designed attenuator have been manufactured and tested, to verify the validity of the proposed design and simulations. The FLG adopted in this work was realized at the National Institute of Nuclear Physics(INFN), Frascati National Laboratories, Italy, by microwave exfoliation method [7], [9].

The measurement setup is as shown in Fig 4*a*. The terminal sections of the microstrip line are connected to an Anritsu test set. Commercial broadband bias tees are needed to bias the graphene with a DC voltage. Since the vias are connected to the ground, it is sufficient to bias the structure between the microstrip line and the ground in order to bias the four FLG pads. DC current flowing through the microstrip line into the ground is measured by the help of a multimeter, and values of graphene resistance are derived from the value of the applied voltage bias. The bias tees are connected to a vector network analyzer to measure the frequency response. Fig 4*b* shows a prototype of the attenuator with two posts, previously presented in [8], while Fig 4*c* illustrates the proposed design with four posts.

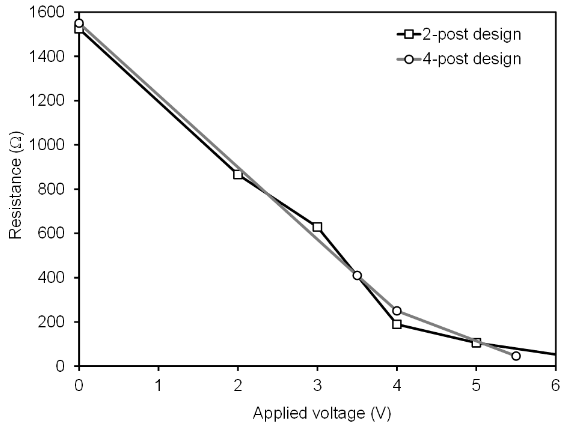


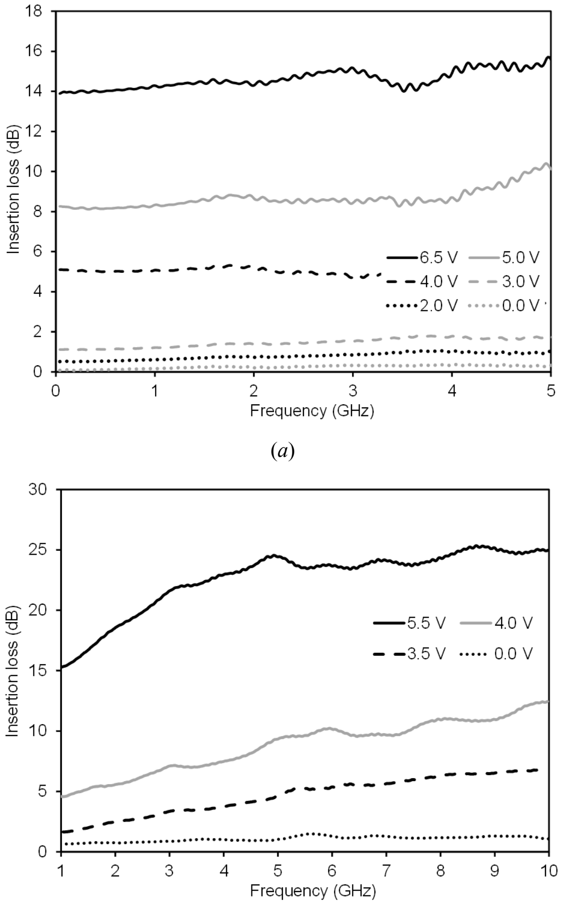
Fig. 5. Measures graphene resistance versus bias voltage, for the attenuators with 2 posts and 4 posts.

Fig. 5 shows the measured graphene resistance versus DC bias voltage, for the attenuators with 2 posts and 4 posts. Increase in the bias voltage results in a decrease in the graphene resistance. It can also be noticed in Fig. 5 that there is a good agreement in measurements for the attenuator in [8] and the new structure proposed in this work.

The measurement results of the insertion loss versus frequency, for different values of bias voltage, are reported in the Fig. 6. In particular, Fig. 6*a* shows the data obtained in [8] for the 2-post design, whereas Fig. 6*b* shows the new data related to the 4-post design. The measured values are in good agreement with simulation data for both types of the tunable microstrip attenuators. While measured data are parametrized with voltage (Fig. 6) and simulation data are parametrized with resistance (Fig. 2), the two sets of curves can be compared by using the results of Fig. 5.

The attenuator with 4-post, proposed in this work, exhibits a tunability of 23 dB as compared to 14 dB of the 2-post attenuator in [8]. Moreover, the 4-post attenuator operates in a band of 10 GHz, twice as wide as that of the 2-post attenuator.

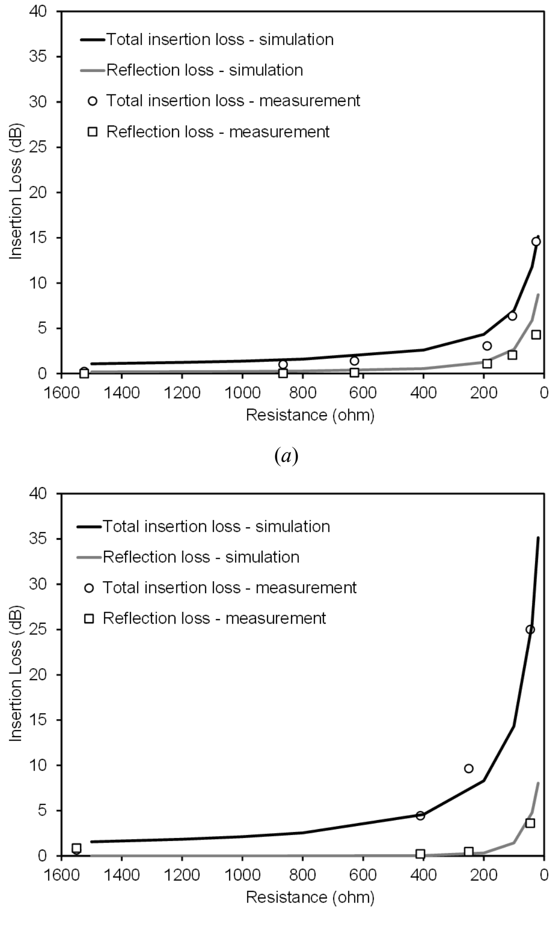
In conclusion, a general comparison of the performance of the two attenuator is shown in Figs. 7*a* and 7*b*, which report Simulated and measured insertion loss and reflection loss versus resistance at the frequency of 5 GHz. It results that, for a similar value of graphene resistance, the insertion loss in the case of the 4-post design is clearly higher than that of the 2-post design.



(*a*)

(*b*)

Fig. 6. Insertion loss vs. frequency: (*a*) measured results for different values of the applied bias voltage in the 2-post design; (*b*) measured results for different values of applied bias voltage in the 4-post design.



(*a*)

(*b*)

Fig. 7. Simulated and measured insertion loss and reflection loss vs. resistance at the frequency of 5 GHz: (*a*) 2-post design; (*b*) 4-post design.

IV. Conclusions

In this paper, a new version of voltage-tunable attenuator based on few layer graphene flakes is proposed. It is based on a microstrip line with two pairs of grounded vias, and graphene is deposited in the gaps between the microstrip and the vias.

The proposed solution represents an extension of a previous design, with only one pair of vias. The new solution outstands the previous design in terms of larger tunability range of the insertion loss (24 dB compared to 14 dB) and broader operation bandwidth (DC to 10 GHz instead of DC to 5 GHz). Moreover, the new attenuator improves the input matching, with the attenuation mainly due to dissipation and not to reflection. Measurements fully validate the simulation data.

Acknowledgement

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