A Planar Antenna With Voltage-Controlled Frequency Tuning Based on Few-Layer Graphene

(Article begins on next page)

A Planar Antenna with Voltage-Controlled Frequency Tuning Based on Few-Layer Graphene

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***Abstract*—This paper presents a voltage-controlled tunable planar antenna based on few layer graphene flakes. The antenna consists of a rectangular patch with a shorted microstrip stub connected to the radiating edge, and a graphene pad located at the input of the stub. The proposed design exploits the variation of the graphene resistance by an applied bias voltage. Without any bias voltage, the graphene pad behaves almost as an open circuit, not allowing any current passing and thus voiding the impact of the stub. Increasing the bias voltage reduces the graphene resistance, thus increasing the current passing through the pad into the stub. This results in the patch antenna radiating at a different frequency. A prototype operating at the frequency of 5 GHz has been designed and tested, demonstrating a frequency tunability larger than 10% with a limited gain degradation.**

***Index Terms*— Graphene, tunable microwave device, patch antenna.**

I. INTRODUCTION

IN THE RECENT YEARS, there has been a rising interest in the use of graphene for microwave applications [1]. The variation of graphene resistance with the applied voltage is an interesting feature at microwave frequencies, which makes it suitable for tunable components and systems [2]-[4].

Among the many forms of graphene and the variety of fabrication techniques, the few-layer graphene (FLG) is particularly interesting, as it is very easy to fabricate, cost effective, and eco-friendly, while preserving its tunability characteristics [4]-[6].

The variation of graphene resistance can be exploited in the design of frequency tunable antennas [7], [8]. In such antennas, the frequency where the antenna exhibits the best input matching and the maximum gain can be modified electronically, by changing the voltage applied to the FLG.

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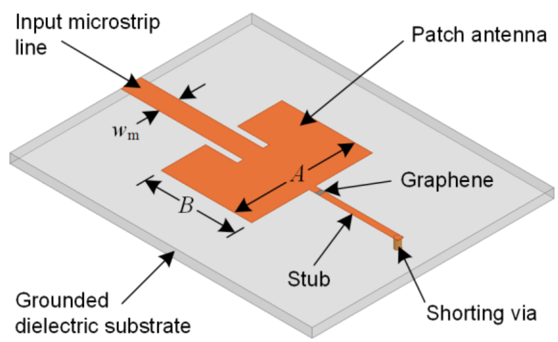


Fig 1. Geometry of the proposed structure.

Large frequency tunability range and limited gain degradation represent the relevant figures of merit for tunable antennas [9].

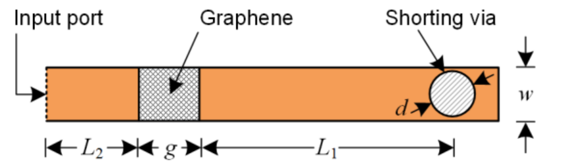
This paper presents a tunable planar antenna, based on FLG flakes. The proposed antenna consists of a rectangular patch connected to a shorted microstrip stub via a graphene pad (Fig. 1). The operation frequency of the antenna can be electronically modified by changing a control voltage of the graphene pad, which allows for varying the graphene resistance. The change in graphene resistance varies the current passing to the stub, which in turn modifies the resonance frequency of the patch antenna. A design of a tunable patch antenna, based on carbon nanotubes, was first proposed in [10], [11]. In this paper, the design and fabrication of a tunable patch antenna, based on FLG and operating around the frequency of 5 GHz, are presented, along with the experimental validation.

II. DESIGN OF THE TUNABLE ANTENNA

The structure shown in Fig. 1 can be modeled as a patch antenna connected to a shorted microstrip stub that exhibits a variable input impedance, depending on the bias voltage applied to the graphene pad.

A. Optimization of the shorted microstrip stub

The effect of the stub is analyzed first. As shown in Fig. 2(a), the stub consists of two microstrip sections: the former has length L_1 and is located between a shorting via and the graphene pad; the latter has length L_2 and it is located between the graphene pad and the radiating edge of the patch. The graphene pad has nominal dimensions g by w and is located in the gap between the two microstrip lines.



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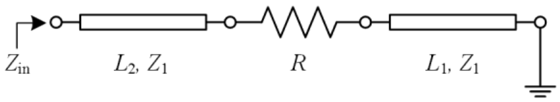


(*b*)

Fig 2. Microstrip shorted stub with the graphene pad: (*a*) Geometry of the stub; (*b*) Equivalent transmission line model.

An equivalent model of the stub is shown in Fig. 2(*b*). A transmission line section with length L_1, shorted at one end, is connected to the graphene at the other end. As discussed in [4], the graphene pad can be modeled as a lumped resistor with resistance $R=\rho\, g/w$, being ρ the graphene sheet resistance. Another transmission line section with length L_2 is connected between the input port and the graphene resistor. The characteristic impedance of the two lines is Z_1. The input impedance Z_{in} is

$$Z_{in} = Z_1 \frac{R + jZ_1 \tan\beta L_1 + jZ_1 \tan\beta L_2}{Z_1 + j(R + jZ_1 \tan\beta L_1)\tan\beta L_2} \qquad (1)$$

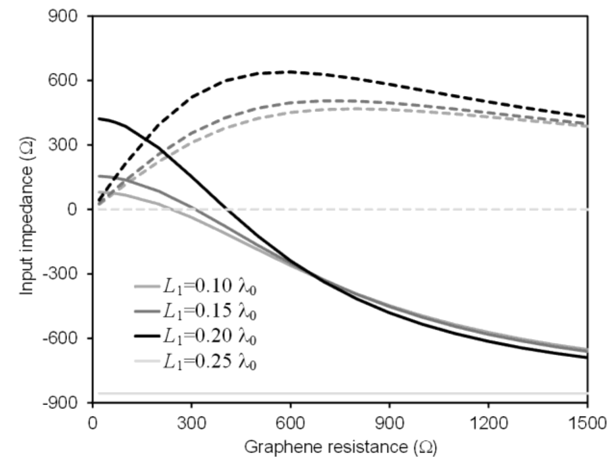
where β represents the propagation constant of the transmission lines at the operation frequency.

There are three variables to be controlled in the optimization of the stub, namely L_1, L_2 and Z_1. The geometrical dimensions of the stub have to be optimized, in order to achieve the maximum variation of the imaginary part of the input impedance versus the range of graphene resistance, while keeping a large and constant real part of the input impedance. To this aim, a parametric study is shown in Fig. 3, at the operation frequency of 5 GHz.

The effect of L_1 is reported in the Fig. 3(*a*), for fixed values of $L_2=\lambda_0/60$ (where λ_0 is the wavelength at the operation frequency) and $Z_1=90\ \Omega$. When the length of the shorted stub L_1 is a quarter wavelength, there is no change in the real and imaginary part of the input impedance, as no current flows across the graphene resistor. By slightly reducing the length L_1, there is noticeable change in the imaginary part (solid line) of the input impedance, with little variation in the real part (dashed line). Further reduction in L_1 causes a reduced variation in the imaginary part of the input impedance. Therefore, the optimum value is $L_1=0.2\ \lambda_0$.

The same approach is used for the study of length L_2, for fixed values $L_1=0.2\ \lambda_0$ and $Z_1=90\ \Omega$. The results are shown in Fig. 3(*b*) and indicate the best value $L_2=\lambda_0/60$, which provides a large range and linear variation of the imaginary part of the input impedance versus the graphene resistance.

The effect of the characteristic impedance Z_1 is shown in the Fig. 3(*c*), for fixed values $L_1=0.2\ \lambda_0$ and $L_2=\lambda_0/60$. The larger the characteristic impedance, the bigger the variation in the imaginary part of the input impedance. However, in our implementation, technological constraints set the minimum width of a microstrip line and, consequently, the characteristic impedance of 90 Ω was adopted.



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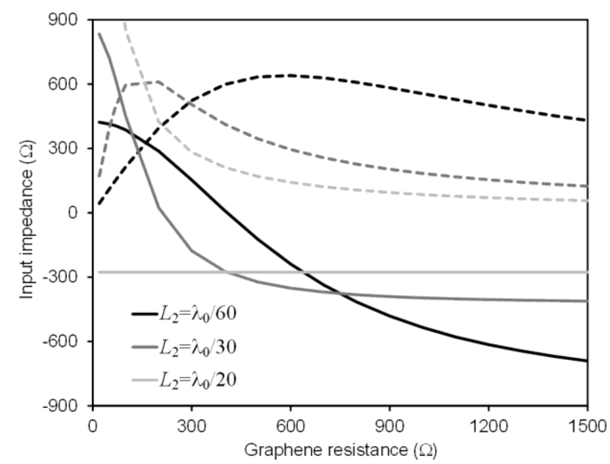

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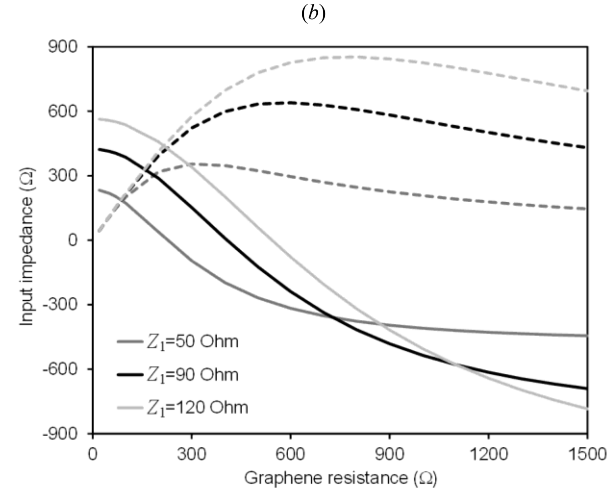


(*c*)

Fig 3. Variation of the input impedance of the stub versus the resistance of the graphene pad at 5 GHz (dashed line correspond to the real part of the input impedance Z_{in}, and solid lines denote the imaginary part): (*a*) For different values of L_1 (with $L_2=\lambda_0/60$, $Z_1=90\ \Omega$); (*b*) For different values of L_2 (with $L_1=0.2\lambda_0$, $Z_1=90\ \Omega$); (*c*) For different values of Z_1 (with $L_1=0.2\lambda_0$, $L_2=\lambda_0/60$).

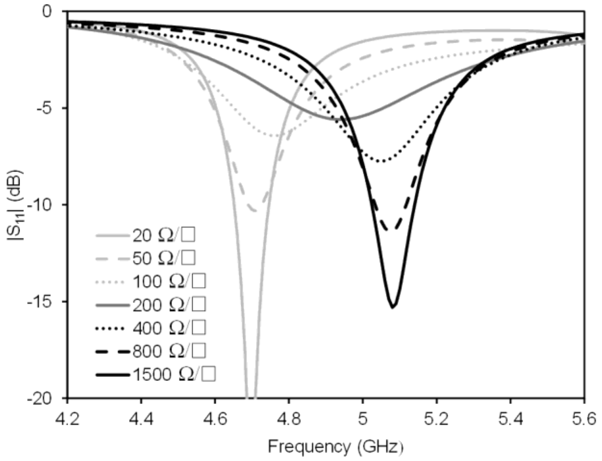


Fig 4. Scattering parameter $|S_{11}|$ of the antenna versus frequency, for different values of the graphene sheet resistance ρ.

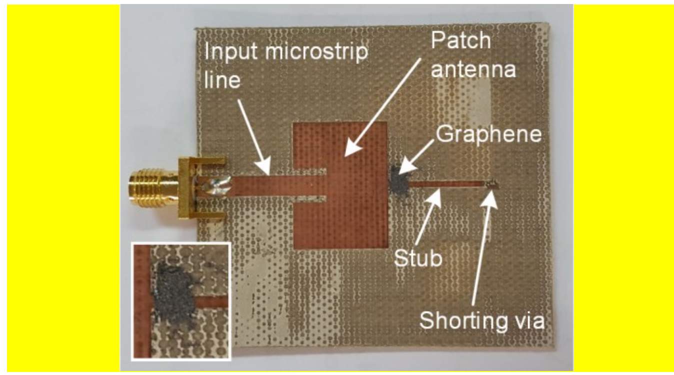
B. *Design of the patch antenna*

Starting from the optimal geometry of the shorted microstrip stub determined in the previous section, the complete antenna was optimized by using the commercial solver Ansys HFSS, based on the finite element method (FEM). In the simulations, the graphene pad was modeled as an infinitely thin resistive pad with a sheet resistance ρ (Ω/☐). The simulations were performed for a range of different values of ρ assigned to the graphene flakes, along the lines of [4].

The substrate of the antenna is a Taconic RF-35 dielectric substrate with thickness h=1.52 mm, permittivity ε_r=3.5, loss tangent tan δ=0.0018, and metal thickness t=35 µm.

The antenna was designed to resonate at the frequency of 5 GHz, thus resulting in a patch width A=20 mm and length B=15 mm (Fig. 1). The antenna is fed through a 50-Ω microstrip line of width w_m=3.26 mm, with inset dimensions 5.25 mm×1.00 mm. The stub is placed on the radiating edge, and has width, w=1 mm, corresponding to a characteristic impedance of 90 Ω. The other dimensions of the stub are L_1=12 mm and L_2=1 mm. The stub is shorted to the ground plane on one end through a via with diameter d=1 mm. The nominal dimensions of the graphene pad are g=0.66 mm and w=1 mm (Fig. 2(a)).

Fig. 4 shows the scattering parameter $|S_{11}|$ of the antenna versus frequency, for different values of the graphene sheet resistance ρ. As expected, changing the resistance of the graphene modifies the input impedance of the stub, thus shifting the resonance frequency of the antenna. In particular, when the graphene resistance is high, the stub is practically void, whereas, when the graphene resistance decreases, the presence of the stub decreases the resonance frequency of the patch antenna. As shown in Fig. 4, the antenna operates at the frequency of 5.08 GHz when the graphene sheet resistance is ρ=1500 Ω/☐, and decreases to 4.7 GHz when the graphene sheet resistance is ρ=20 Ω/☐. The resulting overall frequency shift is 380 MHz.



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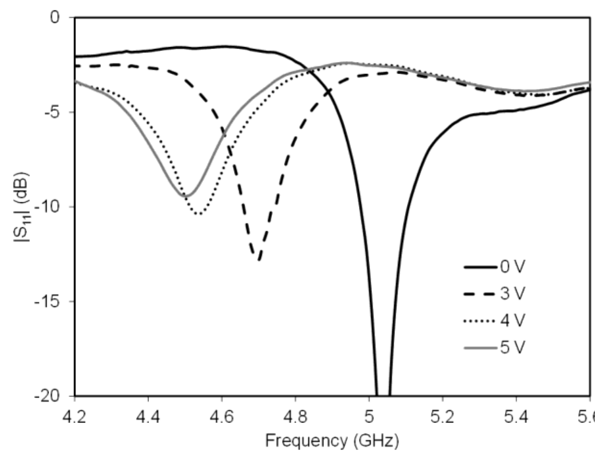


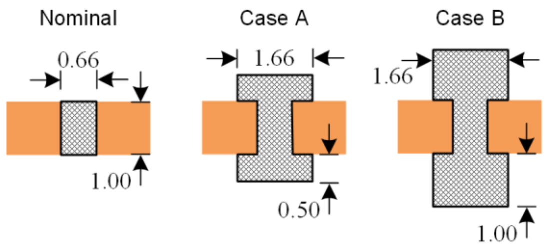
(*b*)

Fig 5. Experimental verification of the tunable patch antenna: (*a*) Prototype of the antenna, with detail of the graphene pad in the inset; (*b*) Scattering parameter $|S_{11}|$ of the antenna versus frequency, for different values of bias voltage.

III. EXPERIMENTAL VALIDATION

In order to verify the performance of the graphene-based tunable patch antenna, a prototype was fabricated as shown in Fig. 5(*a*). The fabrication of the antenna was performed using an LPKF micro-milling machine, and FLG flakes were deposited in the gap of the microstrip stub, according to the procedure described in [4]. This type of FLG flakes exhibit a tunable sheet resistance, depending on the applied bias voltage. The sheet resistance usually ranges from more than 1000 Ω/☐ (with zero bias voltage) to few tens of Ω/☐ (with bias voltage of 5 V to 6 V), as discussed in [4], [5]. The biasing of graphene was performed by using a broadband commercial bias tee, connected between the port of a Vector Network Analyzer (VNA) and input microstrip line of the antenna. In this way, the bias voltage was applied between the ground plane and the patch antenna itself, in such a way that the voltage resulted across the graphene pad.

The measured results of the scattering parameter $|S_{11}|$ of the antenna versus frequency are shown in Fig. 5(*b*), for different values of the bias voltage. The measured shift of the resonance frequency of the antennas is 550 MHz, from the frequency of 5.05 GHz at the bias voltage of 0 V to the frequency of 4.50 GHz at a bias voltage of 5 V.



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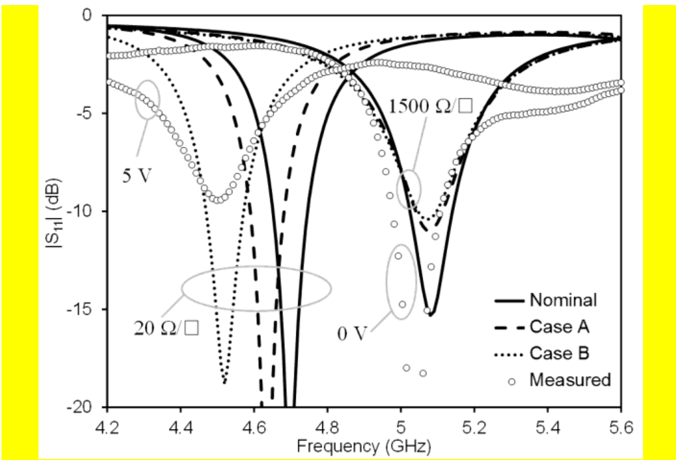

(*b*)

Fig 6. Post-fabrication simulation: (a) Geometry of the considered cases; (*b*) Frequency response of the antenna for different graphene pad size, compared to measured results.

This shift in the radiating frequency is larger than the one obtained from the simulations in Fig. 4. This effect can be attributed to the deposition of graphene, which exceeds the nominal dimensions, as shown in the inset of Fig. 5(*a*).

Post-fabrication simulations were performed to estimate the effect of the geometrical variation of the graphene pad. Two different cases were considered, besides the nominal one (Fig. 6*a*). A larger size of the graphene pad results in lower resistance value, and consequently in a larger frequency shift. Fig. 6*b* shows that, with a greater graphene deposition size, the simulated frequency shift equals the one obtained in the measured results.

Finally, the antenna gain was measured, with different values of bias voltage. The measurement was performed by using an ultra-wideband antenna and a standard-gain antenna. The network analyzer was pre-calibrated at the end of the bias-tee. Tab. I compares the simulated antenna gain for different values of the graphene sheet resistance to the measured antenna gain for different values of bias voltage. Cases with a similar operation frequency of the antenna are compared. The antenna gain decreases when increasing the bias voltage (in the measurement) or when decreasing the graphene resistance (in the simulation). The gain decrease is due to the power dissipated by the graphene pad, which is larger when the bias voltage increases and consequently the sheet resistance decreases. The simulated efficiency ranges from 58% with high resistance to 26% with low resistance.

TABLE I
SIMULATION AND MEASUREMENT OF THE ANTENNA GAIN

Simulation			Measurement		
Sheet resistance (Ω/□)	Frequency (GHz)	Gain (dB)	Voltage (V)	Frequency (GHz)	Gain (dB)
1500	5.08	4.50	0	5.05	2.38
150	4.77	0.95	3	4.69	1.18
20	4.52	0.02	5	4.50	0.76

IV. CONCLUSION

A novel voltage-controlled tunable patch antenna has been presented in this paper. The tunability is obtained by adopting a pad of few-layer graphene flakes at the input of a shorted microstrip stub. The effect of the tuning stub has been investigated in detail, and the design of the antenna has been presented. Experimental results have shown an antenna with tunability range from 5.05 GHz (with zero bias voltage) to 4.50 GHz (with bias of 5 V). The antenna exhibits a limited gain degradation versus the bias voltage.

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