Graphene-Controlled Reconfigurable Patch Antenna Using Shorting Elements

A. Lovascio¹, V. Centonze², A. D’Orazio¹, M. Grande¹

Abstract – This paper reports the design of a patch antenna that uses graphene-based shorting elements to implement advanced functionalities, such as multi-band and beam-steering, which make it extremely attractive for the future Fifth-Generation (5G) wireless networks. The proposed structure has 36.75×29.25 mm² size and it has been designed on a Rogers RT/duriod 5880 substrate, 1.58 mm thick. It is composed by an external slotted rectangular patch that contains an internal circular shape. The internal shape is separated from the external one by a circular slot but it is linked to it by four copper bridges short-circuited to the underlying ground plane through a thin metal pin, one for each bridge. It has been shown that the multi-band and the beam-steering functionalities are strongly affected by the geometric location of the shorting pins. By controlling the connection of the bridges perpendicular to the antenna length, the direction of the antenna main lobe can be changed. By using the Finite Element Method (FEM), the geometric location of the shorting pins has been optimized so that the antenna resonates at 3.5 GHz frequency, exhibiting a 6.6 dBi maximum gain and a -17.55 dB S11 parameter. Moreover, by controlling electronically the connection of the shorting elements using graphene foils, three distinct beams, steering between -22 to +22 degrees, have been obtained. The beams show about 1.4 dBi theoretical antenna gain using graphene foils with 20 Ω/sq sheet resistance. Copyright © 2020 The Authors.

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Keywords: Beam Steering, Multi-Band Patch Antenna, Graphene, Shorting Pins, Fifth-Generation (5G)

I. Introduction

The 5G wireless networks represent the future of the telecommunication. In the last years, many mobile multimedia services that have led to an exponential increase in throughput and bandwidth demand have been developed [1]. Since the current 4G technology cannot sustain such a demand, research efforts have been focused on the improvement of the network infrastructure in order to allow the 5G applications to have a real impact on the society. In this scenario, the propagation losses, the scattering and the interferences in wireless networks define the main bottlenecks since 5G applications are pushing towards higher operating frequencies (where higher bandwidth will be available) in order to satisfy the throughput demand. High bandwidths are a mandatory step in to target the connectivity goals that aim to achieve tens of Gigabits per second [2]. In order to solve the issues regarding higher propagation losses, one of the hottest research fields regards the so-called smart antennas. The antennas are designed to have new and attractive features, such as multi-band, wideband, and beam-steering capability. The general idea is to optimize the connectivity between the radio base station and the end-user (e.g. smartphone) by pointing the maximum antenna gain along the line-of-sight of two communicating systems. In this way, the power transmission will be maximized in such a

Nomenclature

4G Fourth-Generation
5G Fifth-Generation
D Antenna bridge width [mm]
f Resonance frequency [GHz]
E Electric field vector [V/m]
FEM Finite Element Method
J Current density vector [A/m]
L Antenna length [mm]
PEC Perfect Electric Conductor
Rin Radius of the antenna inner shape [mm]
Rout Outer radius of the antenna circular slot [mm]
RS Graphene sheet resistance [Ω/sq]
SOCl₂ Thionyl chloride
Sxx Scattering parameter [dB]
σ Graphene conductivity [Ω⁻¹]
W Antenna width [mm]
Xobj Position of an object on the antenna along the X-axis [mm]
Yobj Position of an object on the antenna along the Y-axis [mm]
direction, and the interference with other neighboring wireless systems will be reduced [3]. Recently, different configurations that implement such features have been proposed. Ultra wideband [4]-[8] and multi-band [9]-[11] antennas have been reported in literature for different applications, which are also suitable for 5G networks.

Moreover, antennas with beam-steering property have been proposed based on antenna arrays combined with reconfigurable systems, such as mechanical rotations [3], lens [12] and phase shifters as the Blass matrices [13], [14]. In this paper, an innovative configuration of a patch antenna assisted by graphene-based shorting elements, which realize the beam steering exploiting the tuning properties of graphene, is proposed. Metallic shorting elements, as the shorting pins, in microstrip antennas have been widely studied: they have been exploited for instance to enhance the gain and directivity [15], to decrease the size at lower frequencies [16], [17], to realize dual-band antenna [18], [19] or multi-band [20].

However, no solutions have been proposed to control the radiation direction in the microwave regime using graphene foils. The ability to integrate graphene, a two-dimensional allotrope of carbon [21], into devices has attracted great attention in recent years due to its enormous potential as a mean of achieving the dynamic control of the electromagnetic response [28]. Graphene has been widely exploited for the realization of amplitude or phase modulation in the microwave, THz and near-infrared ranges [22]-[27]. In the microwave regime, graphene has been successfully exploited to realize several proof-of-principle devices spanning from optically transparent polarizers [28], microwave absorbers [29]-[33] to antennas [34]-[36]. The antenna proposed in this paper has been optimized to resonate at 3.5 GHz (frequency exploited in 5G networks). It exhibits multi-band behavior when three or four shorting pins are used. Moreover, the presence of graphene-based elements in the antenna configuration allows controlling electrically the beam direction.

The paper is organized as follows. In Section II, the design of the patch antenna has been described by comparing the performance of three-pin and four-pin configurations. In Section III, the beam-steering capability of the antenna and the graphene-based solution is discussed.

II. Shorting Elements-Based Antenna Design

The proposed patch antenna is composed of two different geometrical elements: an external slotted rectangular patch that contains inner circular slots. The two patches are connected along X-axis direction by a conductive bridge (width equal to D) short-circuited to the ground plane through a thin metallic pin. In authors’ previous paper [37], two different configurations have been analyzed: the former with only one pin in the antenna geometry; the latter having two pins. It has been showed that the antenna performance, especially in terms of impedance matching and irradiating frequency, has been sensitive to the location and the geometry of the pins while the feeding probe had a weak influence on the impedance matching. The one-pin antenna has showed dual-band capability at 2.24 GHz (lower resonance frequency) and 8.11 GHz (higher resonance frequency), and it has exhibited the following figures of merit:

- Reflection coefficient at lower resonance: -19.05 dB;
- Reflection coefficient at higher resonance: -29 dB;
- Maximum antenna gain at lower resonance: 7.02 dBi;
- Maximum antenna gain at higher resonance: 6.55 dBi.

However, the capability of the antenna to become single-band when a second pin was introduced in the geometry has been observed. Therefore, the presence/absence of the further conducting pins can change the number of resonances introducing several features to the already excellent performance of the antenna. In this paper, a patch antenna exploiting three and four shorting pins integrated with copper elements is considered. The antennas have been designed considering a Rogers RT/duroid 5880 substrate, 1.58 mm thick. The substrate has 64x57 mm² size for the antenna with three shorting pins while a footprint of 67x60 mm² for the one with four shorting pins. The antennas have been numerically simulated in COMSOL Multiphysics using the Finite Element Method (FEM) on a wideband frequency region (1-10 GHz). The metallic parts of the antenna have been modelled as Perfect Electric Conductors (PECs). In order to optimize the numerical simulations, two different calculation domains have been implemented. In 1-4.8 GHz frequency range, the simulations have been performed in a spherical calculation domain with a 100 mm radius, implementing a 20 mm thickness Perfect Matched Layer on the borders. In 4.9-10 GHz frequency range, a cylindrical-shape calculation domain of 60 mm height and of 65 mm diameter has been adopted, and a 10 mm thickness Perfect Matched Layer has been used. For both domains, an extremely fine mesh has been adopted for the entire electromagnetic model, setting to 0.7 mm the maximum element size of the mesh only for the antenna top footprint. In this way, the accuracy of the result has been maintained reducing at the same time the computation time. Regarding the frequency discretization, the whole range from 1 to 10 GHz has been simulated with 100 MHz step, refining the simulation with 40 frequency points on a 200 MHz range around on two lower frequency resonances, and with a 10 times smaller frequency step (10-20 MHz) for the higher frequency resonance.

II.1. Three-Pin Antenna Design

Fig. 1(a) depicts the first configuration based on the patch antenna with three shorting pins and three slots.

This antenna has been designed by setting \( L = 36.75 \) mm, \( W = 29.25 \) mm, \( R_1 = 7.4 \) mm, \( R_2 = 11.3 \) mm, \( D = 2.75 \) mm, \( X_1 = -9.5 \) mm (first pin position along X-axis),
$X_{pin}=12$ mm (second pin position along X-axis), $Y_{pin}=12$ mm (third pin position along Y-axis), $R_{pin}=1$ mm (pin radius, equal for all three pins), $X_{feed}=-1.5$ mm (feeding probe position along X-axis). The footprint is about 9% smaller than the one reported in [37], i.e. 36.75×29.25 mm$^2$. The antenna exhibits a three-band behavior, irradiating at 2.187 GHz ($S_{11}=-12.75$ dB), 3.492 GHz ($S_{11}=-17.55$ dB) and 9.4 GHz ($S_{11}=-35.72$ dB) resonance frequencies, as shown in Fig. 1(b). In Figs. 2 and Fig. 3, the radiation pattern for all the resonance frequencies is shown expressed in terms of E-plane (XZ-plane) and H-plane (YZ-plane). In Figs. 4, the maximum antenna gain as function of the frequency is depicted. Figs. 2 show that the radiation pattern at the 3.492 GHz frequency is strongly affected by the location of the third pin since the main lobe direction of the E-plane radiation pattern changes according to the position of the third pin and bridge. In particular, an inclination of about $+/-22$ degrees in the E-plane radiation pattern has been observed when the third pin is placed at $Y=+12$ mm and $Y=-12$ mm, respectively. The total maximum antenna gain is 6.6 dBi for both configurations. The antenna also exhibits a higher resonance frequency at 9.4 GHz with a 2D radiation pattern shown in Fig. 3. The maximum antenna gain at this frequency is equal to 9.83 dBi regardless of the position of the third pin since the current distribution is mainly concentrated in the inner circle.

Figs. 1. Patch antenna with three shorting pins: (a) geometry. (b) Computed scattering parameter $S_{11}$

Figs. 2. Three-pin antenna radiation pattern computed at 3.5 GHz resonance frequency when the third pin position is at (a) $Y>0$ and at (b) $Y<0$

Fig. 3. 3D radiation pattern at 9.4 GHz computed for the three-pin patch antenna
II.2. Four-Pin Antenna Design

Fig. 5(a) depicts the patch antenna with four metallic shorting pins. It has been designed by setting $L=40.75$ mm, $W=33.25$ mm, $R_{in}=7.4$ mm, $R_{out}=13.3$ mm, $D=2.75$ mm, $X_{pin1}=-11$ mm (first pin position along X-axis), $X_{pin2}=14$ mm (second pin position), $Y_{pin3}=14$ mm (third pin position), $Y_{pin4}=-14$ mm (fourth pin position) $R_{pin}=0.9$ mm, $X_{feed}=-1.5$ mm.

The four-pin configuration allows the antenna to have a three-band behavior, irradiating at 2.43 GHz ($S_{11}=-22.22$ dB), 2.83 GHz ($S_{11}=-18.76$ dB) and 8.51 GHz ($S_{11}=-33.42$ dB) as shown in Fig. 5(b). In this case, the introduction of a fourth pin lowers the distance of the two lowest peaks to 400 MHz (the difference in frequency is related to the asymmetry of the pins along the X-axis direction that is necessary to achieve impedance matching). At the same time, these peaks are originated by the two halves of the external rectangular patch as demonstrated by the current density shown in Fig. 6. The two resonant modes irradiate providing a good radiation efficiency and impedance matching. The reflection coefficient is less than -10 dB for both frequencies.

Figs. 4. Maximum realized antenna gain as function of lower frequencies (a) and higher frequencies (b) computed for the three-pin patch antenna

Figs. 5. Patch antenna with four shorting pins: (a) geometry; (b) computed scattering parameter $S_{11}$

Fig. 6. Computed current density absolute magnitude (A/m$^2$) of the four-pin patch antenna at 2.43 GHz (left image) and 2.83 GHz (right image)

Figs. 7 depict the 2D patterns that show a total maximum antenna gain equal to 4.44 dBi, 6.31 dBi and 9.46 dBi computed at 2.43 GHz, 2.83 GHz, and 8.51 GHz, respectively. The E-plane computed at lower resonances, i.e. 2.43 GHz (Fig. 7(a)) and 2.83 GHz (Fig. 7(b)) is perfectly matched with the one expected by a patch antenna.

The H-plane shows an inclination of the main lobe caused by the asymmetry in the current density, i.e. the two halves shown in Fig. 6. Since these two halves of the rectangular patch create the resonances at lower frequencies, the main lobe direction at these frequencies is oblique with an angle of about 45 degrees for the 2.43 GHz and 15 degrees for the 2.83 GHz frequency with respect to the YZ-plane.
has been also computed and depicted in Figs. 8. In conclusion, the three-pin and the four-pin antennas show similar performance, as summarized in Table I.

Moreover, both antennas exhibit multi-band capability with three different resonances. However, the three-pin antenna is more attractive because the main lobe direction depends on the third pin position and the corresponding bridge respect to the X-axis as shown in Figs. 2. No similar behavior has been observed for the four-pin antenna.

The inclination is symmetrical respect to the Y-axis, thus the maximum gain mainly points along the direction opposite to the plane YZ that defines also the symmetry of the antenna. The difference in the value of the antenna gain and the resonance frequency is likely because the first pin is still inside the bridge, a necessary condition to avoid the arising of the unwanted spurs on the reflection coefficient. In order to complete the analysis, the maximum realized antenna gain as function of frequency

### Table I

**Performance Comparison of the Antennas**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Three-pin</th>
<th>Four-pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>First resonance ($f_1$)</td>
<td>GHz</td>
<td>2.187</td>
<td>2.431</td>
</tr>
<tr>
<td>Second resonance ($f_2$)</td>
<td>GHz</td>
<td>3.492</td>
<td>2.834</td>
</tr>
<tr>
<td>Third resonance ($f_3$)</td>
<td>GHz</td>
<td>9.4</td>
<td>8.51</td>
</tr>
<tr>
<td>$S_{11}$ at $f_1$</td>
<td>dB</td>
<td>-12.75</td>
<td>-22.22</td>
</tr>
<tr>
<td>$S_{11}$ at $f_2$</td>
<td>dB</td>
<td>-17.55</td>
<td>-18.76</td>
</tr>
<tr>
<td>$S_{11}$ at $f_3$</td>
<td>dB</td>
<td>-35.72</td>
<td>-33.42</td>
</tr>
<tr>
<td>Max. antenna gain at $f_1$</td>
<td>dBi</td>
<td>6.6</td>
<td>6.31</td>
</tr>
<tr>
<td>Max. antenna gain at $f_2$</td>
<td>dBi</td>
<td>9.83</td>
<td>9.46</td>
</tr>
<tr>
<td>Max. antenna gain at $f_3$</td>
<td>dBi</td>
<td></td>
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</tbody>
</table>

Figs. 7. 2D radiation pattern of the four-pin patch antenna computed at 2.43 GHz (a), 2.83 GHz (b) and 8.51 GHz (c). The beamwidth on the H-plane is about 170 degrees at 2.43 GHz, 75 degrees at 2.83 GHz and 55 degrees at 8.51 GHz.

Figs. 8. Maximum realized antenna gain as function of lower frequencies (a) and higher frequencies (b) computed for the four-pin patch antenna.
III. Beam-Steering Capability Based on Graphene

In this section, it is discussed how to achieve beam-steering exploiting graphene-based shorting elements in the three-pin antenna configuration. Recent studies have shown that combining the use of thionyl chloride (SOCl₂) chemical doping and multilayer graphene, it is possible to control the sheet resistance so that the graphene is in a quasi-metallic region and acts as an optically transparent metal [28].

Combining such a property with the voltage-dependency of the graphene conductivity [30], an innovative reconfigurable antenna based on the three-pin patch antennas depicted in Figs. 2 has been designed. In this configuration, the copper bridges and their electrical connections to the ground plane have been substituted with graphene foils.

The graphene capability to operate in both quasi-metallic and lossy-dielectric region [28] has been exploited to control the direction of the maximum antenna gain.

The beam steering is obtained by controlling the graphene sheet resistance that can be reduced by applying a sufficient voltage across the graphene foils. If the sheet resistance is reduced such that it is smaller than the critical value (ηc/2 with ηc corresponding to the impedance of free space), the graphene enters in the quasi-metallic region and behaves like a conductor replicating the behavior of the copper. In this paper, a graphene sheet resistance range from 20 (quasi-metallic) to 6000 Ω/sq (lossy dielectric) has been considered. The proposed solution is depicted in Figs. 9.

Four graphene foils are foreseen: two for the tuning of the bridges on the top patch (Fig. 9(a)) and two for the pin islands on the bottom ground plane (Fig. 9(b)) to control its electrical connection with the top bridges. Such antenna configuration allows three possible states:

- Irradiation of the three-pin antenna (case of Fig. 2(a), Y>0) by applying a voltage on the graphene bridge and island in the Y>0 section of the antenna;
- Irradiation of the three-pin antenna (case of Fig. 2(b), Y<0) by applying a voltage on the graphene bridge and island in the Y<0 section of the antenna;
- Irradiation of the four-pin antenna by applying a voltage to both graphene bridges and islands in the Y>0/Y<0 sections of the antenna.

The proposed graphene-based antenna has been implemented in COMSOL modeling the graphene foils using the aforementioned experimental values of the sheet resistance.

Such values of the sheet resistance affect the antenna performance since it impacts on the electric field according to the Ohm Law (1):

\[ J = \sigma E \quad (1) \]

where \( \sigma \) is the graphene conductivity (\( \sigma = 1/R_s \)). The area of the top foils is 2.4x2.75 mm² (its width is equal to the bridge width) while the size of the ones on the ground plane is 3x3 mm². Fig. 10 depicts the simulation results showing the 3D radiation pattern at 3.5 GHz. When a voltage is applied, i.e. when the sheet resistance is changed for example from 30 to 6000 Ω/sq, the antenna behaves like the two three-pin antennas shown in Fig. 2, proving the beam-steering capability as a function of the sheet resistance.

A correlation between the maximum antenna gain and the sheet resistance can be seen. Respect to the case shown in Figs. 2 (where the metal has been modeled as PEC), the gain is decreased to about 0 dBi. This reduction can be justified by considering the finite value of the graphene conductivity.

The antenna gain can be increased up to 1.41 dBi when the sheet resistance is 20 Ω/sq. Finally, Fig. 11 compares the S-parameters evaluated when the sheet resistance of the graphene equal to 20 and 30 Ω/sq is assumed.

The plot shows that the scattering parameter \( S_{11} \) is not affected by the change of the sheet resistance of the graphene at 3.5 GHz while the two curves differ at higher frequencies (e.g. 4.1 GHz).

\[ S_{11} \]

Figs. 9. Proposed solution for the graphene-based antenna: (a) top view; (b) bottom view
Fig. 10. 3D radiation patterns (top view) computed at 3.5 GHz. Left patterns are generated when voltages are applied on graphene foils in Y>0 sections; right ones when voltages are applied on graphene foils in Y<0 sections. The voltage application has been simulated by modifying the graphene sheet resistance from 30 to 6000 Ω/sq (two top images) and from 20 to 6000 Ω/sq (two center images). Two bottom images show the current distribution (top view) after the application of the voltage.

Fig. 11. Graphene-based antenna S_{11} parameter computed for 20 (blue curve) and 30 Ω/sq (green curve) sheet resistance.

IV. Conclusion

In this paper, the design of a graphene-controlled reconfigurable antenna, which exploits three and four shorting pins, has been reported. It has been shown that the shorting pins give the antenna new features such as multi-band and beam-steering. Both antennas exhibit a multi-band behavior. However, the three-pin antenna has also the beam-steering capability that depends on the shorting elements, especially the third pin location. A steering of about 22 degrees in terms of radiation pattern orientation has been demonstrated. The electronic control of the beam has been obtained using graphene foils for the shorting elements. A solution that implements the presence/absence of the third shorting pin by controlling its electrical connection to the ground plane has been discussed. Two 2.4x2.75 mm² graphene foils have been used for the top bridges and two 3x3 mm² graphene foils have been used on the ground plane. Through numerical simulations, the beam-steering operation obtaining 1.41 maximum antenna gain when the graphene sheet resistance is fixed equal to 20 Ω/sq has been shown. The antenna gain could be further increased by gaining more knowledge about the graphene. As demonstrated, the antenna gain depends on the graphene size and the sheet resistance, therefore the possibility to improve the graphene doping and growth will in turn improve the antenna performance. At the same time, the proposed approach could be applied in different configurations in order to increase the number of beam directions or to control the beam width. The presented antenna could be suitable for the 5G applications thanks to its reconfigurable behavior introduced by the presence of graphene sheets. The exceptional property of this material and the innovative proposed antenna configuration could help to overcome the limitations related to the propagation losses, interferences, and so on, that will be the new challenges of the future 5G networks.

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