Gain-Reconfigurable Hybrid Metal-Graphene Printed Yagi Antenna for Energy Harvesting Applications

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***Abstract*—This paper presents a hybrid metal-graphene printed Yagi antenna with reconfigurable gain that operates in the 5.5-GHz band. The balun and the driven elements are made of copper, while the directors are made of graphene. The graphene acts as a tunable material in the design. By switching the conductivity of the graphene, it is achieved a similar effect to adding or subtracting directors in the antenna. Hence the gain of the printed Yagi can be easily controlled. This could be of special interest in RF energy harvesting in the design of reconfigurable harvesting elements.**

***Index Terms*—Graphene, Yagi antenna, tunable material, energy harvesting, reconfigurability.**

I. Introduction

The progressive global increase over time in the number of radiofrequency (RF) transmitters has increased the level of available spectral power in the environment. Subsequently, RF energy harvesting has turned into a feasible power supply and many low-power applications have taken advantage of it [1]. In a scenario where the location of the radiating source is known, the antenna gain should be increased in order to optimize the acquired power. Thus, the power delivered from the antenna to the nonlinear conditioning circuit is higher and the rectifying efficiency is therefore increased. Some authors take this approach in the design of the harvesting element. For instance, making use of directional Yagi-Uda antennas [2], [3]. On the other hand, it is preferable to treat with omnidirectional antennas if the location of the source is unknown or there are many equally distributed sources. This is how the authors of [4] – [6] try to assure that no spatial direction prevails in their designs of the harvesting element. The use of tunable materials [7] such as ferroelectrics, liquid crystal or graphene can play an important role in this issue. With them, not only the antenna gain can be controlled to maximize the power acquisition, but the operation frequency or any other radiation parameter in the antenna.

Graphene is called to be one of the most promising tunable materials. It is a planar monoatomic layer of carbon atoms densely packed into a hexagonal pattern [8]. It is included into the group of 2-D materials, such as insulating hexagonal boron nitride (h-BN) or black phosphorus (BP) [9]. The atomic scale and uniform thickness (~0.5 nm) in each layer of 2-D materials allows the production of flexible and transparent electric and optoelectronic devices [10], [11]. Generally, graphene antennas have been mainly studied for use in submillimeter and infrared frequencies [12] – [14] since the antenna area that must be covered with graphene is more reduced. Nevertheless, the authors of [15] have studied the properties of graphene for wireless wearable communication applications from 1 to 5 GHz. They have tested graphene in flexible printed transmission lines and in microwave on-body wearable antennas, showing excellent results.

Fully made graphene antennas are expected to have low antenna efficiencies and reduced reconfigurability [16], [17]. Thus, the authors of [18] introduce the design proposal of hybrid metal-graphene antennas in terahertz frequencies in order to reduce ohmic losses. The area covered by graphene is reduced and the reconfigurability in the antenna is maintained. Afterwards, the authors of [19], [20] transfer the idea to the microwave LTE and WiFi bands. In the first paper, they design a microstrip patch with graphene extensions. Thus, the operation frequency in the antenna can be easily controlled. In the second paper, they control the polarization (circular and linear) of a squared patch by switching on or off a few graphene strips located in the four corners of the antenna. Both studies are further developed in more detail in [21].

The document is organized as follows: Section I introduces the topic and reviews recent advances on graphene reconfigurable antennas. Section II depicts the design of the hybrid metal-graphene printed Yagi antenna. Section III shows some interesting results that verify the reconfigurability of the antenna. Finally, conclusions are drawn in Section IV.

II. Global Design

The structure and the different layers that conform the hybrid metal-graphene printed Yagi antenna are shown in Fig. 1. Typically, a Yagi-Uda antenna is formed by three elements [2]-[3], [22]: the reflector, the driven element and the directors. In our particular design, the driven element and the directors are half-wave printed dipoles. The driven element is made of copper and is fed through a half-wave printed balun in order to balance the currents. The directors are made of graphene and they can be switched between the ON and OFF states according to the applied polarization voltage V. Therefore, the gain of the antenna can be simply

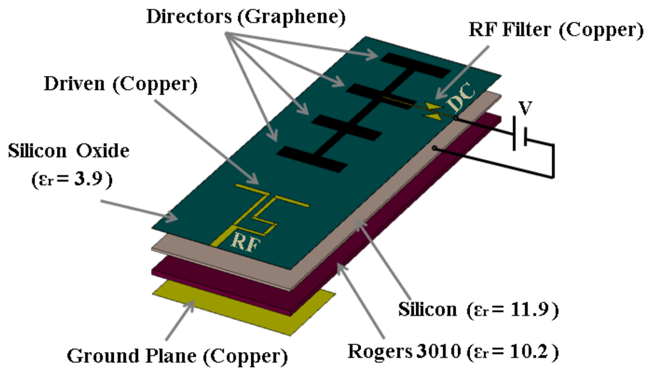


Fig. 1. Hybrid metal-graphene printed Yagi antenna and its layers.

controlled. A RF filter, formed by a high-impedance line with two radial stubs, separates DC polarization signals from the RF signals in the antenna. To ease the design of the bias circuit, all directors are physically connected. Hence, they are either switched on or off at the same time (2 bits).

The voltage V that is necessary to polarize the graphene is proportional to the separation between the graphene strips and the copper ground plane [21]. Thus, the substrate of the antenna (Rogers 3010) leads to an elevated bias voltage. To reduce it, a silicon sheet is placed over the substrate. The silicon acts as the ground plane for the polarization (DC) of the graphene and does not modify the effective permittivity of the antenna. Additionally, a very thin silicon oxide sheet (SiO_2) is placed in between to prevent silicon oxidation.

The placement of these two additional layers can hinder the design of the antenna, but this can be easily solved by taking into account the effective permittivity of a single equivalent layer. However, there are two interfaces through which the electric field must cross from the copper/graphene strips towards the ground plane. The higher the difference in permittivity between the media, the higher the amplitude of the reflected wave. Thus, a 1.28 mm high-permittivity Rogers 3010 ($\varepsilon_r = 10.2$) is placed as the antenna substrate to improve the transmission and to subsequently increase the radiation efficiency. Conversely, nothing can be done in the silicon-silicon oxide boundary. Fortunately, the height of the silicon oxide foil (< 100 nm) is much smaller than the silicon sheet.

A. Balun and Driven Dipole

As briefly discussed before, it is necessary to balance the currents in order to feed the dipole. A phase shift of 180 degrees between the arms of the dipole can be obtained by extending one arm of the balun half wavelength more than the other. This fact can be noticed in Fig. 2, where the reddish tone in the color plot indicates a positive phase and the bluish one a negative phase of opposite sign. Once the phase difference has been achieved in the balun, the ground plane must be cut off a little before reaching the dipole, as shown in Fig. 2. This is how the odd mode is properly excited.

The large difference in the effective permittivity of the substrate ($\varepsilon_r \approx 11$) with respect to the air surrounding the antenna causes a guiding effect on the wave, as can be seen

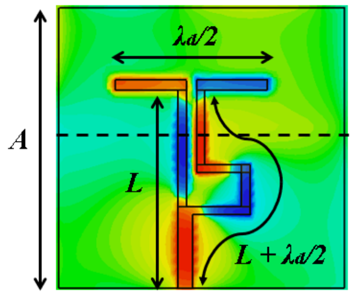


Fig. 2. Electric field distribution over the printed dipole and the balun. The dashed line delimits the ground plane size.

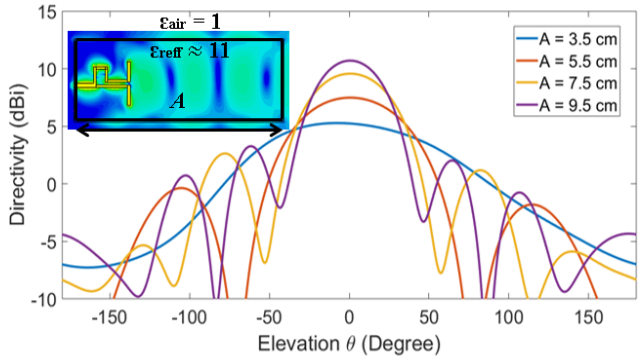
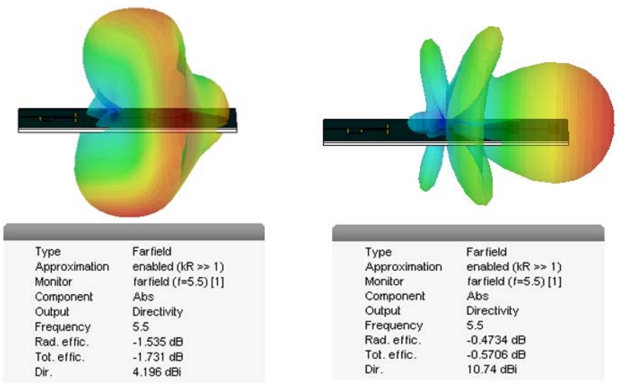


Fig. 3. Increased directivity as a result of extending the length of the antenna substrate *A*.

in the upper-left corner of Fig. 3. As a result, Fig. 3 illustrates how the directivity of the antenna increases 5 dBi by just extending the substrate 6 cm in length. This makes the effect of the directors in increasing the directivity to be minimal, regardless of the configuration of separations, lengths and widths they have. This is how the design of the printed antenna has taken an alternative path. It has been observed that the directors can act as reflective elements. Thus, the directivity of the metal-graphene Yagi can be considerably reduced if the size and position of the directors are optimized. All without a drastic reduction in the antenna efficiency.

III. Simulation Results

As discussed, the task of the directors is the inverse of the expected one in a Yagi antenna. Since the guiding effect cannot be avoided, the directors act here as reflective structures. They reduce the gain of the printed antenna in proportion to the conductivity of the graphene. When the graphene is polarized, its conductivity increases and it acts as a metal (copper), reflecting the incident wave and reducing the gain. When it is not polarized, its effect on the antenna is negligible and the antenna gain is fixed by the length A of the structure (Fig. 3). Hence, the gain is maximum in this case. For simplicity, in practice most authors use the concept of sheet resistance R_s (Ω/sq) instead of conductivity [21]. They are inversely related: the bigger R_s, the worse is the conductivity. The antenna shown in Fig. 1 has dimensions of 9.5 ×3.5 cm. Its radiation parameters have been tested in simulation for different values of graphene sheet resistance.



(a) (b)

Fig. 4. 3D farfield pattern as a function of the graphene sheet resistance: $R_s = 6$ Ω/sq (a) and $R_s = 2580$ Ω/sq (b).

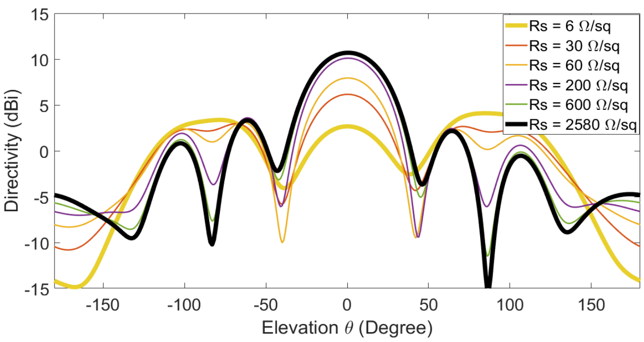


Fig. 5. Directivity as a function of the graphene sheet resistance for a cut in the plane $\varphi = 90$ degree.

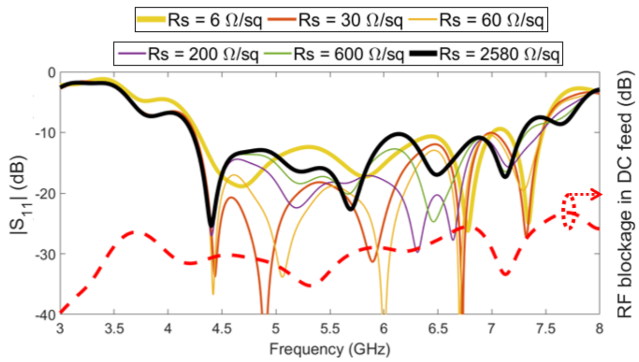


Fig. 6. Reflection coefficient as a function of the graphene sheet resistance and the RF blockage level in the DC bias point.

Thus, the 3D farfield is plotted in Fig. 4, showing the directivity and efficiencies of the antenna when the graphene acts as a good ($R_s = 6$ Ω/sq) and as a bad ($R_s = 2580$ Ω/sq) conductor. Despite the directors reflect the incident wave in order to reduce the Yagi gain, the efficiency of the antenna is over the 67 % in both cases.

In Fig. 5, we plot the directivity for a cut in the plane $\varphi = 90$ degrees. It can be seen that the maximum directivity (10.74 dBi) occurs when the graphene is not polarized. On the other hand, the directivity is minimum (2.67 dBi) when the graphene is polarized with an elevated voltage. If we set a bias voltage between both ends, any directivity value D ($2.67 < D < 10.74$ dBi) can be obtained. However, Fig. 5 shows that the highest variation in directivity is achieved for the lowest sheet resistance values ($6 < R_s < 200$ Ω/sq). From 200 Ω/sq onwards the range of variation in the directivity is minimum. Besides that, note that the main beam is splitted in three beams in Fig. 4a (and in the yellow line of Fig.5). This opens the possibility of doing beamforming if the position of the directors is modified. Fig. 6 presents the reflection coefficient and the RF filtering level (RF blockage) in the DC feed. As noticed, the antenna is well matched in all cases with a considerable operation bandwidth, and the RF signal is attenuated (RF filter) more than 26 dB when reaches the DC bias point (dashed red line in Fig. 6).

Considering all these results, prototypes are being manufactured for validation. These prototype results are expected to be presented in the conference.

IV. Conclusion

A novel hybrid metal-graphene printed Yagi antenna with reconfigurable gain has been presented. It has been discussed how the directors act as reflecting strips, reducing the antenna gain when they are properly polarized. Thus, the antenna gain can be controlled by switching on and off the graphene directors. In these conditions, the directivity of the antenna can vary between 2.67 dBi and 10.74 dBi, depending on the applied bias voltage. This is of great interest for RF energy harvesting, as the power acquired by the antenna can be maximized by choosing the appropriate gain for each scenario, for each spatial distribution of RF transmitters.

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