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Gain and phase control in a graphene-loaded reconfigurable antenna

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Abstract

We propose a reconfigurable scheme consisting of an antenna loaded by a CVD graphene capacitor. We show how the gated-graphene can actively control the antenna gain by about 2-3 dB and the phase of far-field electric field by about 45 degrees. The proposed idea could be efficiently adapted to antennas with different geometries and operating frequencies becoming transparent with respect to antenna technologies. We believe that these results clear a path towards graphene-based antenna systems for reconfigurable and smart telecommunication systems.

Introduction

Modern communications demand reconfigurable antennas that offer the possibility to control and modify: the radiation pattern, the polarization, and the desired frequency [1]. Several solutions have been explored in order to modify the radiation behavior of antennas such as RF-MEMS, PIN diodes, photoconductive materials, ferrites and liquid crystals [1]. In these cases, reconfigurable antennas modify the current distribution of the radiating element modifying the far-field response of the antenna itself. For example, Ref. [2] reports on a compact, semicircular slot antenna operating at 3.4 GHz (sub-6GHz range communications) able to switch between two circular polarization states by means of two PIN diodes.

On the other hand, phased arrays can control directivity, side-lobes, zeros (for unwanted signals) by engineering the Array Factor that multiplies the single antenna radiation pattern [3].

These systems rely on the amplitude and phase control of each single antenna. It is worth noting that these configurations require complex electronic circuits to control each single antenna in the array [3]. For example, in 2013, Samsung proposed a 32-element phased array that operates at 28 GHz [4] while Mitsubishi Electric Corporation and Nokia have developed an active phased array antenna prototype for multi-beamforming technology [5]. In 2016, researchers at the University of California, San Diego (UCSD) presented the first 60-GHz wafer-scale transmit phased arrays with 64- and 256-elements with a compact footprint [6].

Both reconfigurable antennas and phased arrays are at the basis of smart antennas where the hardware and algorithms are mixed together [7]. All these examples show how the control of amplitude and phase is crucial for upcoming communications technologies.

In this scenario, graphene finds interesting applications due to the ability to modify and tune its electromagnetic behavior, in both photonic and microwave ranges thanks to its pronounced electric field effect [8].

To date, graphene has been only proposed in numerical simulations for reconfigurable antennas where the graphene acts as conductive material for tunable antennas in the THz range showing tunable conductivity [9-11]. At the same time, a few examples envisioned graphene as a switch (variation of conductivity) for microwave and wireless antennas [12-14]. It is worth highlighting that these designs are based on theoretical assumptions/models and no experimental evidence are reported for the simulated conductivity.

In this regard, the present authors have experimentally demonstrated the possibility to tune the amplitude and phase of a ring resonator operating in the microwave range [15]. This static configuration showed the possibility to achieve amplitude and phase modulation. At the same time, we have recently experimentally demonstrated the possibility to realize a first prototype of optically transparent antenna exploiting highly doped CVD graphene as the conductive material [16] for large-area applications.

In this paper, we propose a different reconfigurable scheme where an antenna is loaded by a CVD graphene capacitor. In particular, we show how the electrolyte-gated graphene, in the double-layer capacitor, can actively control the gain and the phase of the far-field electric field. Without loss of generality, we consider a standard, patch antenna for GPS applications. This simple system allowed us to verify the idea of graphene-based gain and phase control on a mature antenna technology. At the same time, it also allowed us to test this approach on a large area CVD graphene. In particular, we analyze the antenna response in terms of: (i) reflection coefficient (scattering parameter S_{11}); and (ii) far-field behavior by considering the antenna gain and the phase of the electric field when the gate voltage of graphene-capacitor is changed in the electrochemical window.

It is worth noting that the proposed idea could be translated to higher frequencies, since graphene response at microwaves is frequency independent [17], and may also be combined with other antenna geometries and technologies taking also advantage of graphene optical transparency. In our view, this is a winning point of our scheme since the proposed configuration can be adjusted for the operating frequency becoming independent with respect to antenna technologies.

Results and discussion

Figure 1(a) shows the picture of the Global Positioning System (GPS) antenna loaded with the graphene capacitor. The GPS patch antenna operates in the L band. The double-layer capacitor is realized by sandwiching the electrolyte (thickness equal to 100 microns) between two bilayer (2L) graphene sheets that are supported by PET substrates. Further details on the graphene capacitor are reported here [18]. The size of the graphene area is larger than the GPS patch. In this configuration graphene sheets can be modelled as two boundary conditions introducing two sheet currents (J= σ*E, where σ=1/Rs, Rs is the sheet resistance [17]). Blue squares in Figure 1(b) shows the experimental sheet resistance of the front layer (the one close to the antenna,) while red dots refer to the back layer when the gate voltage V_g is varied. We can consider this symmetric behavior since two layers act in a similar way as demonstrated afterwards.

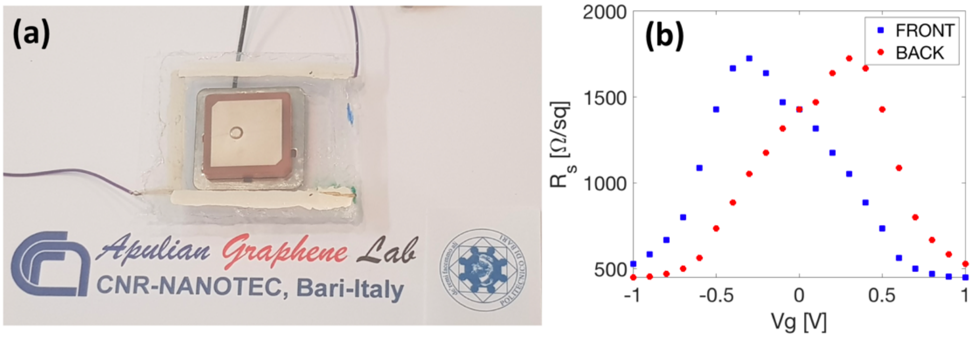

Figure 1: (a) Picture of the graphene-loaded GPS antenna. (b) Experimental sheet resistance of the front 2L graphene close to the antenna (blue dots) and of the back layer (red dots) when the gate voltage V_g is varied in the electrochemical window.

The scattering parameter S_{11} of the antenna was measured by means of a Vector Network Analyzer (Keysight N9923A FieldFox) as shown in Figure 2 (a). The gate voltage was increased from -1 V to +1 V, with a step of +0.4 V, and the scattering parameter S_{11} of the loaded antenna was measured at each voltage step. The plots reveal that for a null gate voltage, the S_{11} is about -25dB at 1.55 GHz. Scattering parameter S_{11} reaches about -18 dB and -32 dB when the gate voltage is equal to -1 V and +1 V, respectively. Over the electrochemical window there is an S_{11} variation of almost 15 dB. The minimum is slightly shifted of about 3 MHz from 1.554 GHz (f_{min}) down to 1.551 GHz, when the gate voltage is decreased from +1 V to -1 V. In this case, this asymmetric behavior can be explained by considering that the boundary conditions swap/switch with the inversion of the polarity. This behavior is translated in the variation of the phase of the scattering parameter S_{11} as displayed in Figure 2 (b). The phase is unchanged at the f_m (equal to 1.554 GHz) while the phase increases (decrease) when $f < f_{min}$ and decreases (increases) when $f > f_{min}$ moving from 0V to -1V (moving from 0V to +1V). The maximum phase shift for the reflection coefficient is about 60 degrees at1.547 GHz).

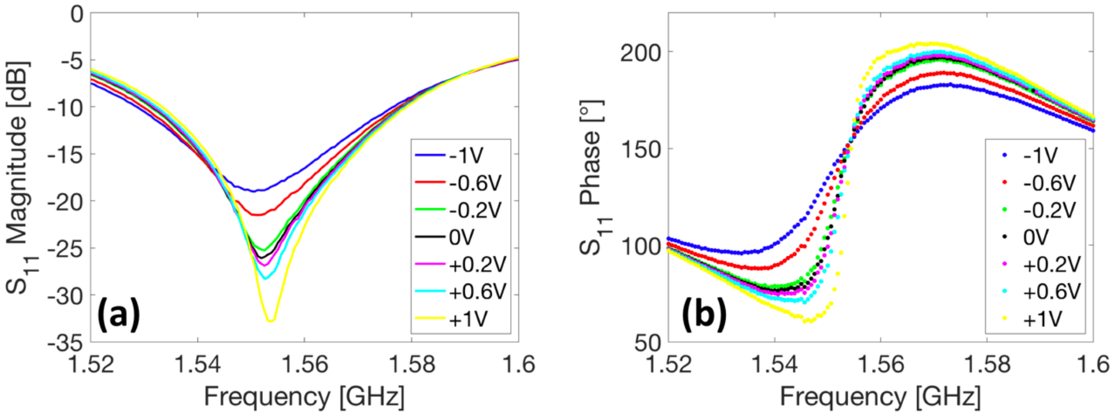

Figure 2: (a) Measured S_{11} magnitude and (b) measured phase of the antenna scattering parameter S_{11} when the gate voltage V_g is varied in the electrochemical window.

The far-field behavior of the antenna was investigated by means of the anechoic chamber StarLab from Satimo in the 1.5-1.6 GHz range [16]. The system allows performing rapid 3D measurements of the radiation pattern reconstructing the Far Field (FF) from the Near Field (NF) by means of the Huygens' principle.

Figure 3(a) shows the boresight gain measured at normal direction with respect to the antenna plane (y-axis in Figure 5). In this case, the maximum gain is achieved at null gate voltage since the graphene exhibits lossy-dielectric behavior. As the modulus of the voltage is increased, the gain is reduced since the graphene moves towards metallic behavior. Interestingly, the gain curves for V_g equal to ±0.2V almost overlap while the curves for ±0.6V and ±1V are very close. These results demonstrate once again that the behavior of the front and back layers is almost identical. All plots exhibit the same trend. Therefore, the presence of the graphene capacitor does not alter/distort the gain function.

This is confirmed by the plot in Figure 3(b), which shows the gain at 1.55 GHz (frequency of the maximum gain in Figure 3(a)) when the gate voltage is varied in the electrochemical window. In particular, an almost linear variation of about 2.3 dB is experimentally demonstrated between -1.9 and -4.2 dB (the gain for the unloaded antenna is about 5 dB). The experimental results reveal that changing the polarity of the gate voltage does not have a strong influence on the far-field response of the graphene-loaded antenna. This means that the presence of two graphene layers does not affect the far-field response. This is opposite to the behavior shown by the reflection coefficient as demonstrated in Figure 2.

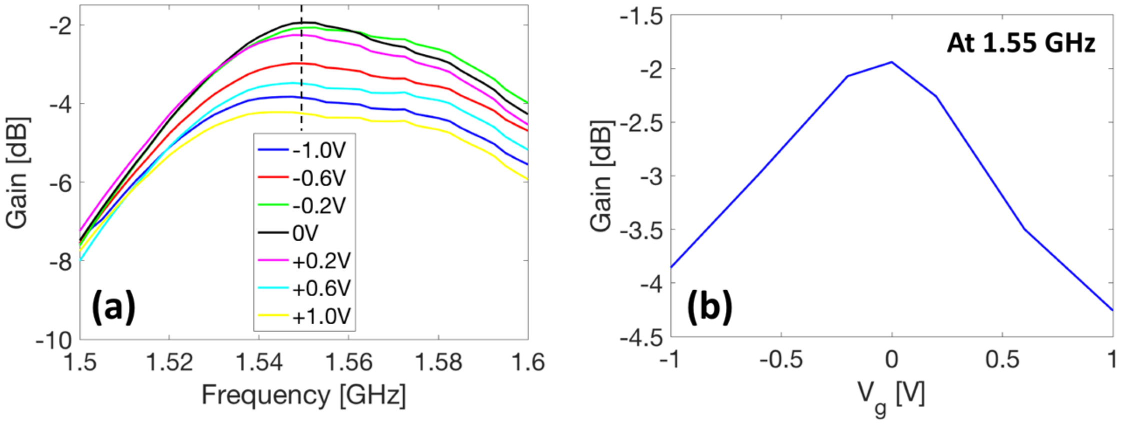

Figure 3: (a) Measured gain in the frequency range of interest when the gate voltage is varied. (b) Measured gain vs in the gate voltage.

The test station StarLab also allowed us to measure the phase of the far-field electric field in terms of E_θ and E_φ when the normal direction with respect to the antenna plane is considered. Experimental measurements show that E_φ is insensitive (the change is in the 1-3 degrees range) while the phase of E_θ changes with the gate voltage. Figure 4(a) shows the phase of E_φ in the 1.5-1.6 GHz range. In this case, the phase curves for V_g referring to ±0.2V and ±0.6V almost overlap while the curves for ±1V are very close. Figure 4(b) reports the phase of E_θ at 1.55 GHz in the electrochemical window with a maximum variation of 45 degrees. The curve in Figure 4(b) is also symmetric as expected due to the symmetry of the front and back layers. Finally, the curve trend of phase of E_θ resembles that of the gain in Figure 3(b).

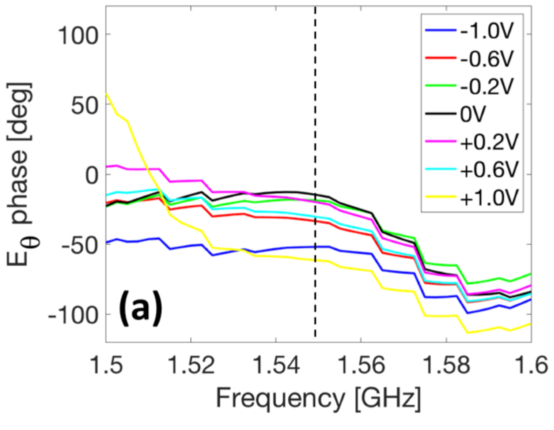

Figure 4: (a) Measured E_θ phase variation in the frequency range of interest when the gate voltage is varied. (b) Measured E_θ phase at 1.55 GHz when the gate voltage is varied in the electrochemical window.

Finally, we considered the radiation pattern of the graphene-loaded GPS antenna. Figure 5 shows the polar plot of the radiation patterns in the xz-plane (φ=90°) at 1.55 GHz for positive gate voltage (radiation patterns for φ=0° and negative gate voltages display almost identical behavior and, hence, they are not shown for clarity). Figure 5(b) illustrates the experimental 3D radiation pattern of the graphene-loaded antenna at V_g=0 V. As expected the gain is changed while the phase is significantly affected.

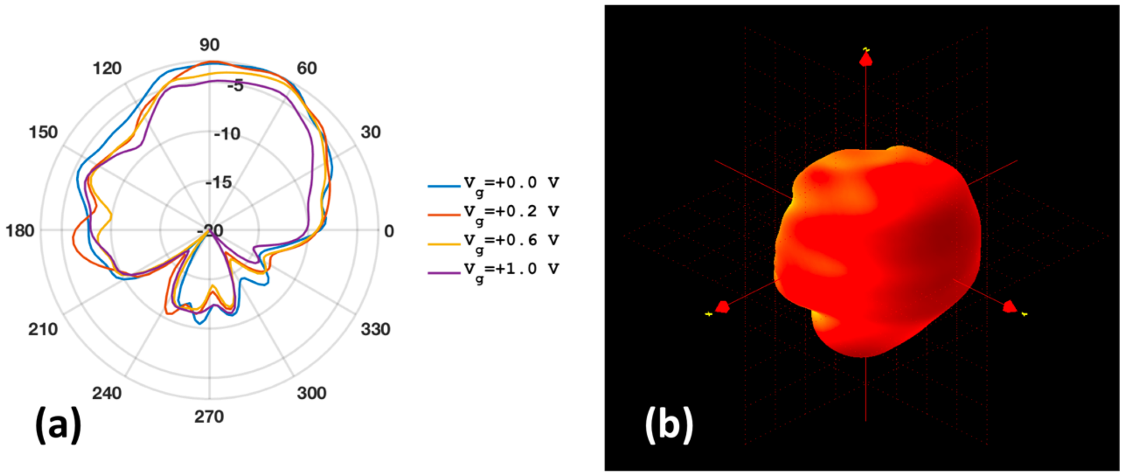

Figure 5: (a) Radiation pattern in the xz-plane (φ=90°), at 1.55 GHz when the gate voltage is varied. The tilt in the patterns is also evident in the unloaded GPS antenna. (b) Experimental 3D radiation pattern at V_g=0 V.

Conclusion

In conclusion, we have proposed a reconfigurable scheme consisting of an antenna loaded by a CVD graphene capacitor. The proposed scheme offers the ability to vary the antenna gain by about 2-3 dB and the phase of far-field electric field of about 45 degrees. This is a first mere example of how graphene can be efficiently integrated in telecommunications systems for smart antennas.

We also believe that these results point to a way towards optimized configurations that could increase the range of the gain and phase control.

These results also raise new challenges about the possibility of integrating and extending this approach to other microwave devices such as filters, matching circuits, microwave resonators moving from static configurations to reconfigurable ones.

Graphene could be easily integrated in different antenna geometries based on patches, slots, DRAs, aperture antennas, parasitic steerable arrays leading to innovative architectures. Our scheme could also be extended to antennas arrays covering the array leading to transmit-arrays [19], where the electromagnetic field can pass through the graphene capacitor. At the same time, the proposed approach could be also applied beginning with quasi-metallic graphene in order to work in reflection as for reflectarrays and active frequency selective surface [20].

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