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Metamaterial-Based Reconfigurable Intelligent Surface: 3-D Meta-Atoms Controlled by Graphene Structures

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ABSTRACT

The upcoming high-speed wireless communication systems will be hosted by millimeter and sub-millimeter-wave frequency bands. At these frequencies, electromagnetic waves suffer from severe propagation losses and non-line-of-sight (NLOS) scenarios. A new wireless communication paradigm has arrived to resolve this situation through the use of reconfigurable intelligent surfaces (RIS). These metadevices are designed to reconfigure the wireless environment in a smart way. Traditional RIS designs based on the implementation of 2-D configurations have been considered up to now. However, 3-D structures enable an extra degree of freedom in the design that can be taken as an advantage for the development of improved RIS structures with advanced functionalities. This article proposes the implementation of a novel electronically-reconfigurable RIS based on the use of 3-D graphene meta-atoms. The reconfigurability lies on the graphene conductivity, easily tunable with a biasing voltage. Different conductivity values vary the meta-atom electromagnetic response, modifying the RIS functionality. A multi-objective optimization framework determines the optimal phase state of each meta-atom to accomplish the desired RIS performance. The operation of the RIS as an efficient beam steerer/splitter, absorber and polarization selector is validated with full-wave results.

INTRODUCTION

Wireless communications in the present 5G and future 6G systems will dramatically provide an enhancement of several key performance indicators such as the user data rate, the spectral efficiency and latency [1]. These improvements in the requirements of the communication system entail breakthroughs in the employed technologies. The use of millimeter-waves (mm-waves) and terahertz communications, beamforming capability of the antennas or ultra-dense networks are some of the proposed technologies to achieve the latter communications requirements. A recent paradigm for wireless communication is based on reconfigurable intelligent surface (RIS) [2]. It allows smart modifications of the communication environment in order to fulfill the needs of the wireless links among users. Some of the desirable functionalities for a RIS are: beam steering, beam splitting, wave absorption, polarization and phase control of the reflected wave [3], [4]. The applications of these RIS functionalities in the wireless communication are the avoidance of the non-line-of-sight (NLOS) scenarios,

interference mitigation, block of eavesdropping and jamming or multi-user coverage. Normally, the design and implementation of the RIS is based on coding metasurfaces composed by unit cells called meta-atoms [2]. The meta-atoms must incorporate reconfigurable elements, e. g. PIN diodes, to set the functionality of the RIS [5] according to the requirements of the users.

Diversity of designs and implementations of RIS are beginning to emerge [4], [6]. Most of them employ PIN diodes in the unit cell to achieve different phase shift responses to define the phase states of the meta-atom. Besides, printed circuit boards (PCB) technology is the preferable manufacturing technique for the implementation of the RIS unit cells. Recently, huge advances in 3-D manufacturing technology as well as numerous options to fabricate tridimensional designs are commercially available. Specially, this kind of manufacturing technique enables the cost-effective realization of 3-D complex prototypes, sometimes infeasible with traditional techniques, e.g. computer numerical control (CNC). This new reality of multiple 3D-printing manufacturing processes has been leveraged by the antenna engineering community to realize radiofrequency (RF) designs covering from microwave band to millimeter-waves.

3-D metastructures offer advanced functionalities compared to classical 1-D and 2-D metasurfaces (see Table I). First, fully metallic configurations can be conceived in 3-D configurations, avoiding the presence of dielectrics (and the associated dielectric losses) and enhancing the efficiency of the device. Additionally, in 1-D and 2-D metasurfaces, the degrees of freedom controlling the structure behavior are mainly included in the elements extended along the transverse x and y components. This is the case, for example, given in PCB manufacturing. However, 3-D printing techniques allow for the inclusion of elements not only along the plane containing the transverse directions (as in 2-D designs), but also along the propagation direction z . This additional degree of freedom associated to 3-D structures can be exploited in the design of novel RIS with advanced functionalities: beam steering, beam splitting, absorption and polarization selectivity. In particular, polarization control of the incident electromagnetic waves is a challenging task in conventional 2-D metasurfaces, since independent current control of the different polarization states is hardly achievable. This is different in 3-D structures, where an independent control of the polarization states is possible, as it will be discussed in detail later.

2-D reconfigurable metagratings [7], [8] have recently

emerged as an alternative of gradient metasurfaces such as RIS. They present an enhanced beam steering with greater simplicity from the geometrical and analytical point of view, since they are based on classical gratings and patch arrays. However, their beam directions in beam steering- and beam splitting-operations are restricted to a few pointing angles.

An interesting alternative to conventional PIN diodes for reconfigurability is the inclusion of biasing-controlled graphene layers in the meta-atom. This kind of reconfigurable structures are being increasingly employed to design RF devices such as attenuators, tunable antennas, absorbers, etc [9]. The graphene sheet is biased by a given voltage. The variation of this voltage modifies the conductivity of graphene and therefore, the surface resistance of the layer. For example, a graphene pad placed in the middle of a microstrip line allows good propagation for a certain value of the sheet resistance, and otherwise increases the insertion losses if a different value is induced. The result is a reconfigurable microstrip attenuator. Graphene structures have been implemented for layered structures only for RIS working in the terahertz band [10]. In this article, we present a novel RIS design based on 3-D meta-atoms with reconfigurability performance provided by graphene structures. A convenient tuning of the surface resistance drastically changes the behavior of the meta-atom. The proposed design conceives a step further from the conventional RIS by profiting the third dimension in the meta-atom. Additionally, the negligible polarization time of graphene is potential for real-time reconfiguration of the radiation performance of the RIS, which is a key feature in future communication systems.

The article is organized as follows. The following section depicts the proposed RIS based on 3-D meta-atoms and the reconfigurable mechanism based on graphene structures. Then, we detail the design procedure followed to obtain the required functionality in a RIS. Later, we discuss the multiple functions provided by the RIS that are analyzed by full-wave electromagnetic simulations. Finally, the conclusions are drawn in the last section.

3-D META-ATOMS STRUCTURE

Metallic meta-atoms with 3-D architecture are actually unit-cell configurations exploiting the three spatial dimensions for the control of electromagnetic waves. Unlike 2-D devices, 3-D meta-atoms use the propagation direction to add new degrees of freedom [11]. This issue is key, resulting in the increase of the number of functionalities of the RIS. 3-D metallic meta-atoms are based on multi-purpose waveguide architectures, as for instance, waveguides with square, triangular or hexagonal sections. The scattering control of the electromagnetic waves demands small dimensions of the waveguide, in order to avoid diffractive and dispersive phenomena that would introduce additional handicaps. This is a design constraint assumed, leading us to impose waveguide dimensions no longer than $\lambda/2$ at the desired operation frequency.

The structure of the RIS under consideration is shown in Fig. 1, consisting of a fully-metallic configuration comprising modified square waveguide sections backed by a metallic

2-D structures	Feature	3-D structures
PCB technology and layer stacking	Manufacturing	3-D printing (Single piece)
Dielectric losses (Substrates)	Losses	Ohmic losses (Printed/coated metal)
Standard	Functionalities	Advanced (More degrees of freedom)
Not proportional to increasing frequency (Complex to scale)	Profile at mm-waves	Proportional to increasing frequency (Easy to scale)
Low cost (PCB manufacturing)	Price	Medium cost (3-D printing + coating)
Challenging (Complex current control)	Polarization Control	Easy (Independent pol. states)

TABLE I: Feature comparison between 2-D and 3-D structures for RIS design.

plane. Fully-metallic designs are desired in RF since they avoid dielectric losses. Moreover the operation frequency in fully-metallic designs can readily be translated to other frequency ranges just by applying a simple scaling in the dimensions of the structure.

The 3-D meta-atoms of the proposed RIS are placed periodically along horizontal x - and vertical y - directions. The square geometry of the waveguide section supports the existence of degenerate modes; namely, modes that are orthogonal to each other and have the same cutoff frequency. This fact encourages us to address a control of different field polarizations by using both degenerate modes, as shown in Fig. 1 for horizontal (H-pol) and vertical (V-pol) polarizations. This could potentially lead to enhanced information transmission, as data can be multiplexed in both degenerate (orthogonal) states.

The ground plane at the bottom of the structure ensures full-reflection response. This means that the square waveguides that define each meta-atom are short-circuited at the end. This scenario imposes the incident radiation to be reflected back. The intelligent behavior of the structure comes from an efficient manipulation of these reflected waves. This is achieved by adding electromagnetic resonators at each lateral walls of the waveguide in the form of apertures, as illustrated in Fig. 1. The presence of these resonators does not alter the amplitude response of the reflected wave, but does change its phase response. In other words, each meta-atom acts as an individual phase shifter. The outgoing phase associated with every single meta-atom then depends on the geometry of their resonators. Certain resonator geometries facilitate the phase control. A suitable aperture geometry is the splitting resonator, that has been object of study in the field of metamaterial design [12].

The reconfigurability of RIS by using the structure presented in this work is easily achievable by modifying artificially the geometry of the split rings per meta-atom. For this, graphene sections printed on silicon-slabs are a good alternative. Graphene sheets are in physical contact with the split rings as it is shown in Fig. 1. An ON/OFF-switching behavior is easily induced in graphene just by biasing it with a given voltage V_b . Higher-voltages biasing induce an effective high conductivity in the graphene layer, thus graphene becomes a

Fig. 1: Proposed RIS design formed by reconfigurable 3-D meta-atoms based on graphene structures, and key geometries and structures of the meta-atom.

good conductor. Lower voltages reduce considerably the conductivity in graphene, so graphene becomes worse conductor. The surface resistance R_s of the graphene sheet moves from lower values (ON) to higher values (OFF) [9]. The dichotomy between better/worse conductor is conceived as an ON/OFF switching, respectively. When ON is activated, the graphene layers act as additional metallic sections of the split ring, modifying its original shape. This provokes a global reduction of the length of the resonator. When OFF is activated, this additional layer does not act, and the split-ring recovers its original shape. The double shape of the split rings induced by the graphene sheets is translated to the outgoing phase in the form of two different phase states. A first phase state is defined at 0 degrees, related to graphene in ON. A second state is defined at 180 degrees, induced by graphene in OFF. It is worth remarking that an operation frequency is previously selected in order to decide the split ring dimensions.

Concerning the manufacturing process of the structure under consideration, several 3-D printing options are available to achieve a successful fabrication. Stereolithography (SLA) followed by a metal plating is one of the most interesting option to realize 3-D components since it provides high-precision at printing millimeter-wave devices [11]. Higher precision in the 3-D manufacturing is also feasible employing micromachining techniques with a later metallization, such as the SU-8 or deep reactive ion etching (DRIE) processes, which are now emerging as suitable manufacturing techniques for sub-millimeter wave structures. Another option to manufacture fully-metallic structures is the direct metal laser sintering (DMLS). This last, unlike the above manufacturing options, directly prints the structure on a metallic piece. Nonetheless, it is important to consider that this 3-D printing technique suffers from moderate roughness surface and consequently, the performance of the structure can be affected by efficiency losses.

RECONFIGURABLE MATERIALS

Different materials can be employed in order to reconfigure the meta-atoms. Although the proposed one in Fig. 1 is graphene, other materials could be employed with this goal. For example, binary or ternary chalcogenide alloys like GeTe or GeSbTe present high resistance in the amorphous off-state and low resistance in the crystalline on-state [13]. The phase transition between the two states is reversible and can be achieved by short heating pulses either by electrical current or by light. Moreover, other 2-D materials can be used: transition metal dichalcogenides, TMDs (MoS_2 , WS_2 , MoSe_2 , WSe_2 , HfS_2 , and others) and 2-D dielectrics such as hexagonal boron nitride (hBN) could be deposited by chemical vapor deposition on sacrificial substrates. Once the 2-D material layers are grown, they are transferred to the target substrate for its structural and electrical characterization. An open issue is the comparison of conductivity tunability of these structures with the one obtained with graphene.

Graphene is a zero-bandgap material (i.e., a semimetal) showing an ambipolar behavior. The conductivity of the graphene layer can be electrostatically modulated by a perpendicular electric field. Such an electric field can be obtained, for example, by capacitively coupling a graphene layer on top of a silicon oxide (SiO_2) and silicon (Si) structure, and applying a DC voltage between the graphene and the SiO_2/Si substrate, as illustrated in Fig. 1. The SiO_2 acts as an insulator in order to prevent the short-circuit between the graphene and the silicon when the voltage is applied. This principle is extensively exploded in graphene field-effect transistors GFETs [9], and GFET chemical sensors.

High-quality graphene layers can be obtained through mechanical exfoliation of highly oriented pyrolytic graphite (HOPG), by epitaxially growth on silicon carbide (SiC) substrates, and by CVD on sacrificial metal foils and later transfer to the final substrates [9]. In opposite to mechanical exfoliation and epitaxially growth techniques, CVD and plasma chemical vapor deposition (PCVD) can provide graphene samples with a few centimeters of size at the time that they keep the high

Fig. 2: Flowchart that describes the design procedure of the metamaterial-based RIS.

quality of the graphene sheet. This technique would be the suitable one for the fabrication of the employed graphene structures inserted in the 3-D meta-atom. The graphene layers are in physical contact with metallic walls of each 3-D meta-atom while the silicon substrates do not touch any point of that structure. In this way, an adequate voltage polarization can be carried out by grounding the metallic-structure of the RIS and wiring each silicon slab in order to apply certain voltage to generate the ON/OFF states.

As it is pointed above, graphene structures are placed at the split-rings of the 3-D meta-atom to tune its geometry. When the graphene has low surface resistance (high conductivity) the slit that defines the split-ring is shortened and therefore, modifying the phase shift response from the original split-ring. Nevertheless, the range of values for the surface resistance of the graphene is not discrete and depends on the polarization voltage. In this range, there may be values that allow the 3-D meta-atom to absorb the power of the incident wave. As it is shown in [14], the maximum losses produced by the graphene are in a determined range of surface resistance values (Ω/sq). The absorption should occur when there is good impedance matching between the incident wave and reconfigurable meta-atom. In this case, the energy that carries the incident wave is not reflected but dissipated in the graphene structures due to the favorable impedance matching between the RIS and the free space.

DESIGN PROCEDURE

From a formal point of view, the total radiation of the RIS can be decomposed into the sum of the individual contributions of the meta-atoms that form it. Thus, the radiation of each meta-atom contributes to create constructive or destructive patterns at certain spatial regions. By properly adjusting the states (ON/OFF) of the meta-atoms, the energy can, for example,

be concentrated at a particular direction of space. As previously discussed, these states correspond to a variation of the outgoing phase when the incident wave impinges the structure. For the present configuration, the geometrical parameters of the meta-atoms are engineered so that the ON/OFF states show a phase difference of 180 degrees while maintaining the same amplitude level. In other words, the information of the ON/OFF states can be codified with the phase states 0 and 180 degrees, respectively. This fact simplifies the design of the structure, since the RIS can be equivalently seen as a 1-bit reconfigurable reflectarray whose elements are assumed to have identical amplitudes but can take two different phase states.

Fig. 2 presents the flowchart that summarizes the design procedure. We rely on the use of a self-implemented ray-tracing tool to find the optimal coding arrangement of the meta-atoms that ensure the correct performance of the RIS considering the selected operation mode and the distance that can exist between the RIS and the emitting source. The phase distribution of the meta-atoms is then optimized with a multi-objective genetic algorithm based on a Java framework, jMetal [15]. Genetic algorithms are suitable in this kind of scenarios, where multiple objectives, input variables and variable restrictions must be jointly considered. These algorithms typically start with a random initial population (in our case, the phase arrangements in the RIS) and use the information provided by the evaluation of the current population of individuals to create the next population. The validity of the solutions is tested with a fitness value/s produced by a single or several cost functions depending of the optimization goals. The selection of the fitness criteria will depend on the operation mode of the RIS. As an example, the beam-steering mode seeks to redirect the main beam in a single region of space. Thus, the fitness function relates the amount of energy concentrated in that

particular region of space, which must be maximized by the multi-objective optimization. Specifically, the multi-objective algorithm employed is the Non-dominated Sorting Genetic Algorithm (NSGA-II) with binary type variables. The selection is based on a binary tournament selection while the crossover is based on a self-implemented code that exchanges random parts of the selected individuals, i.e., exchanges subzones of the phase arrangements representing each selected individual. All these optimization options and the type of employed multi-objective algorithm are configurable and modifiable because jMetal is an open-source optimization framework.

The ray-tracing tool is a computationally-efficient technique that allows to significantly reduce computational efforts when estimating the optimal coding arrangement of the graphene meta-atoms. However, ray theory does not consider complex phenomena such as interference and diffraction, as well as it assumes zero coupling between adjacent meta-atoms. These simplifications imply that the optimal solution extracted from the ray-tracing method has to be validated with more precise full-wave techniques. Full-wave simulators are general-purpose electromagnetic software that solve the complete set of Maxwell's equations without any simplifying assumptions. In our particular case, we make use of commercial simulator *CST Microwave Studio* to test the validity of the optimal solution. Slight modifications in the simulated model of the RIS could be applied to adjust the performance to the solution given by the ray-tracing tool. If the design requirements are finally met, then the RIS would be fully operational.

FUNCTIONALITIES

The reconfigurability of the intelligent structure by means of the graphene layers provokes that the proposed RIS is suitable for a wide variety of communications scenarios. As an example, the meta-atoms of the RIS can be configured in order to add diversity to the communication channel, so that the channel efficiency is increased [4]. Interferences and unwanted incoming signals that could degrade the performance of the system can be also blocked by taking advantage of the lossy nature of graphene. However, the focusing capabilities of the RIS make the intelligent structure particularly useful in real-time mobile communication systems for multi-user coverage and radio localization enhancement.

BEAM STEERING

One of the most representative functionalities of the RIS consists in the electronic reconfiguration of the beam angle direction to provide LOS user connection in NLOS scenarios. This is achieved by properly modifying the ON/OFF states of the meta-atoms that constitute the RIS. In the design under consideration, the operating frequency is 28 GHz, one of the potential bands for future 5G communications links. For a given angular direction of the incident wave, the coding arrangement of the RIS is determined with the multi-objective optimization algorithm. In this particular scenario, a single objective suffices to find the optimal coding arrangement. Thus, the gain of the RIS should be maximized at the desired pointing direction. The level of the secondary lobes

is automatically reduced as the gain is maximized, since the energy is concentrated at a single direction.

Fig. 3 illustrates the beam steering capabilities of our intelligent structure as well as the coding arrangement of the different configurations. The states of the graphene are modeled with an effective surface resistance of $2 \Omega/\text{sq}$ in the ON state and $2500 \Omega/\text{sq}$ for the OFF state. No significant ohmic losses are achieved in both states. Graphene becomes a good conductor for a low surface-resistance value, and it turns a non-conducting material when this value switches to a big number [14]. The main beam can be redirected in an efficient manner by simply changing the bias-voltage values of graphene. A focused beam with reduced secondary lobes is formed when all the meta-atoms contribute constructively to radiate an equal-phase wavefront at the desired spatial direction. Thus, each meta-atom should compensate the phase delay provoked by the incident spherical wave, leading to the ring-like coding arrangements observed in Fig. 3. Note that the arrangement of the rings changes proportionally as the main beam is steered, for instance in the Configuration 2, the arrangement of rings move downwards along the x and y axis to tilt the beam in elevation and azimuth directions.

BEAM SPLITTING

Another remarkable feature of the RIS is the ability to split the incident wave in N main lobes. This is of great interest in present wireless communication systems in order to provide multi-user coverage. For this operation mode of the RIS, the multi-objective genetic algorithm includes three objectives to optimize in this particular scenario. First, the gain of the RIS must be maximized at the desired pointing directions. Second, the difference between the amplitudes of the main lobes should be minimized, so all the users receive the same amount of power. The first two objectives do not guarantee by themselves that non-desired secondary lobes that carry an important energy contribution could appear. This is solved by introducing a third objective, which seeks to minimize the radiated energy outside the main lobe direction. A set of trade-off solutions (Pareto front) arise from the multiple objectives included in the optimization process. A decision marker is used to determine which of these trade-off solutions is finally implemented in the full-wave simulator. This decision marker is calculated as the ratio of the sum of gains at the main lobe directions and the difference between their values times the radiated energy outside the desired directions. As a design criteria, we choose the solution of the Pareto front whose value of the decision marker is the highest.

Fig. 3 also shows the beam splitting capabilities of the RIS (Configurations 3 and 4). As a proof of concept, the energy that carries the incident spherical wave that illuminates the structure is divided into two main beams. Similar to the beam-steering operation mode, the ON/OFF states of graphene are modeled with two surface resistance values of $2 \Omega/\text{sq}$ and $2500 \Omega/\text{sq}$, respectively. As shown in the figure, both beams have similar gain values and the secondary lobes have been minimized. With the use of the multi-objective optimization algorithm, this scenario can be straightforwardly generalized to

Fig. 3: Beam steering and beam splitting capabilities of the RIS. The reflected beams have the following pointing angles. Configuration 1: $(\phi, \theta) = (90^\circ, 0^\circ)$; Configuration 2: $(\phi, \theta) = (240^\circ, 20^\circ)$; Configuration 3: $(\phi, \theta) = (250^\circ, 20^\circ)$, and $(\phi, \theta) = (300^\circ, 20^\circ)$; Configuration 4: $(\phi, \theta) = (180^\circ, 20^\circ)$, and $(\phi, \theta) = (300^\circ, 30^\circ)$. The azimuth and elevation angles of the incident wave are $\phi_i = 90^\circ$ and $\theta_i = -10^\circ$, respectively.

the creation of N main beams, demonstrating the applicability of the proposed RIS.

ADVANCED FUNCTIONALITIES

Apart from previous functionalities, the combination of 3-D structures and graphene in a meta-atom can enable advanced functionalities. Thanks to the square waveguide, which contains a split-ring resonator on each lateral wall, the RIS function for each incident polarization is achieved if the graphene state is selected in pairs, i.e., surface resistance of the graphene in opposite waveguide walls should be the same. Fig. 4 illustrates the performance of the proposed RIS when a vertically polarized wave (V-pol) is steered and a horizontally polarized wave (H-pol) is split (Fig. 4(a)) or it is absorbed (Fig. 4(b)). For both cases, the graphene state placed at each lateral wall of the meta-atom is the same and forms the phase arrangement shown in Configuration 2 for vertically polarized waves. Alternatively, the beam splitting in horizontally polarized waves is controlled by the graphene located at top and bottom walls of the meta-atom. The phase arrangement for this RIS function is the one illustrated in Configuration 3. An additional functionality can be invoked by considering a third state, profiting the capability of graphene for absorption. There exist a series of bias-voltage values that make the conductivity of graphene favorable for this scenario as it was explained before. Since the cell is under cut-off, no propagating field can be found inside. However, this field is practically confined in the split-rings regions at resonance. Graphene, in direct contact with the split rings, exploits its lossy character and absorbs it. The performance of the absorption function is shown in Fig. 4(b) for horizontally polarized waves. For this case, the graphene sheet has an effective surface resistance of $75 \Omega/\text{sq}$. The reflected wave is below -13 dB regarding the maximum of the beam-steering case (absorption higher than 90%).

CONCLUSIONS

In this article, we have explored the novel concept of 3-D RIS. The inclusion of an additional dimension compared

Fig. 4: Selection of the RIS function depending on the incident polarization: (a) beam steering (V-pol) and beam splitting (H-pol), and (b) beam steering (V-pol) and absorption (H-pol).

to conventional 2-D configurations brings an extra degree of freedom to the design, leading to an improved RIS with enhanced functionalities. Among the existing and emerging reconfigurable materials, the graphene has been selected to carry out the adjustable behavior of the proposed 3-D RIS. By properly setting the discrete states (ON/OFF) of the graphene meta-atoms, the radiation properties of the RIS can be electronically reconfigured. In order to set the states of the 3-D meta-atoms to fulfill the desired RIS function, a design procedure has been proposed. The main tools that form this design procedure are a self-implemented ray-tracing tool and a multi-objective optimization framework. In this way, an optimal coding arrangement for the RIS is found, ensuring the correct performance of selected operation mode. To validate the proposal, we design a 3-D RIS formed by a mesh of

15×15 graphene meta-atoms operating at 28 GHz. The full-wave results show the beam-steering/splitting and absorption capabilities of the intelligent structure, as well as its operation as a polarization selector. This demonstrates the potential of the proposed RIS for application in real-time multi-user scenarios of future-generation wireless communication systems.

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