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PROJECT FINAL REPORT

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Project acronym: RASTREO

Project title: multi-Reconfigurable Antenna SoluTions based on REflectarray technOlogy

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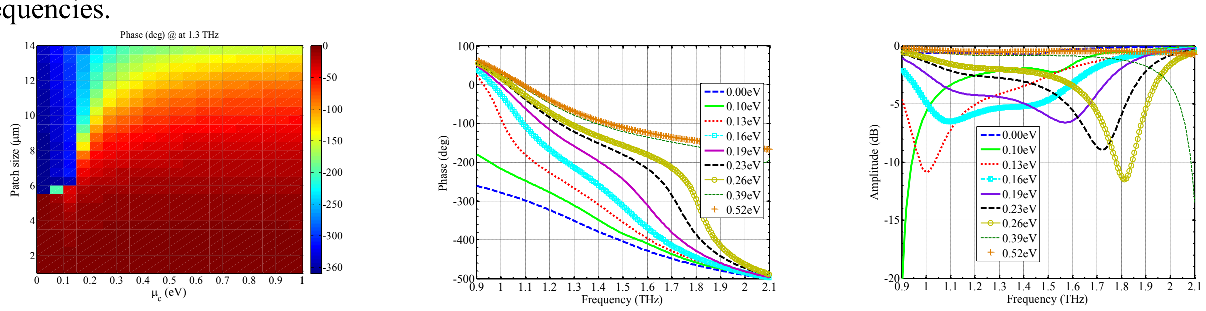
[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

Final publishable summary report

Reflectarray antennas are comprised of an array of radiating elements, reflecting the energy that is impinged from a primary feed. These antennas are interesting hybrids between aperture antennas (reflectors) and conventional arrays. They are spatially-fed, which means that they do not require a lossy feeding network with dedicated transceivers, reducing the overall losses, the production cost and the manufacturing complexity, allowing also the introduction of electronic phase control. Reflectarrays have been studied extensively in the last years, mainly for fixed-beam. However, if dynamically control is implemented at the element level, the reflectarray allows steering the beam towards a predefined direction or even changing the shape of the beam. Reflectarrays offer a simple feeding mechanism combined with the independent control at the element level in order to provide very versatile capabilities. The Marie Curie IEF project RASTREO (multi-Reconfigurable Antenna SoluTions based on REflectarray technology, http://mnwave.epfl.ch/rastreo) has contributed to addressing new challenges in the dynamic reconfiguration, including not only spatial reconfiguration, but also polarization and frequency reconfiguration. It is worth mention that in the case of spatial reconfiguration, the use of graphene as a reconfiguration technique in reflectarrays has been proposed for the first time. Although the use of this new material was not included in the initial proposal, the experienced researcher and the former scientist in charge (Prof. Perruisseau-Carrier) together agreed to explore the interesting properties of graphene with the aim of implementing scanned-beam reflectarray antennas in Terahertz (in the second year the research was extended to the infrared band). In any case, this update cannot be considered as a deviation respect to the original gaols of the project, contrary, the obtained results have opened a very promising research line with interesting applications in different fields and allowing the proposed reconfiguration capabilities. For the case of polarization and frequency reconfiguration, other reconfiguration methods have been analyzed (solid state switches or liquid metal). In the following lines, a summary of the public final results obtained in the framework of RASTREO are presented.

Beam bending in reflectarrays by using graphene at THz and mid-Infrared

Graphene is a true 2-D material (monatomic layer of carbon atoms arranged in a honeycomb structure), which has attracted tremendous interest thanks to its unique electrical and mechanical properties. Graphene's complex conductivity can be efficiently controlled via a perpendicular bias electric field. As a result graphene is envisioned for a variety of applications at THz and optical frequencies, including the possibility of dynamic tuning via the electric field effect. This dynamic tuning was demonstrated at 1.3 THz by using graphene patches. The patch resonance occurred when its size was around $\lambda_0/24$ (into a $\lambda_0/16$ unit cell). This phenomenon is due to the well-known slow-wave propagation associated with graphene plasmonic modes. Fig. 1(a) shows the phase of reflection coefficient, at 1.3THz produced by a square graphene patch as a function of both, the patch size and the chemical potential which is varied by electronically gating the graphene. The maximum phase variation is obtained for patches of 10 µm, yielding a range of around 300° in a large bandwidth, which is enough for producing a pencil-beam. Fig. 1(b) and (c) shows respectively the phase and amplitude of the proposed element when the chemical potential is varying from 0.0eV to 0.52eV. It is also observed that the phase shift experiences an almost constant phase variation with small errors. For instance, phase errors lower than 37° in the frequency band from 1.1 THz to 1.5 THz has been obtained. This is a 31% of bandwidth (namely, large bandwidth). The loss of the element varies between 0.5 dB and 6 dB on the whole range between 1.1 THz and 1.6 THz, which is another very promising performance at such frequencies.



(a) (b) (c)

Figure 1: Phase-shift introduced by graphene square patches (a) As a function of the size and the chemical potential, at 1.3 THz. (b) Phase and (c) Amplitude of the reflection coefficient in free-space, as a function of the frequency, for a 10 µm-side square patch made of graphene varying the chemical potential.

As aforementioned, surface plasmons can concentrate electromagnetic energy at the subwavelength scale. These electron oscillations appear in graphene nanoribbons at much lower frequencies than in their noble metals counterpart, providing subwavelength confinement from mid-infrared down to terahertz frequencies for a vast range of applications. In a new design, the control of a light beam at nanoscale level is proposed by using an array of reflective graphene nanoribbons. The array is between a gating superstrate and a grounded substrate. The difference respect the case of a square patch is that, in the late proposed concept the switching of the reflected beam is produced using a very simple biasing structure, providing a confined beam and low losses of energy. According to Fig. 2(a), the working principle of the proposed array of graphene nanoribbons is as follows. A mid-Infrared laser beam collimated into free space as a Gaussian beam is focused so that the waist of the Gaussian beam impinges with certain incidence angle on a 224-element array. By properly adjusting the physical width of each nanoribbon, a progressive phase-shift is introduced upon reflection along the array in the x-axis direction. This phase difference can be fixed in order to produce a constructive interference of all the reflected waves at each ribbon, as usual in microwave antenna arrays. This interference collimates a far-field beam towards certain direction. In this case, all the nanoribbons are electrically doped with a chemical potential μ_{c1}, equivalent to certain gating voltage. The physical width of the graphene nanoribbons cannot be modified. However, if the electrical doping is turned to a value μc_2, capable of producing a constant phase of the reflection coefficient for all the ribbons of the array, a far-field beam is collimated towards the specular direction. Fig. 2(b) shows the lateral view of the unitary element in the array which can be physically modelled by an equivalent circuit (Fig. 2(c)). Using transmission line theory, the reflection coefficient of each element can be computed at a reference plane in both amplitude and phase. The substrate and the superstrate can be represented as a transmission line with their respective characteristic impedance Z_0 and propagation constant β, while the graphene nanorribbon can be modelled using a surface impedance Z_g which depends on the geometry of the graphene strip and the surface conductivity obtained by the Kubo formula. The short-circuit represents the ground plane, while the line is loaded with the intrinsic impedance of free space, η. Fig. 3 shows the resulted bent beams.

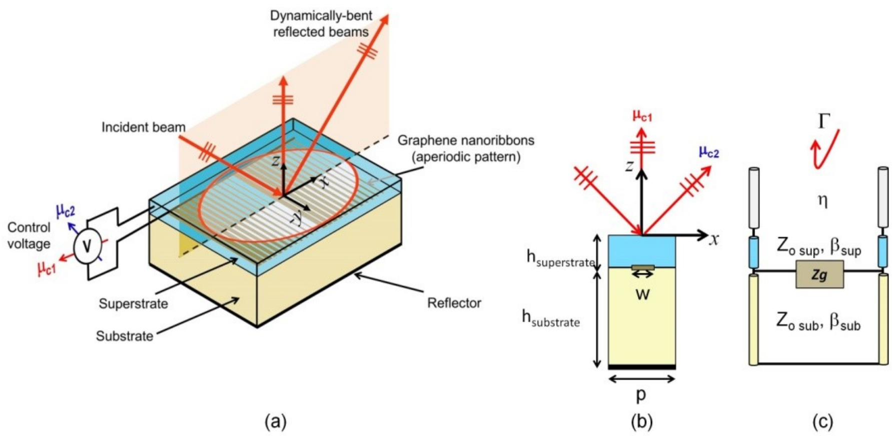


Figure 2: Plasmonic graphene nanoribbons array. (a) Expanded view of the array. (b) Lateral view of one nanoribbon formed by a metallic reflector, a substrate (SiO2), an aperiodic array of patterned graphene, and a superstrate (ion-gel). (c) Equivalent circuit for one element of the proposed array.

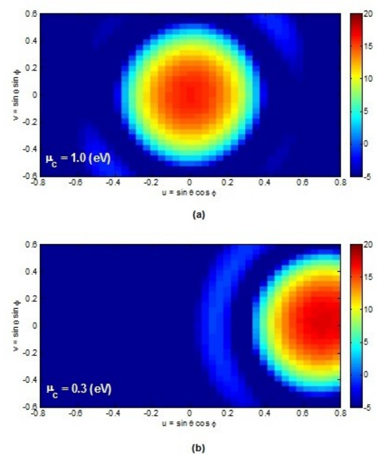


Fig. 3 Far-field radiation pattern produced by the array for two values of gating. (a) Boresight. (b) Specular.

[1] Eduardo Carrasco, Julien Perruisseau-Carrier, “Reflectarray Antenna at Terahertz Using Graphene”, IEEE Antennas and Wireless Propag. Lett., vol. 12, pp. 253-256, 2013.

[2] Eduardo Carrasco, Michele Tamagnone, Julien Perruisseau-Carrier, “Tunable Graphene Reflective Cells for THz Reflectarrays and Generalized Law of Reflection”, Applied Physics Letters, 102, 104103, 2013.

[3] Eduardo Carrasco, Tony Low, Julien Perruisseau-Carrier, “Graphene-Based Plasmonic Arrays for Dynamic Light Bending”, Graphene Conference 2014, Toulouse, France, May 2014.

[4] Eduardo Carrasco, Tony Low, Julien Perruisseau-Carrier, “Dynamic light bending with graphene plasmonic structures”, 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META2014, Singapore, May 2014.

4.1 Use and dissemination of foreground

Section A (public)

RASTREO project results have been published in 2 international high-impact journals (at least 2 more papers are in preparation to be submitted) and 17 dissemination activities, including peer reviewed international conferences, posters, workshops and invited seminars.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	*Reflectarray Antenna at Terahertz Using Graphene*	*Eduardo Carrasco, Julien Perruisseau-Carrier,*	*IEEE Antennas and Wireless Propag. Letters*	*Vol. 12*	*IEEE*	*USA*	*2013*	*pp. 253-256*	*DOI: 10.1109/LAWP. 2013.2247557*	*No*
2	*Tunable Graphene Reflective Cells for THz Reflectarrays and Generalized Law of Reflection*	*Eduardo Carrasco, Michele Tamagnone, Julien Perruisseau-Carrier*	*Applied Physics Letters*	*Vol 102*	*American Institute of Physics*	*USA*	*2012*	*pp. 1104103*	*DOI: 10.1063/1.4795 787*	*No*
3	*Active mid-infrared light bending with graphene nanoribbons*	*Eduardo Carrasco, Michele Tamagnone, Juan R. Mosig, Tony Low and Julien Perruisseau-Carrier*	*Nanoletters*	*To be submitted*	*ACS Publications*	*USA*	*N/A*	*N/A*	*N/A*	*No*
4	*Reflectarray Element With Simultaneous Reconfiguration of Phase and Polarization*	*Eduardo Carrasco, Mariano Barba, Julien Perruisseau-Carrier*	*IEEE Antennas and Wireless Propag. Letters*	*To be submitted*	*IEEE*	*USA*	*N/A*	*N/A*	*N/A*	*No*

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	*Conference*	***Eduardo Carrasco****, Tony Low and Julien Perruisseau.Carrier*	*"Graphene-Based Plasmonic Arrays for Dynamic Light Bending", Graphene Conference 2014*	*May 2014*	*Toulouse, France*	*Scientific Community*		*France*
2	*Conference*	***Eduardo Carrasco****, Tony Low and Julien Perruisseau-Carrier*	*"Dynamic light bending with graphene plasmonic structures", 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META2014*	*May 2014*	*Singapore, Republic of Singapore*	*Scientific Community*		*Republic of Singapore*
3	*Conference*	***Eduardo Carrasco****, Julien Perruisseau-Carrier*	*"Dynamic Spatial Manipulation on Infrared Light Using Arrays of Plasmonic Graphene Nanoantennas", Nanotech Meeting 20014*	*April 2014*	*Hammamet, Tunisia*	*Scientific Community*		*Tunisia*
4	*Conference*	*José A. Encinar, Carolina Tienda, Mariano Barba,* ***Eduardo Carrasco*** *and Manuel Arrebola*	*"Analysis, Design and Prototyping of Reflectarray Antennas for Space Applications", Loughborough Antennas & Propagation Conference, LAPC 2013*	*Nov. 2013*	*Loughborough, UK*	*Scientific Community*		*UK*
5	*Conference*	*Julien Perruisseau-Carrier, Michele Tamagnone, Juan S. Gomez-Diaz,* ***Eduardo Carrasco***	*"Graphene Antennas: Can Integration and Reconfigurability Compensate for the Loss?", European Microwave Week*	*Oct. 2013*	*Nuremberg, Germany*	*Scientific Community*		*Germany*

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

6	*Conference*	***Eduardo Carrasco**, Julien Perruisseau-Carrier*	*"Fixed and Reconfigurable THz Reflectarrays using Graphene", Progress in Electromagnetics Research Symp., PIERS*	*Aug. 2013*	*Stockholm, Sweden*	*Scientific Community*		*Sweden*
7	*Conference*	*Julien Perruisseau-Carrier, **Eduardo Carrasco***	*"Compound Reconfiguration in Reflectarrays for Cognitive Radio Applications", Progress in Electromagnetics Research Symp., PIERS*	*Aug. 2013*	*Stockholm, Sweden*	*Scientific Community*		*Sweden*
8	*Conference*	*José A. Encinar, Manuel Arrebola, Carolina Tienda, Mariano Barba, **Eduardo Carrasco***	*"Recent Developments of Multi-band and Wide-band Reflectarrays", Progress in Electromagnetics Research Symp., PIERS 2013*	*Aug. 2013*	*Stockholm, Sweden*	*Scientific Community*		*Sweden*
9	*Conference*	***Eduardo Carrasco**, Julien Perruisseau-Carrier*	*"Graphene for THz Beam-Scanning Reflectarrays", 2013 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*	*Jul. 2013*	*Orlando, USA*	*Scientific Community*		*USA*
10	*Conference*	***Eduardo Carrasco**, Mariano Barba, José A. Encinar and Julien Perruisseau-Carrier*	*"Two-Bit Reflectarray Elements with Phase and Polarization Reconfiguration", 2013 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*	*Jul. 2013*	*Orlando, USA*	*Scientific Community*		*USA*
11	*Conference*	*Julien Perruisseau-Carrier, **Eduardo Carrasco**, Arya Fallahi*	*"Periodic and Quasi-Periodic Graphene-Based Reconfigurable Surfaces", International Symposium on Electromagnetic Theory" (EMTS 2013)*	*May 2013*	*Hiroshima, Japan*	*Scientific Community*		*Japan*
12	*Conference*	***Eduardo Carrasco,** Michele Tamagnone, Julien Perruisseau-Carrier*	*"Tunable Graphene-Based Reflectarray Element for Reconfigurable Beams", Seventh European Conference on Antennas and Propagation,EuCAP2013*	*April 2013*	*Goteborg, Sweden*	*Scientific Community*		*Sweden*
13	*Conference*	*Julien Perruisseau-Carrier, J. S. Gomez-Diaz, Michele*	*"Graphene nanophotonics methods and devices: what can we learn from the microwave*	*Mar. 2013*	*Benasque, Spain*	*Scientific Community*		

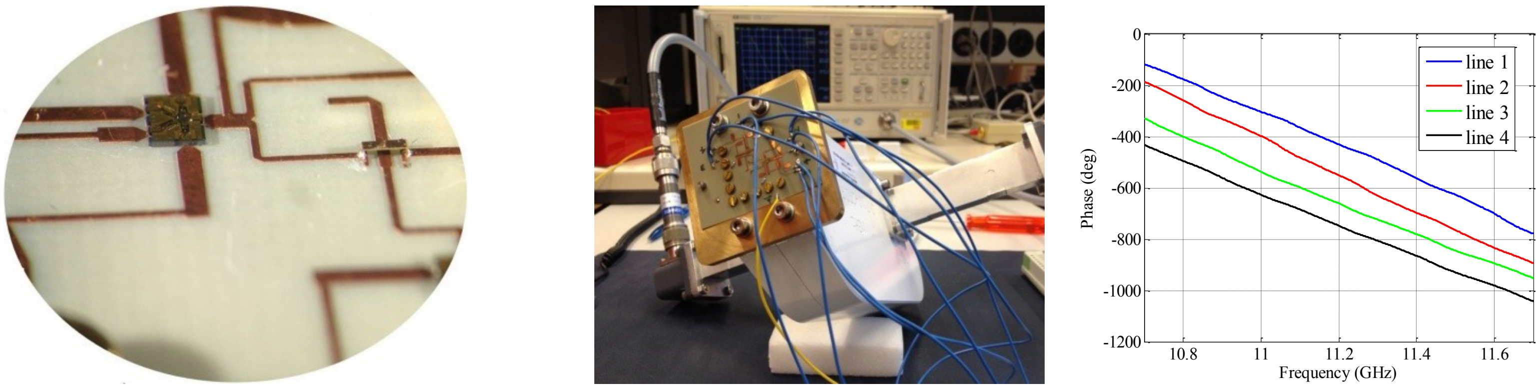
		Tamagnone, Juan R. Mosig, Arya Fallahi and ***Eduardo Carrasco***	*field?", Graphene Nanophotonics*					
14	*Conference*	***Eduardo Carrasco****, Mariano Barba, José A. Encinar and Julien Perruisseau-Carrier*	*"Reflectarray Element for Beam Scanning with Polarization Flexibility", International Symposium on Antennas and Propagation, ISAP*	*Nov. 2012*	*Nagoya, Japan*	*Scientific Community*		*Japan*
15	*Poster*	*Julien Perruisseau-Carrier, Michele Tamagnone, Pietro Romano, Philippe Dreyer, Daniel Rodrigo,* ***Eduardo Carrasco****, J. Sebastian Gomez-Diaz*	*"Reconfigurable and MicroNano Electromagnetics for Space Applications", EPFL Space Day*	*December 2013*	*Lausanne, Switzerland*	*Students + Scientific Community*		*Switzerland*
16	*Invited Technical Seminar*	***Eduardo Carrasco***	*"Advanced Concepts for Reflectarray Antennas with Dynamic Reconfiguration",* Deutsches Zentrum *für Luft- und Raumfahrt (DLR)*	*May 2014*	*Munich, Germany*	*Scientific Community*		*Germany*
17	*Invited Technical Seminar*	***Eduardo Carrasco***	*"Reflectarray Antennas for Space Applications", Workshop on Developing Science and Technology for Earth Observation from Space with Synthetic Aperture Radars*	*Oct. 2013*	*Mérida, México*	*Students + Scientific Community*		*México*

Section B (Confidential[6] or public: confidential information to be marked clearly)

<u>Some of the following results are not published yet. For this reason, the researcher prefers to maintain the following sections in a confidential form until their publication.</u>

Simultaneous phase and polarization dynamic control in reflectarray elements

Reflecting cells for reconfigurable-beam reflectarrays which allow controlling independently and at the same time the polarization of the antenna, regardless of the feed-horn polarization, were extensively studied in this project. This means that the antenna can be feed using a LP (V, H or both) or a CP (RHCP or LHCP) feed, while reflecting the field with any polarization. Two topologies for the element were selected and one of them optimized (including the biasing circuit), fabricated and tested in waveguide simulator (WGS). In both cases, 2-bit phase-shifter resolution is achieved, which is enough for scanning the beam and introducing the 90° phase difference required between orthogonal polarizations for producing CP. The proposed elements have been designed to operate at X-band. The elements are based on aperture-coupled topology which has been chosen to compensate the effects of the differential spatial phase delay. Fig. 4 shows the manufactured prototype, using a commercial SP4T switch from MACOM. The four outputs of the switch are connected to different microstrip line segments that produce the required phase-delay. In this way, each LP polarization can be controlled with a single device. To enable the two microstrip lines crossing over each other, an air-bridge has been accurately designed to cancel any mismatch. Very good results in terms of phase of the reflection coefficient were obtained (Fig. 4(c)), with maximum errors around 30º, which is an optimistic value for this kind of implementations.



(a) (b) (c)

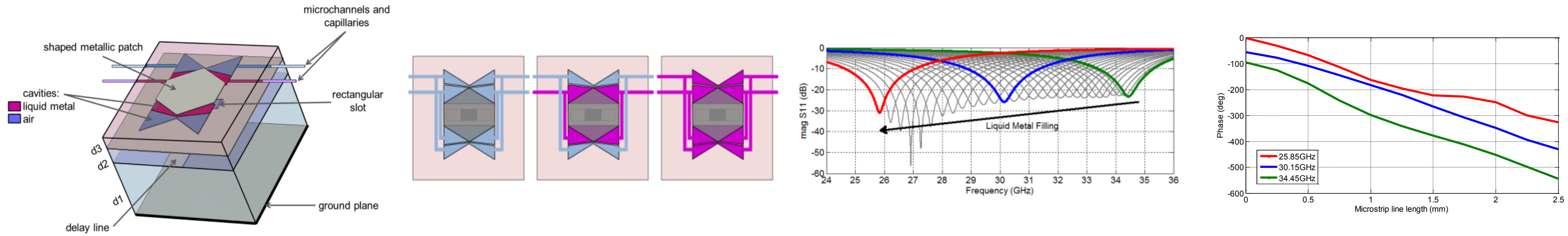
Figure 4: Simultaneous and independent dynamic control of phase and polarization in reflectarray antennas. (a) Detailed view of the switching device implemented in microstrip technology. (b) WGS measures set using an orthomode. (c) Measured phase of the reflection coefficient for the four outputs of the SP4T switch.

[6] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[1] Eduardo Carrasco, Mariano Barba, José A. Encinar and Julien Perruisseau-Carrier, "Two-Bit Reflectarray Elements with Phase and Polarization Reconfiguration", 2013 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, Orlando, Fl., July 7-13 2013.
[2] Eduardo Carrasco, Mariano Barba, José A. Encinar, Julien Perruisseau-Carrier, "Reflectarray Element for Beam Scanning with Polarization Flexibility", International Symposium on Antennas and Propagation, Nagoya, Japan, November 2012.
[3] Eduardo Carrasco, Mariano Barba, Julien Perruisseau-Carrier, "Reflectarray Element With Simultaneous Reconfiguration of Phase and Polarization", IEEE Antennas and Wireless Propag. Lett., *to be submitted*.

4.1.3 Simultaneous phase and frequency dynamic control in reflectarray elements

Derived from their application during almost two decades in chemistry, biology and medicine, microfluidics-based technology offers a wide range of micro-devices as valves, mixers, pumps, or even lab-on-chip systems. These devices and the associated fluid materials can be exploited for manipulating the electrical properties in antennas. The simultaneous and independent control of phase and frequency in reflectarray elements was proposed. The element allows to dynamically scanning the beam at the required frequency in a broadband. The concept is shown in Fig. 5(a)-(d). The cell is based on the well-known aperture-coupled topology which allows controlling the phase of the reflection coefficient by means of varactors, PIN diodes or MEMS. On the other hand, the frequency is adjusted by optimizing the shape of a discontinuous patch made of conventional and liquid metal. The patch is formed by a copper section printed on the upper substrate (d3) and a discrete number of 34-µm-thick cavities, situated 50-µm inside the substrate. The cavities and their associated micro-channels can be fabricated using a combined process of laser ablation and lamination, which is a common process in microfluidics. These cavities can be dynamically filled or emptied with a non-toxic liquid alloy, commercially available as Galinstan®, with electrical conductivity 3.29MS/m and melting point around -19°C. Depending on the number of cavities, the operation frequency can be adjusted, allowing a potential continuous tuning in the band from 25GHz to 35GHz. Fig. 5(e) shows the matching at the input of the microstrip line for different volumes of liquid metal, while the phase or the reflected field is shown in Fig. 5(f) for 3 frequencies.

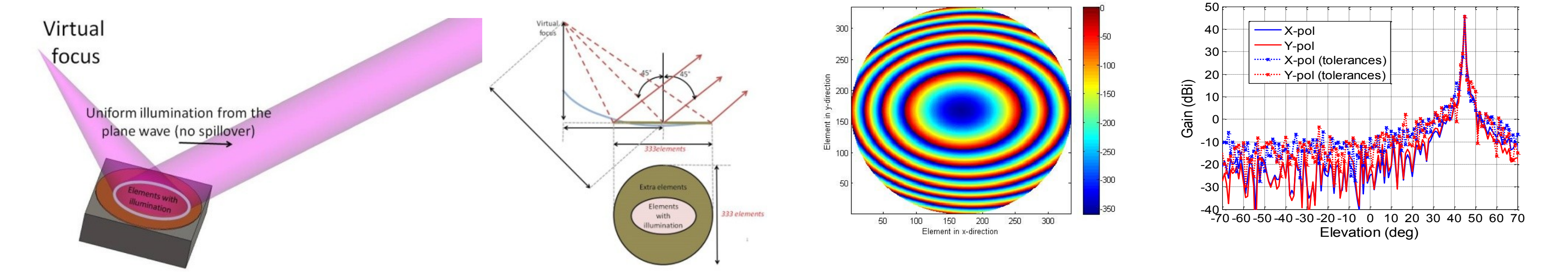


(a) (b) (c) (d) (e) (f)

Figure 5: Dynamic and independent control of phase and frequency in reflectarray antennas. (a) Expanded view of the proposed reflectarray element. (b) Configuration for upper (c) central and (d) lower frequencies (e) Matching of the propossed reflective cell for different volumes of the liquid metal. (f) Phase of the reflection coefficient for the three states, as a function of the microstrip line length, when a plane wave is impinging.

Design of a fixed-beam reflectarray antenna using dielectric resonators at 1 THz

A research line in collaboration with Adelaide University (Prof. C. Fumeaux) was established. It consisted in the design of a reflectarray emulating a parabolic mirror at 1THz, using dielectric resonators. Fig. 6 shows the final design as well as the required phase at each element for radiating a near-field beam (The reflectarray has more than 8000 elements, but because of the confidentiality reasons the main dimensions are not included).



(a) (b) (c)

Figure 6: Reflectarray antenna as parabolic mirror. (a) General topology. (b) Required phase at each element. (c) Virtual far field.

RASTREO project contributed to the future development of efficient multi-reconfigurable antennas, which means the possibility of dynamically adapt more than one parameter of the antenna (beam orientation, beam shape, polarization, frequency, etc), according to the demands of the system. On the other hand, the recent improvements in technology platforms, e.g. solid-state devices, micro electromechanical systems (MEMS), ferro-electric films, liquid crystal (LC), graphene and even liquid metal, for RF dynamic control, make space-fed reconfigurable antennas (reflectarrays but also transmitarrays) a very attractive technology for implementing electronic reconfiguration with new multifunction capabilities.

There is no patent or IPR application related to the work carried out in the project.