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► **To cite this version:**

Vladislav Popov, Badreddine Ratni, Fabrice Boust, Shah Nawaz Burokur. Reconfigurable Sparse Metasurface: Beamforming Beyond Phase Gradient Heuristics. 14th European Conference on Antennas and Propagation (EUCAP 2020), Mar 2020, COPENHAGUE, Denmark. hal-02907061

HAL Id: hal-02907061

<https://hal.science/hal-02907061>

Submitted on 27 Jul 2020

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Reconfigurable Sparse Metasurface: Beamforming Beyond Phase Gradient Heuristics

Vladislav Popov¹, Badreddine Ratni², Fabrice Boust^{1,3}, Shah Nawaz Burokur²

¹ SONDRRA, CentraleSupélec, Université Paris-Saclay, F-91190, Gif-sur-Yvette, France, uladzislau.papou@centralesupelec.fr

² LEME, UPL, Univ Paris Nanterre, F-92410, Ville d'Avray, France

³ DEMR, ONERA, Université Paris-Saclay, F-91123, Palaiseau, France

Abstract—We present the design of a reconfigurable *sparse* metasurface operating at microwave frequencies (X-band). The operating principle of the metasurface *does not* rely on established phase gradient along its surface such that it allows one to overcome common limitations of the phase-gradient-based devices. Instead, we have developed a rigorous microscopic approach that allows one to take into account the interaction between the neighboring elements and engineer the individual response of each scatterer to meet a required functionality. By varying the applied bias voltage, we experimentally demonstrate beam steering as well as generation and steering of two (and more) beams with a single feeding horn antenna.

Index Terms—metamaterials, reflectarray, electronically scanned array, sparse metasurfaces.

I. INTRODUCTION

Absolute majority of reconfigurable metasurfaces including reflectarrays and transmitarrays either operate in accordance with the concept of generalized Snell's law [1] or as digital metasurfaces [2] by using discrete states of a unit cell and evolutionary algorithms to manipulate scattered waves. In both scenarios one struggles to achieve wide phase response of a unit cell (ideally 2π), which is particularly challenging when tunable elements such as varactor or PIN diodes are incorporated. Indeed, as varactor and PIN diodes always bring additional ohmic losses to the system, they broaden the resonance and narrows the phase response range of a unit cell. The same is true for other mechanisms used to achieve tunability in different frequency ranges: phase-change materials, semiconductors, liquid crystals, etc. Furthermore, when one relies solely on the phase response of a unit cell, there are fundamental limitations of metasurface performance [3]. A theoretical solution proposed to improve the efficiency suggests implementing a strongly non-local metasurface [3]. It implies existence of a substantial interaction between distant parts of the metasurface via surface waves propagating along it, see illustration in Fig. 1(a).

In this study, a radically new approach is proposed to design *sparse* metasurfaces for manipulating the scattered field. Based on a rigorous engineering procedure and a numerical method of calculating Green's function, the approach allows one to accurately adjust the scattering response of each individual meta-atom and solve the inverse scattering problem. The intrinsic strong non-local response

of sparse metasurfaces overcomes the fundamental efficiency constraint of their “dense” counterparts [4, 5]. To validate the developed theory, we design a reconfigurable sparse metasurfaces and experimentally demonstrate its superiority over conventional phase gradient metasurfaces by performing anomalous reflections at extreme angles.

A tunable sparse metasurface can be very attractive for controlling many beams with a single excitation source [5-8]. Basically, a reconfigurable sparse metasurface represents itself as a uniform array of loaded wires incorporating tunable elements. It allows one to control polarization currents in each loaded wire and thus perform transformations of the radiation pattern with the same device. Since the distance between the loaded wires is of the order of wavelength, the amount of tunable elements can be significantly reduced in comparison to common metasurface-based reconfigurable antennas. The choice of tunable elements is mainly determined by its resistance which results in enhanced ohmic losses depending however on the frequency range. Conventionally, PIN diodes, RF-MEMS or varactor diodes are used in X-band [9-10]. Conversely to RF-MEMS, PIN and varactor diodes are easily available, based on mature technologies that do not require expertise but introduce quite high losses at X-band frequencies.

II. DESIGN AND EXPERIMENTAL TESTS

We construct a metasurface of a finite array of N loaded wires having deeply subwavelength thickness, as shown in Fig. 1(a)-(c). The impedance density is a proper characteristic of loaded wires comprising a sparse metasurface: it does not depend on either the thickness of the substrate or the separation between neighboring wires [6]. The array of loaded wires is placed on top of a metal-backed dielectric substrate. Incident wave generated by a horn antenna excites polarization currents I_q in the wires which shape the field scattered by the metasurface. The separation between the neighboring wires is $\lambda/2$ (λ is the central operating wavelength), being in strong contrast with common implementations of reconfigurable metasurfaces as *dense arrays* of meta-atoms. A schematic of the sparse metasurface is shown in Fig. 1(b). *Sparse* configuration of the metasurface allows us to accurately take into account the interactions between the wires via Ohm's law [5, 7]:

$$Z_q I_q = E_x^{(exc)}(\mathbf{r}_q) - \sum_{p=1}^N Z_{qp}^{(m)} I_p. \quad (1)$$

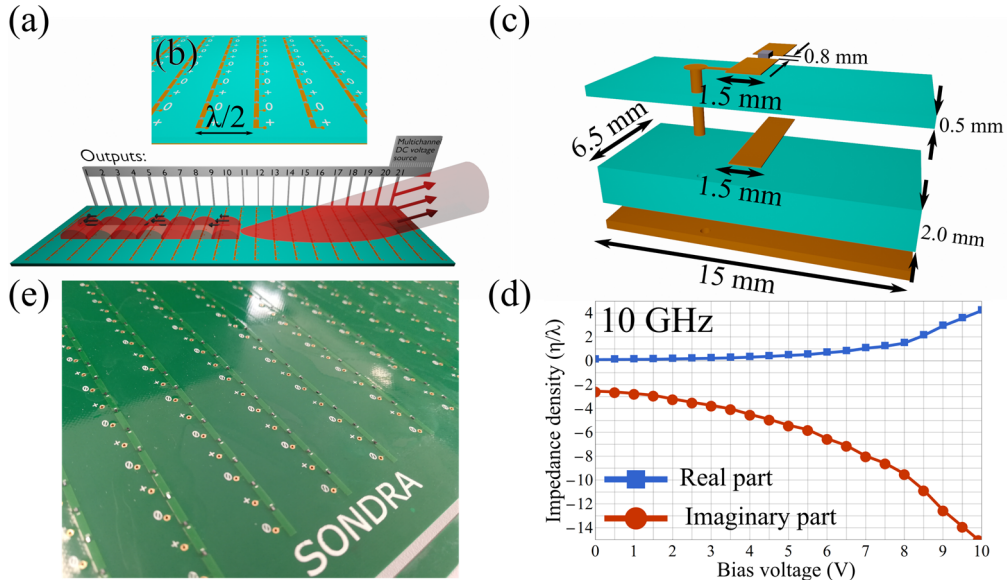


Fig. 1. (a) Illustration of the sparse metasurface performing large-angle anomalous reflection: the sample is illuminated by a horn antenna brought at the distance of 35 cm and appropriate bias voltages are set by means of a multichannel DC voltage source (controlling individually all 21 loaded wires that comprise the sample). Propagating evanescent wave illustrates strongly non-local response of the sample. (b) A close-up illustration of the sparse metasurface. (c) Schematics of the unit cell, the brighter and darker regions correspond, respectively, to dielectric substrates and copper traces. Total thickness of the metasurface is 2.65 mm (including the thickness of the glue layer). (d) Impedance density of a loaded wire (composed of unit cells in (c)) as a function of applied bias voltage established by means of full-wave simulations and experimental characterizations. (e) A close-up photo of the experimental sample.

The right-hand side of (1) represents the total electric field at the position of the q^{th} wire, $E_x^{(exc)}(\mathbf{r}_q)$ is the incident wave plus its specular reflection from the metal-backed substrate, $Z_{qp}^{(m)}$ is the mutual-impedance density (the electric field created by the p^{th} wire at the position of the q^{th} wire).

By gaining control over the impedance densities Z_q of the wires, we are able to adjust the currents I_q and manipulate the scattered field. In order to realize the control of the impedance densities at microwave frequencies, we use a radio-frequency varactor diode (MAVR-011020-1411) as a reconfigurable element. The capacitance of the varactor diode can be changed when applying a bias voltage. It allows one to implement a wire whose impedance density can be controlled in real time by changing the external bias voltage. Individual control of each element in the metasurface is possible via a multichannel DC voltage source.

The design of a unit cell is performed with the help of local periodic approximation (LPA) developed recently for sparse metasurfaces [6]. Schematics of the developed reconfigurable unit cell is shown in Fig. 1(c). One can distinguish three principal parts of the unit cell: the varactor loaded microstrip line (top), the microstrip line (middle), and the bias via (alongside). The microstrip lines together with the varactor diode form an effective parallel RLC circuit, the middle microstrip line playing the role of an inductance. It allows one to effectively decrease the minimal capacitance of the varactor diode and expand the dynamic range of the impedance density Z_q as a function of bias voltage (without increasing the number of varactor diodes per unit wire's length). The latter is extremely important when one tends to decrease the ohmic losses in varactor diodes. The biasing

voltage is applied to the varactor diode through the metallic via changing the overall response of the unit cell. The bias network is hidden behind the ground plate.

Once the metasurface is fabricated, Fig. 1(e), it is characterized to establish the dependence of the impedance density Z_q on the biasing voltage. To that end, complex amplitude of the specular reflection from the sample was measured when equal voltages are applied to all varactor diodes. The complex amplitude is normalized to the one measured from a metallic plate of the same size and thickness as the sample. Then the retrieval procedure described in [6] is used to extract impedance density Z_q presented in Fig. 1(d).

This dependence is used to set appropriate bias voltages (in accordance with the theory presented in [7]) to all the wires and perform beam forming. A photo of the experimental setup is shown in Fig. 2(a). Figs. 2(b)-(e) show experimentally measured far-field scattering profiles at 9.5 and 10 GHz. The results demonstrate the ability to perform beam steering and excitation of multiple beams with the reconfigurable sparse metasurface. In the first set of measurements the incidence angle is set to 45° (to conform the numerical example above), operating frequency is 10 GHz. Figure 2(b) demonstrates dynamic beam-steering from 20° up to -70° , the spurious scattering in the far-field remains below the -10 dB level being well beyond the limits of gradient metasurfaces for large reflection angles. The efficient large-angle anomalous reflection serves as an indirect manifestation of a strong non-locality by the fabricated sparse reconfigurable metasurface [3, 5]. Figures 2(c), (e) demonstrate the sample's agility with respect to the incidence angle which had been changed to 0° .

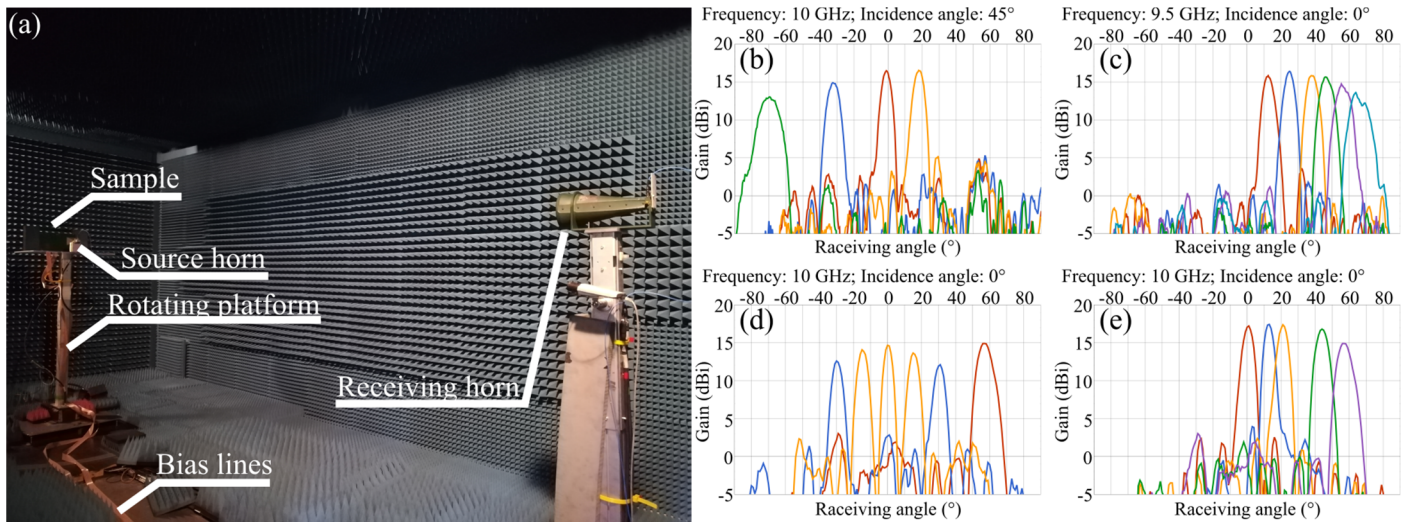


Fig. 2. (a) A photograph of the experimental setup: measurements were performed in an anechoic chamber, the sample and an illuminating horn are placed on a rotating platform, radiation pattern is measured by a receiving horn antenna. (b) – (e) Measurement results of radiation patterns (gain in dBi versus receiving angle) for different set of input voltages. (b) Steering of a single beam, when the incidence angle is 45° . (c), (e) Steering of a single beam at 9.5 and 10 GHz, respectively, when the incidence angle is 0° . (d) An example of controlling the number of beams at 10 GHz, incidence angle is 0° . In all cases there is only a single illumination source (a horn antenna at 35 cm distance from the sample).

More complex examples of beam-forming are illustrated in Fig. 2(d), which demonstrates dynamic control of the number of excited beams. High performance of the sample is due to the rigorous theoretical model behind: we account for the mutual interactions between the elements, consider real-type excitation (non-planar incident wavefront) and precisely solve the inverse scattering problem.

III. CONCLUSION

In summary, we have presented the design of a reconfigurable sparse metasurface operating at microwave frequencies (X-band). By varying the applied bias voltage, we have been able to experimentally demonstrate beam steering as well as generate and steer two (and more) beams with a single feeding horn antenna. Since the operating principle of the fabricated metasurface *does not* rely on established phase gradient along its surface, it allows one to overcome common limitations of the phase-gradient-based devices. To achieve this, we have developed a rigorous microscopic approach that allows one to take into account the interaction between the neighboring elements and engineer the individual response of each scatterer to meet a required functionality.

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