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Beamforming with Reconfigurable Metagrating: Design and Experimental Demonstration

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***Abstract*—Recently, metamaterial-inspired diffraction gratings (or metagratings) have demonstrated unprecedented efficiency in wavefront manipulation by means of relatively simple structures. Conventional one-dimensional (1D) gratings have a profile modulation in one direction and a translation symmetry in the other. In 1D metagratings, the translation invariant direction is engineered at a subwavelength scale, which allows one to accurately control polarization line currents and, consequently, the scattering pattern. In this paper, we present the design and experimental results of a reconfigurable metagrating operating at 14 GHz. The unit cell of the metagrating incorporates a varactor diode as a tunable element and an additional passive inductive grid is used to effectively decrease the minimum capacitance of the varactor. By varying the applied bias voltage, one is able to perform beam steering as well as generate multiple beams with a single feeding horn antenna.**

Keywords— metagratings, reflectarray, electronically scanned array

I. Introduction

Metagratings demonstrated unprecedented capabilities for efficient manipulation of scattering patterns [1-4]. A metagrating can be represented as a one-dimensional periodic array of polarization line currents which are excited in thin loaded wires by an incident wave. The prefix "meta" implies that the wires are constructed from meta-atoms that are small compared to the wavelength such that it becomes possible to define an averaged macroscopic quantity like an impedance density. Meanwhile, the distance d between the different wires always remains on the order of operating wavelength which does not allow one to introduce averaged surface impedance (conversely to metasurfaces). The possibility to engineer the impedance density and an accurate analytical model allows one to overcome the limitations of metasurfaces in manipulating wavefronts. We consider a reflective-type metagrating when the wires are placed on top of a perfect electric conductor (PEC)-backed dielectric substrate. The scattering pattern from a metagrating is formed by propagating diffraction orders. The way towards control over arbitrary number of propagating diffraction orders by means of many unit cells based metagratings was outlined in [2].

A tunable metagrating can be very attractive for controlling many beams with a single excitation source. Basically, a tunable metagrating represent itself as a uniform array of wires incorporating tunable elements. It allows one to control polarization currents in each "wire" and, thus, perform all possible transformations of the diffraction pattern with a single device. Since the distance between wires is of the order of wavelength, the amount of tunable elements can be significantly reduced in comparison to metasurface-based reconfigurable antennas. The choice of tunable elements is mainly determined by the intrinsic resistance which results in enhanced Joule losses depending, however, on the frequency range. Conventionally, PIN diodes, RF-MEMS or varactor diodes are used in X-band [5, 6]. Conversely to RF-MEMS, PIN diodes and varactor diodes are easily available, based on mature technologies, and do not require expertise but introduce quite high losses at X-band frequencies. Eventually, we have chosen varactor diode as tunable element for integration in a metagrating's unit cell as it provides higher flexibility.

II. Design of Tunable Metagrating

Local periodic approximation (LPA) has been used to design metasurfaces as well as reflect- and transmit-array antennas [5, 7]. It represents a method to estimate scattering properties of a single unit cell in a nonuniform array. To that end, a unit cell is placed in the corresponding uniform array of the same unit cells which scattering parameters are then attributed to the unit cell in the nonuniform array. Scattering parameters of the uniform array are usually found from numerical simulations. However, there are also particularly simple cases that can be treated analytically (like PEC square patches).

Previously we have developed an analog of the LPA to design metagratings [3]. Thus, a "wire" constituting a metagrating's supercell is placed in the corresponding 1D uniform array (period $d < \lambda$) of the same wires. Found from 3D full-wave simulations, reflection coefficient is used to calculate the corresponding polarization current in the wire. Then, we harness rigorous analytical approach to extract the impedance density of a single "wire" carefully accounting for the impact of the adjacent wires. Noteworthy, the interaction between the wires and with the substrate is accurately taken into consideration analytically via mutual-impedance density [3]. Thus, the LPA can be rigorously applied for metagratings represented by nonuniform arrays of wires (in bright contrast to the case of metasurfaces).

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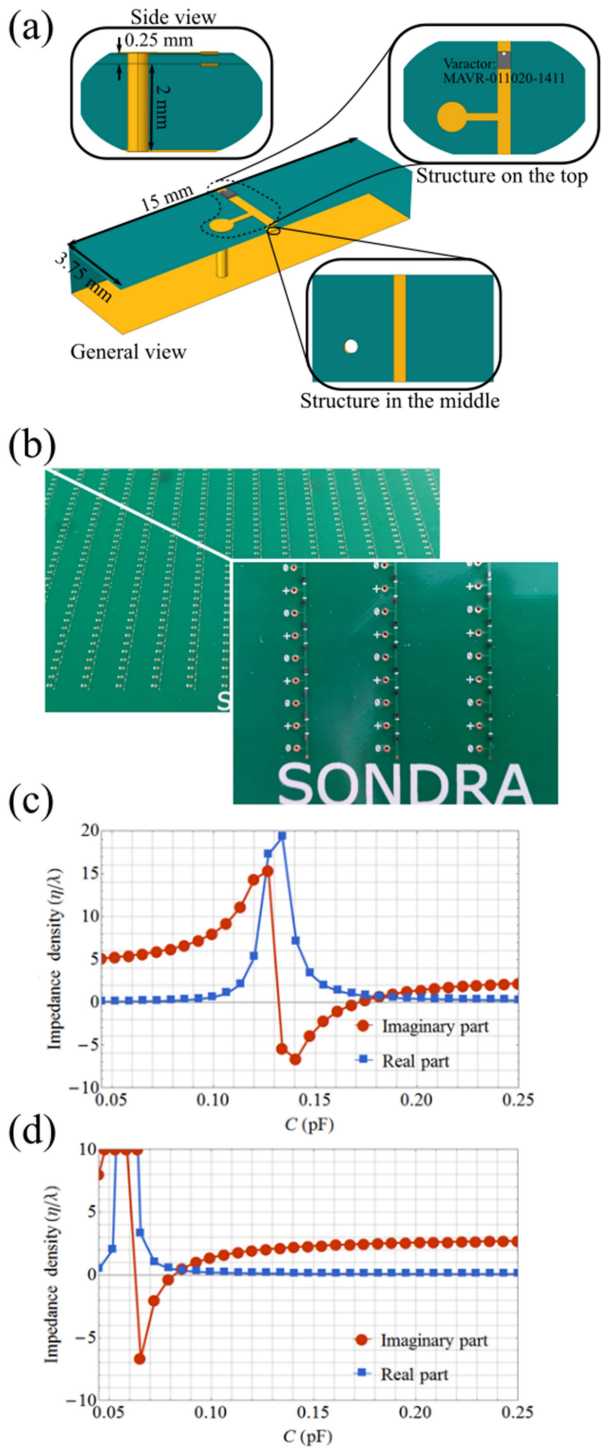

FIG. 1. (a) Schematics of a unit cell of a reconfigurable metagrating. (b) Photography of the fabricated sample. Computed impedance density of the reconfigurable unit cell versus varactor's capacitance. Frequencies are 10 GHz (c) and 14 GHz (d). We consider illuminating plane-wave incident at angles 45° (c) and 5° (d).

Design of a unit cell of a tunable metagrating is achieved by means of the developed LPA and schematically presented in Fig. 1(a). Overall, it represents a six layer PCB with the bottom layer (not shown in Fig. 1(a)) reserved for the bias network. A metallic via is used to bias the varactor. Chosen varactor diode (MAVR-011020-1411) has a capacitance range varying from 0.045 pF to 0.25 pF. An inductive grid is added to the bottom of the first layer in order to effectively decrease capacitance of the varactor and be able to cover a wider range of available impedance densities at 10 GHz, as shown in Fig. 1(c). A photography of the fabricated sample is shown in Fig. 1(b).

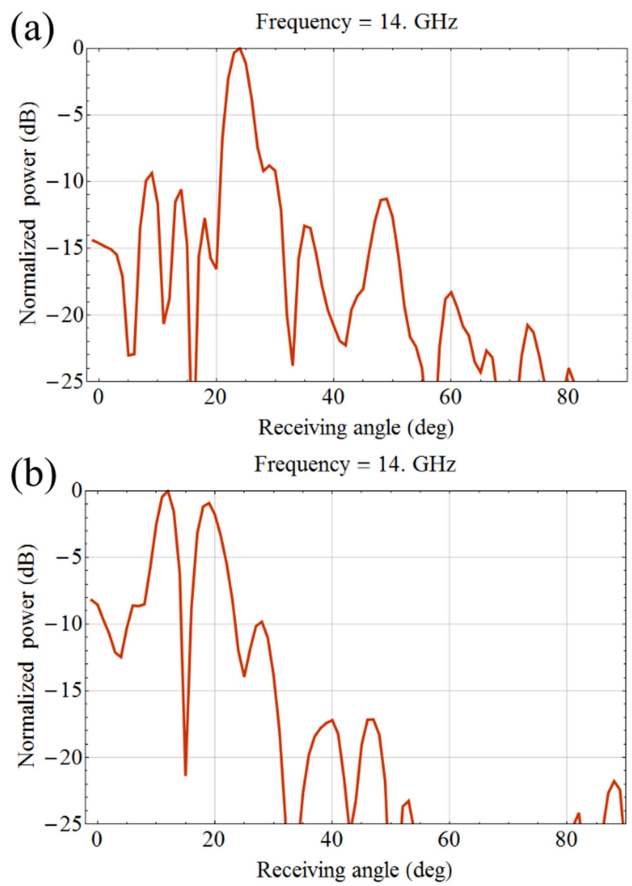

FIG. 2. Scattering profiles measured experimentally at 14 GHz with an incidence angle of -5°. The figures demonstrate examples of (a) beam steering at 25° and (b) excitation of multiple beams at 12.5° and 20.3°.

III. Experimental Demonstration of Wavefronts Control

From the computed response of the unit cell at 10 GHz (following [3]), we can see that when approaching the resonance there is an increase of the real part of the wire's impedance density resulting in high Joule losses (due to significant resistance value of the varactor diode). In the case of metagratigs, the losses may completely destroy desirable response (side lobes become unacceptable). On the other hand, at higher frequencies the resonance can be shifted outside the working range of the varactor's capacitances, as it happens at 14 GHz (compare Figs. 2(c) and (d)), where we are able to demonstrate beamforming.

In a first step, the sample was characterized (by applying the same bias voltage to all varactor diodes) to derive the dependence of the bias voltage on the varactor's capacitance. To that end, we measure the frequency dependence of the amplitude of the specularly reflected wave form the sample

and compare it with numerical simulations. To be more specific, we compare the positions of the resonances and obtain the relation between the bias voltage and the varactor's capacitance. This dependence is used to set appropriate bias voltages (in accordance to the theory presented in [2]) to all the wires and perform beam forming. Fig. 2 shows the experimental measurements performed in an anechoic chamber dedicated to bistatic radar cross-section measurements of the far-field scattering profiles at 14 GHz. The results demonstrate the ability to perform beam steering and excitation of multiple beams with the reconfigurable metagrating.

IV. Conclusion

In summary, we have presented the design of a reconfigurable metagrating operating at microwave frequencies. By varying the applied bias voltage to the varactor diodes incorporated in the metagrating, we have been able to experimentally demonstrate beam steering as well as generate two beams with a single feeding horn antenna. We have also pointed out that the varactor's resistance may significantly influence the performance of a reconfigurable metagrating, when the unit cell shows a resonance at the desired operating frequency. Therefore, our further research will be particularly focused on reducing the impact of the varactor's resistance by designing a larger unit cell in the transverse direction, which will further reduce the number of varactors per unit length.

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