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Reconfigurable Metasurface Antenna based on a Single Control Signal

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***Abstract*—A doble-layer reconfigurable metasurface antenna controlled by varactor diodes is presented. The structure is composed by a sinusoidally modulated metasurface on top, which is backed by a uniform metasurface loaded with varactor diodes and designed to accurately control the phase propagation. Beam-scanning dictated by a single parameter is performed. Numerical results are reported, demonstrating the good performance in terms of beam shape and aperture field control.**

I. Introduction

Wireless connectivity has kept an extremely fast growing trend over the last decades. After five generations, the expected improvements of wireless networks operating on the end-points of the channels are bounded. Therefore, requirements such as end-to-end latencies below one millisecond, data rates of the order of 1 Tb/s and high energy efficiency cannot be met. In order to unlock new limits in terms of performance metrics, new theoretical communication models which treat the environment as an optimization problem are emerging [1]. Future wireless networks will follow the previous paradigm by leaving end-point governed channels to give way to controllable scenarios [2].

6G environments require electromagnetic devices able to survive to this evolution of communication networks. At the transmitter, reconfigurable antennas based on electronic devices are promising solutions [3]. Typically, network operators find troubles to provide uninterrupted connectivity to users, which can be afforded by implementing beam-scanning based on switching elements. Furthermore, this feature increases the spectral efficiency due to its reduced interference [2].

Specifically, leaky-wave phenomenology based on sub-resonant elements defining a periodic impedance boundary condition (IBC) is a potential solution to produce reconfigurable transmitters. It is worth mentioning its low-cost manufacturing, low envelope and flexible control of the aperture tapering [4]. Fabrication costs and power consumption are still major drawbacks in this field of research. The originality of this study is that it exploites the concept of modulated metasurface antenna to propose a compact topology, with simple biasing arrangements and suitable for the implementation of a varactor model tuned within a narrow set of capacitances, allowing for the optimization of the losses.

II. Single control antenna design: Scanning through the average impedance

Uniform leaky-wave antennas (LWAs) are generally dispersive due to their boundary conditions (BCs). When they are excited at a proper frequency, transverse resonance occurs and a radiation angle is consequently defined $sin(\theta_R) = \frac{k_p}{k_0}$. Where θ_R is the radiation angle, k_p is the propagation constant and k_0 is the free-space wavenumber. The radiation mechanism of our proposed topology is not based on the propagation modes of a wave-guiding structure, but on impedance sheets that support slow waves [5]. Here, by properly introducing periodic discontinuities, the consequent Floquet harmonics can resonate from a transverse point of view, achieving far-field radiation. In our case, since we work with electrically small cells, BCs are homogenized and periodic variations are implemented through a smooth modulation of the surface impedance.

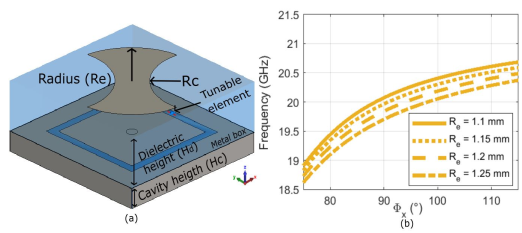

Fig. 1. (a) Unit cell. (b) Dispersion analysis for different R_e values.

Fig. 1b shows the proposed unit cell, which can be equivalently regarded as a resonant circuit with capacitances on top, defined by the gap between top elements. The bottom layer consists of a metal cavity slotted on its upper wall. This unit cell is analyzed in a periodic environment. A variable capacitance bridges the slot and tunes the cell near the bandgap of the periodic structure. Thanks to it, a slight variation of the dimension R_e strongly influences the surface wave velocity, as represented in Fig. 1b. In this manner, a sufficient impedance dynamic can be obtained to implement the periodic IBC of Fig. 2b. It must be clarified that the elements are sub-resonant, with a size of $\frac{\lambda}{5}$ at $f = 20$ GHz, but they work near the resonance due to the presence of varactors.

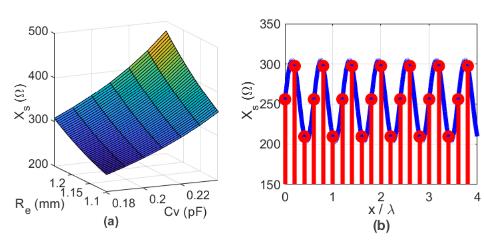

Fig. 2. (a) Database for the implementation of the IBC. (b) Recreation of the IBC through pixels.

Fig. 2 plots the solutions for the resonance equation. This map is used to implement a smooth periodic variation of the impedance. As a consequence, the fields become periodic and can be decomposed into an infinite expansion of spatial harmonics. In this way, through the database of Fig. 2a, we can define the periodic IBC and control the radiation of the $n = -1$ Floquet wave.

$$Z_s(x) = jX_s \left[1 + sin\left(\frac{2\pi x}{d}\right)\right] \tag{1}$$

where X_s is the average surface impedance, m the modulation depth and d the period. With a proper choice of the modulation period, the vertical component of the wavenumber of the $n = -1$ Floquet wave becomes real, getting radiated power travelling away from the antenna.

$$sin(\theta_{Rad}^{n=-1}) = \frac{k_0\sqrt{1+X_s'^2} - \frac{2\pi}{d}}{k_0} \tag{2}$$

As (2) proves, the pointing angle can be controlled by X_s. Since the top elements are sinusoidally modulated, this layer is responsible for the radiation. The uniform underneath metasurface is designed to control the average level of the modulation. The capacitance and inductance associated to both the slot and the pin (Fig. 1a) can be optimized at $f = 20$ GHz to work near the resonance of our cells. As a result of it, a global reconfiguration of the varactors within the range of $0.18 - 0.24$ pF allows to significantly slow down the surface wave (Fig. 3). Hence, the proposed scanning technique is based on the adjustment of the surface wave wavelength (λ_{sw}) for a fixed periodicity.

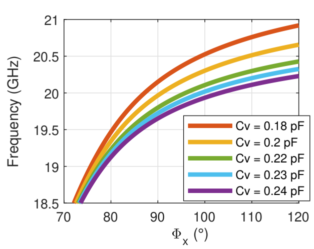

Fig. 3. Resonance tuning of the unit cell for $R_e = 1.2$ mm.

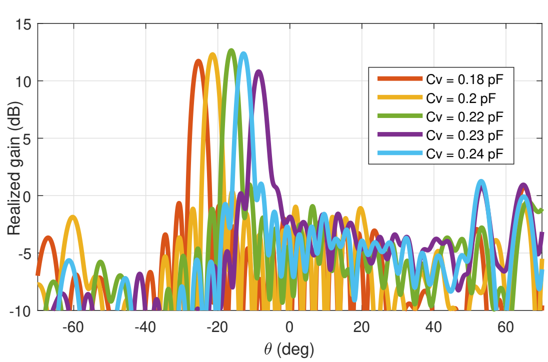

Fig. 4. Scanning pattern of the single control structure.

Full-wave results of a structure composed by $N = 80$ elements with a total length of $L = 16\lambda$ are plotted in Fig. 4. The model MAVR-000120-141 from MACOM provides the desired capacitance range. Fig. 5 shows its retrieved equivalent parameters for our frequency of design.

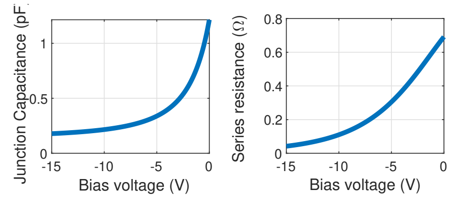

Fig. 5. Equivalent parameters obtained from the SPICE model of the MAVR-000120-141 varactor diode from MACOM

As Fig. 6 shows, radiation efficiency (η_{rad}) degrades from 70% to 33%. This can be explained from the losses introduced by the varactors as the reverse voltage increases. Moreover, the field of view is limited due to the decline of group velocity with the variable capacitance C_v (Fig. 3). This latter can be enhanced by adding a matched layer on top. However, electronic scanning dictated by a single biasing signal can be implemented with this topology, overcoming one of the key issues of reconfigurable antennas design.

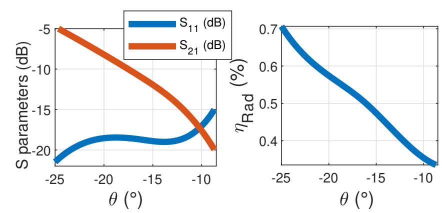

Fig. 6. Scattering parameters and radiation efficiency for every configuration at $f = 20$ GHz.

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