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Reconfigurable coaxial metasurface radar absorber using varactor diode tuning

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Abstract—Metasurfaces can be used as radar absorbers. However, passive metasurfaces are intrinsically limited in their bandwidth-to-thickness ratio. Thus, it is difficult to design a metasurface which is both thin and wideband. To overcome such limitation, we design a reconfigurable metasurface using varactor diodes. Their bias-dependent variable capacitance offer a range of resonance frequencies that can cover most of the VHF-UHF range. Such behavior is here highlighted on a coaxial metasurface by simulation. Reconfigurability is intended to serve as a preliminary step towards time-modulated metasurfaces.

Index Terms—metasurface, varactor diode, reconfigurability, radar absorber, finite-element simulation

I. INTRODUCTION

In surveillance radars context, the detectability of a target is measured by its radar cross section [1] – should the signal-to-noise ratio be greater than the false alarm threshold, a target presence is noticed. The only solution to greater stealth lies in the drastic reduction of scattered power. This can be achieved using radar absorbers – devices depriving electromagnetic impinging waves of power by conversion to heat. In an effort to improve stealth devices, researchers have turned to metasurfaces in the last 20 years [2]. However, as with any passive radar absorbers, metasurfaces are limited in their bandwidth-to-thickness ratio by the Rozanov bound [3]. As a preliminary step towards designing better devices, this paper focuses on the reconfigurability of a metasurface radar absorber. Such mechanism is enabled by the use of varactor diodes whose capacitance is a function of applied biasing.

This paper is structured as follows. Section II focuses on the design of the metasurface, the absorption requirements, and the choice of the lumped electronic components. Section III presents finite-element simulations highlighting both agility in frequency but also sensitivity to varactor diodes' parasitic elements. Section IV then concludes and provides perspectives

for turning such a reconfigurable metasurface into a time-modulated metasurface to overcome the Rozanov bound [4].

II. RECONFIGURABLE COAXIAL METASURFACE

A. Coaxial radar absorbing metasurface

Over the frequency range of interest [100, 700] MHz, the wavelengths are in the order of 1 m – a whole metasurface, even using deeply subwavelength patterns, is thus impractical. In order to overcome this, we chose to work with a 1D coaxial metasurface. In Fig. 1, both a *a*) capacitive and an *b*) inductive 1D metasurfaces are transposed from a cartesian to a coaxial geometry. This geometry makes for a much more compact setup and greatly reduces measurement times and fabrication costs.

The circuit given in Fig. 2 is obtained with an equivalent circuit analysis of the propagation of a TEM wave within the short-circuited coaxial waveguide into which the metasurface is inserted. Being electrically thin, the metasurface can be modeled as a single admittance Y_{MS} . The reflection coefficient Γ seen by the impinging wave of admittance Y_0 is therefore

$$\Gamma = \frac{Y_0 - Y_{in}}{Y_0 + Y_{in}} \quad (1)$$

where $Y_{in} = Y_{MS} + Y_{SC}$ is the admittance of the short-circuited metasurface. According to transmission line theory [5], since this short-circuit stands at a distance $\ell \ll \lambda$, it acts as an inductance of value $L_{SC} = \mu_0 \mu_r \ell$. In such configuration, the absorption conditions are such that

$$\begin{cases} \text{Re}(Y_{MS}) = Y_0 \\ \text{Im}(Y_{MS}) = -\frac{1}{j\omega L_{SC}} \end{cases} \quad (2)$$

To satisfy this first equation, the metasurface must have a resistive component, while to satisfy this second equation, the metasurface would have to be non-Foster, which is not the path

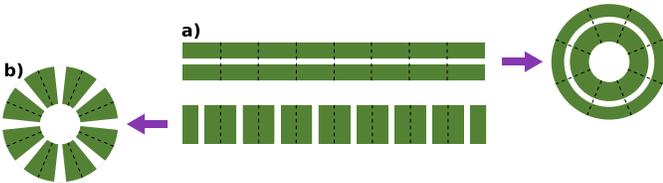


Fig. 1. 1D Cartesian metasurfaces of a) capacitive (horizontal slit) and b) inductive (vertical slit) iris pattern transposed into the a) capacitive coaxial metasurface of interest and b) an equivalent inductive coaxial metasurface.

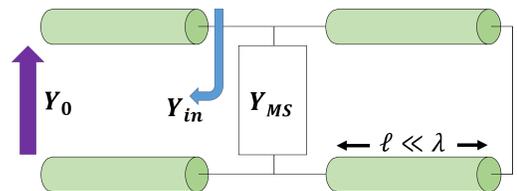


Fig. 2. Equivalent circuit model of the network formed by the coaxial metasurface of interest inserted into a short-circuited coaxial waveguide.

followed here. However, over a reduced bandwidth, a good-enough solution is to use a capacitive behavior – hence the choice of the capacitive [5] iris of metasurface *a*) in Fig. 1.

B. Choice of the lumped electronic elements

The metasurface of Fig. 1 does not meet the absorption requirements (2) without the use of lumped elements, as confirmed by an analysis similar to the one done in [6]. Resistive and capacitive components are therefore added to the short-circuited metasurface, turning the equivalent circuit of Fig. 2 into that of a parallel RLC circuit. It therefore resonates – and absorbs – at a frequency f_r such that

$$f_r = \frac{1}{2\pi\sqrt{L_{SC}C_{MS}}} \quad (3)$$

with C_{MS} the metasurface’s capacitance, composed of both intrinsic (iris) and extrinsic (electronic) elements.

The lumped elements are surface-mounted alternatively across the coaxial aperture in 45° increments as shown of Fig. 3 (actual prototype, ongoing measurements). To meet the 50Ω impedance matching requirements, four 200Ω resistors are therefore soldered in parallel, while to allow for reconfigurability of the resonance frequency, four variable capacitances in the form of varactor diodes are used. The SMV1249 model by Skyworks® [7] is chosen for its total capacitance, lying in the [37.35, 2.38] pF range for biases from 0 to 5 V, resulting in resonances within the frequency range of interest.

III. SIMULATION

A model of such a reconfigurable metasurface is used for simulations with the finite-element software COMSOL® to quantify its absorbing properties. The varactor diode’s SPICE model [7] is provided on Fig. 4. It is composed of the diode’s PN-junction variable capacitor (C_D), a bias-dependent series resistor (R_S) and the packaging’s parasitic inductor (L_S) and capacitor (C_P).

One may first notice on the S_{11} -parameter simulation results of Fig. 4 the absorbing behavior of the metasurface as the blue curves. The reflection coefficient is drastically reduced around the resonance frequency of each configuration obtained at different biases. Absorption peaks are thus obtained from 160 MHz at 0 V all the way to 490 MHz at 5 V.

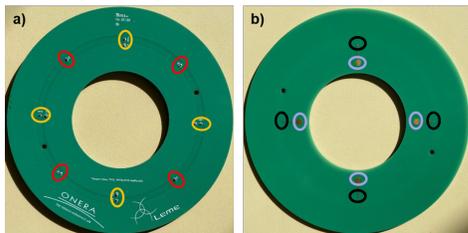


Fig. 3. a) Prototype of the coaxial metasurface exhibiting alternatively resistors (dark, red circles) and varactor diodes (light, orange circles) at 45° increments across the coaxial aperture and b) biasing back plane showing DC pads (dark, black circles) and vias (light, purple circles).

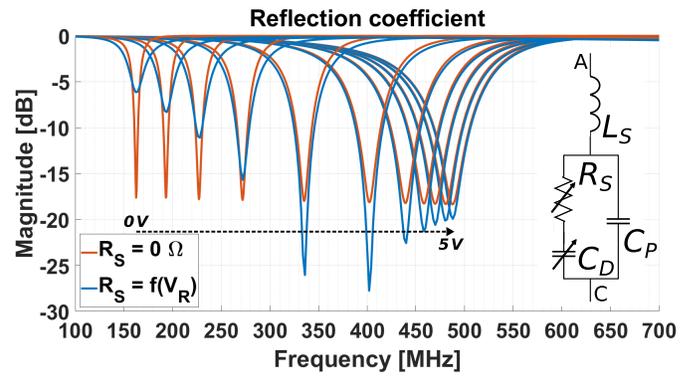


Fig. 4. Simulation results of the S_{11} -parameter of the network formed by the short-circuited coaxial metasurface over [100, 700] MHz obtained for reverse biasing voltages within [0, 5] V of the Skyworks® SMV1249 varactor diode of given SPICE model. Curves in blue use datasheet, bias-dependent values of the series resistor while curves in red are produced using an idealized model of null series resistance.

One may also notice variations in the magnitude of the absorption peaks of the model using bias-dependent values of the series resistor (blue). As confirmed by the set of curves from an altered model (red) – for which $R_S = 0 \Omega$ no matter the bias –, this is an unwanted artifact emerging from the varactor diode’s variable resistance, leading to impedance mismatch.

IV. CONCLUSIONS

Simulations highlighted the reconfigurability of a radar absorbing metasurface of coaxial geometry using varactor diode tuning. Absorption peaks are obtained within a broad [160, 490] MHz frequency range for biasing comprised in the [0, 5] voltage range. However, these simulations also brought to light that the choice of varactor diode should not depend solely on its capacitance range, but also on its series resistor. A capacitance-ratio-to-series-resistance trade-off is therefore required and further investigations are expected to provide good compromise practices for better varactor diode picking.

In further developments of this project, this reconfigurable metasurface is intended to serve as a time-varying radar absorber. Temporal modulation of the embedded varactor diodes is expected to help in overcoming the Rozanov bound [4].

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