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# Quasi-Optical Excitation of a Circularly-Polarized Metasurface Antenna at K-band

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**Abstract**—This paper presents a new concept of modulated metasurface (MTS) antenna for satellite communications. As opposed to using cylindrical surface waves (SW) to excite circular apertures, we employ a quasi-optical beamformer to launch a plane SW. This architecture enables an efficient illumination of rectangular apertures. In addition, the use of anisotropic MTS elements allows us to obtain circularly-polarized beams with excellent characteristics in terms of cross-polarization discrimination. We present the design process of a prototype at K-band and the obtained simulation results, which prove the suitability of this antenna for satellite data links.

**Index Terms**—Metasurface antennas, leaky waves, circular polarization, satellite communications, CubeSats.

## I. INTRODUCTION

Satellite communications usually require high-gain antennas with circular polarization and beam steering capabilities. In the case of moving platforms (e.g. drones and spacecrafts), these features are often obtained by employing heavy and bulky reflector antennas [1] or complex phased arrays [2]. Modulated metasurface (MTS) antennas offer an interesting alternative for some applications, since they are able to comply with the high gains required by satellite communications, while keeping a light weight and a low profile [3].

MTSs typically consist of arrangements of sub-wavelength patches on a grounded dielectric slab [4]–[7] or metallic pins grown on a metal base-plate [8]. These elements are distributed on a regular grid and their size is generally smaller than  $\lambda_0/6$ , where  $\lambda_0$  is the free-space wavelength. Provided that the aperture is finely discretized at a given frequency, a surface wave (SW) supported by the MTS layer will see the textured surface as a continuous impedance boundary condition (IBC). By properly modulating this equivalent IBC, one can transform the bounded SW into a leaky wave (LW), obtaining a directive radiation effect [9]. Furthermore, the pointing angle of the radiated beam can be controlled by tuning the parameters of the modulation, as explained in [6], [9].

In circular apertures, the SW launcher is usually placed at the center and utilizes a coaxial pin, so that the intrinsic cylindrical symmetry of this configuration helps to illuminate uniformly the circular area [3]–[5]. However, this configuration is not suitable when dealing with rectangular apertures, since the cylindrical wavefront is not adapted to the aperture geometry anymore. For rectangular shapes, a plane SW is

needed and the feeder must be adapted. A lens can be employed to collimate a cylindrical SW [10], but an additional area is necessary to place the beamformer. A more compact possibility is the use of a pillbox quasi-optical system [11]. It consists of two substrate layers that are vertically stacked. A horn in the bottom layer is used to launch a wave that impinges on a reflector and is finally transformed into a plane SW in the top layer. Then, this plane SW can be used to illuminate a modulated MTS set on the upper layer, thus obtaining a compact MTS antenna.

The high degree of control of the aperture fields provided by modulated MTSs allows one, among other possibilities, to achieve the desired polarization for the radiated wave. In the case of satellite communications, circular polarization is commonly demanded, and this is also affordable by MTS antennas. Circular apertures have been typically employed for this purpose [3]–[5], [7], [8], [12], since the circular geometry eases the generation of circular polarization. For some specific platforms, such as CubeSats [13], [14], rectangular antennas could be more appropriate in terms of form factor agreement. Although linear LW antennas with circular polarization have been proposed [15], high-gain prototypes (directivity larger than 25dB) are not so commonly found in literature.

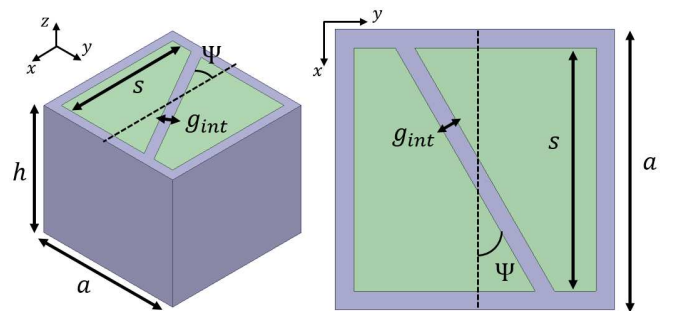


Fig. 1. Unit-cell used to implement the MTS. The fixed parameters are  $h = 1.28\text{mm}$  and  $a = 1.5\text{mm}$ , the others are swept to generate the database.

In this work, we combine a modulated MTS with a pillbox beamformer to obtain a rectangular MTS antenna with right-handed circular polarization (RHCP). To this end, we use an equivalent tensor IBC that presents an anisotropic distribution. The MTS design includes the correct choice of the metallic

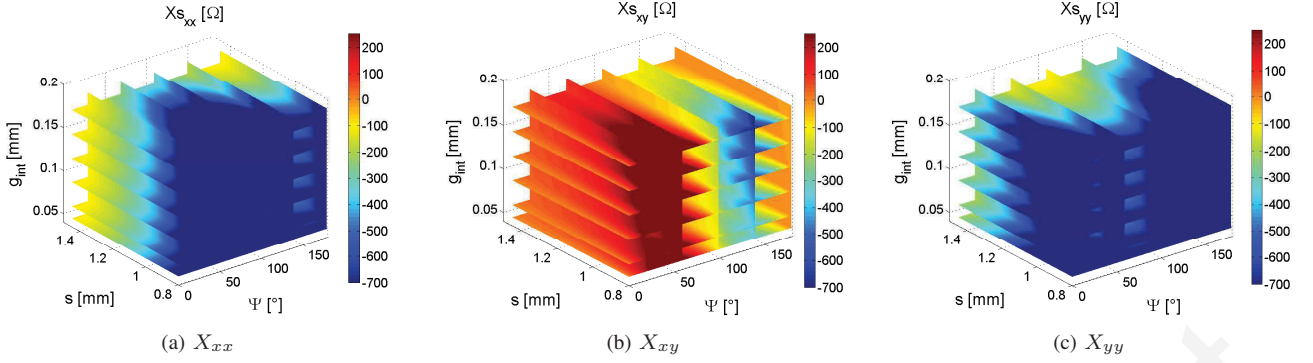


Fig. 2. 3-dimensional database relating the impedance components of (1) with the geometry of the patch in Fig. 1, where  $g_{int}$  is the internal gap size,  $s$  is the patch size and  $\Psi$  is the gap rotation.

patch to implement the tensor IBC, as well as a suitable arrangement along a Cartesian layout. In the next section, we describe the configuration of this MTS and we show the simulation results of the final structure. Throughout the paper, we will refer to a Cartesian reference system with coordinates  $(x, y, z)$  and unit vectors  $(\hat{x}, \hat{y}, \hat{z})$ .

## II. RIGHT-HAND CIRCULARLY-POLARIZED METASURFACE ANTENNA FED BY A PILLBOX BEAMFORMER

Next, we present a specific design to describe the proposed architecture. In this particular case, we apply a transparent impedance [4] (or sheet transition IBC [16])  $\underline{Z}_s = j\underline{X}_s$  to introduce the dispersion effect by the grounded dielectric slab in the design procedure. We choose to direct the beam at  $\theta_0 = -5^\circ$  at a central frequency of  $f = 20.7\text{GHz}$ . The employed material in both pillbox layers is Rogers RO3006 ( $\epsilon_r = 6.15$ ,  $\tan \delta = 0.002$ ) with thickness  $d = 1.28\text{mm}$ . As mentioned, we need to impose an anisotropic MTS for our proposal. Hence, we model our MTS as a reactance tensor of form

$$\underline{X}_s = \left[ \hat{x}\hat{x}X_s^{xx} + (\hat{x}\hat{y} + \hat{y}\hat{x})X_s^{xy} + \hat{y}\hat{y}X_s^{yy} \right], \quad (1)$$

whose tensor components are modulated along  $x$  as

$$\begin{aligned} X_s^{xx}(x) &= X_{av}(1 + M \cos(2\pi x/p)), \\ X_s^{xy}(x) &= X_{av}(M \sin(2\pi x/p)), \\ X_s^{yy}(x) &= X_{av}(1 - M \cos(2\pi x/p)). \end{aligned} \quad (2)$$

In (2),  $X_{av}$  is the average reactance,  $M$  the modulation index ( $0 \leq M \leq 1$ ), and  $p$  the period of the modulation. The form of the modulation in (1)-(2) results from the holographic product of the reference plane SW with the object beam pointing at  $\theta_0$ .

In order to implement (1), we use the patch shown in Fig. 1. By varying its size  $s$ , the internal gap size  $g_{int}$  and the rotation of the gap  $\Psi$ , we generate the 3D database in Fig. 2, that relates the entries of the tensor IBC with the geometry of the patch. We use the method in [17] to extract the impedance value for each patch configuration. From the constructed database, we

compute the geometry of the patches required to implement the space-dependent impedance in (1). The obtained MTS layout implements the ideal tensor IBC components in (2) with a relative implementation error lower than 2% for all the components of  $\underline{X}_s$ . Then, we place this layout on the pillbox top layer to get our final structure, shown in Fig. 3. A matching section consisting of a slot array is placed after the pillbox upper parallel plate to match its impedance to that of the MTS. It is worth noting that both the SW launcher (the pillbox beamformer) and the radiating aperture (the modulated MTS) are within the same footprint. That is, we do not need any additional space to include the feeder, which makes our system very compact.

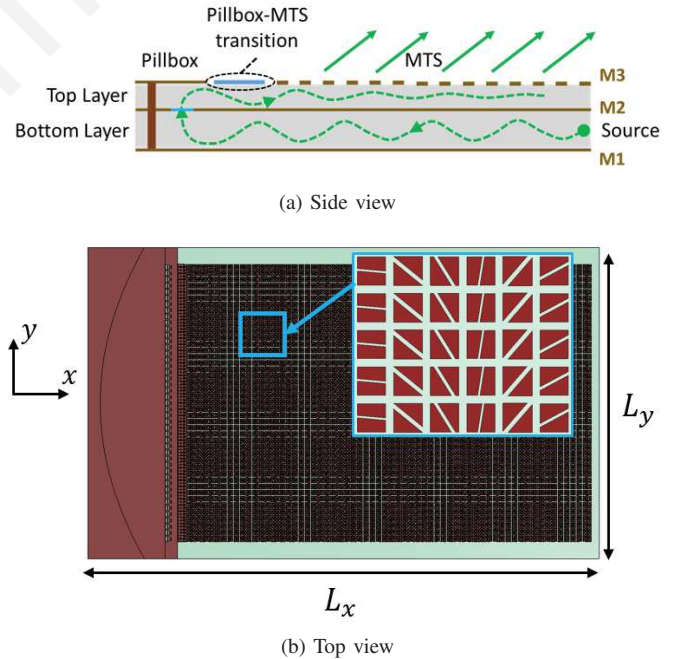


Fig. 3. Final antenna configuration. The two-layer structure is represented in (a), while the modulated MTS and the pillbox top layer are shown in (b). The dimensions of the antenna are  $L_x = 17\lambda_0$  and  $L_y = 10.4\lambda_0$ , where  $\lambda_0$  is the free-space wavelength for  $f = 20.7\text{GHz}$ .

Finally, the antenna is simulated with CST Microwave

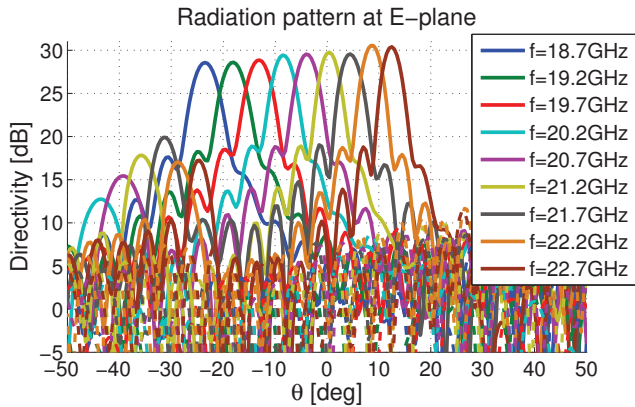


Fig. 4. Antenna radiation pattern for frequencies from 18.7GHz to 22.7GHz in steps of 0.5GHz. Solid lines correspond to the co-polarized (RHCP) components and dash lines to the cross-polarized (LHCP) ones.

Studio. The resulting radiation patterns are shown in Fig. 4, where we include the radiated beams in the  $E$ -plane for different frequencies within the K-band. We can see that the directivity  $D_{RHCP}$  varies between 28.6dB and 30.6dB, so the high-gain performance is maintained for all the frequencies. This produces an aperture efficiency of  $A_{eff} \geq 50\%$ , being up to  $A_{eff} = 73\%$  in the best case. The same good behaviour is observed for the cross-polarization level, which is below  $-30.6$ dB for the entire simulated band. The aperture efficiency, and then directivity, could be increased by tapering the amplitude of the aperture fields [3]–[5]. The aforementioned matching transition leads to the reflection coefficient  $S_{11}$  represented in Fig. 5.

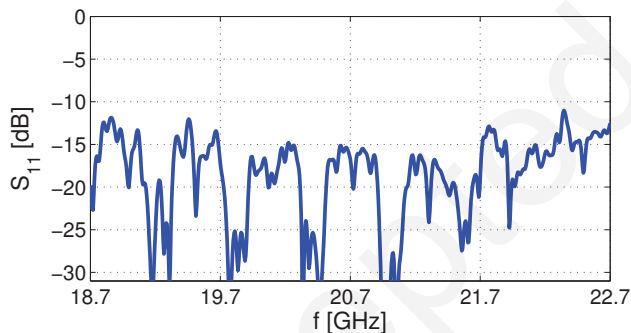


Fig. 5. Magnitude of the reflection coefficient in dB for the simulated antenna port.

### III. CONCLUSION

This work presents the design of a new antenna system based on a pillbox quasi-optical beamformer and a modulated MTS. The use of a pillbox beamformer as a SW launcher produces a very compact structure, enclosing feeder and MTS in the same aperture. Our model is able to radiate a right-hand circularly-polarized beam for different frequencies at the low K-band, keeping a high-gain performance ( $28.6\text{dB} < D_{RHCP} < 30.6\text{dB}$ ) and a very good cross-polarization discrimination (higher than  $30.6\text{dB}$ ). Regarding the aperture effi-

ciency, the presented structure offers a similar performance as MTS antennas consisting of circular apertures. Therefore, the proposed high-gain and low profile modulated MTS antenna constitutes an attractive solution for satellite communications in moving platforms. The rectangular footprint of the system makes it especially interesting for CubeSats and, in general, SmallSats applications, as it fits perfectly the form factor of these platforms.

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