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A Metasurface Antenna for Space Application

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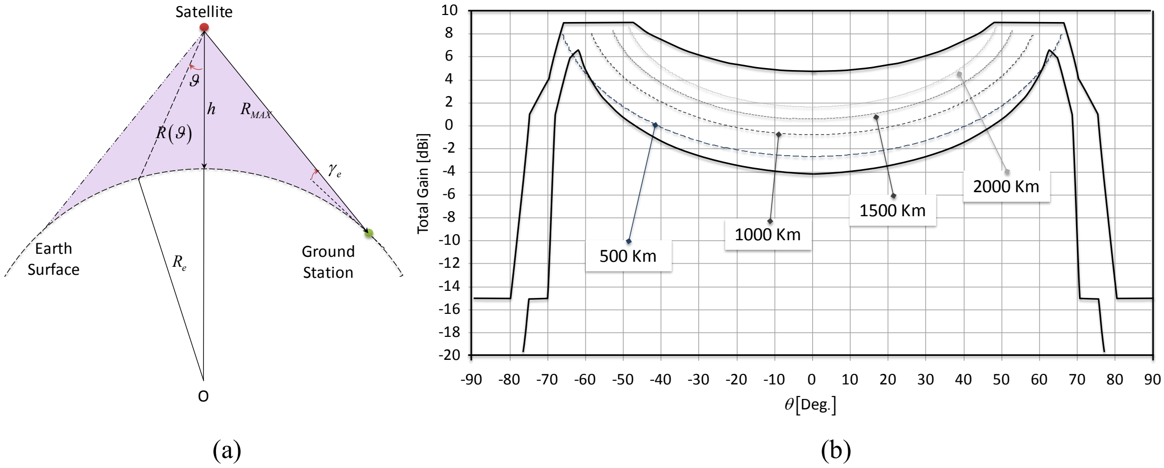
1. Introduction

We present the main results of a study on the use of anisotropic metasurfaces to realize an antenna radiating a circularly polarized field in an isoflux shaped beam pattern, suitable for LEO satellite application. We summarize the theory on which the design process is founded and provide a numerical validation relevant to an already manufactured antenna prototype. Measurement results will be presented during the oral session.

The antenna we designed is a low-mass and low-cost prototype representing a good candidate for payload data handling and transmissions device with optimal shaped beams. These antennas are a major asset for space missions and play an important role in Earth Observation, where high transmission rate is necessary to acquire Earth images. Future satellite missions will require new antennas with more demanding performances for the radiation pattern, especially in terms of cross-polarization discrimination. The antenna on the satellite platform shall distribute a uniform power density over a well-defined portion of the visible Earth surface. The relevant shaped beam is referred to as *isoflux pattern*. LEO satellite antennas shall provide EM isoflux coverage to the Earth surface on a visibility conical angle of about 120° of aperture. This requirement is extremely difficult to satisfy for many typologies of antennas, as a significant portion of the radiation needs to be spread over a very large angular region. The prototype antenna we present here, despite the use of a new technology, closely satisfies the gain pattern requirements in the requested frequency band (8.5-8.7 GHz), with excellent circular polarization on the wide angular range.

2. Isoflux Pattern for LEO Satellite

In the reference scenario an antenna is located on a LEO satellite orbiting at distance h over the sea level between 500 and 2000 Km. The satellite must be visible from the ground station at a minimum elevation angle $\gamma_e = 10°$ (Figure 1).



(a)

(b)

Figure 1: (a) Geometry of the reference scenario (the visibility cone is highlighted) and (b) envelope of the isoflux pattern for several satellite orbits (all the patterns are comprised between upper and lower limit masks)

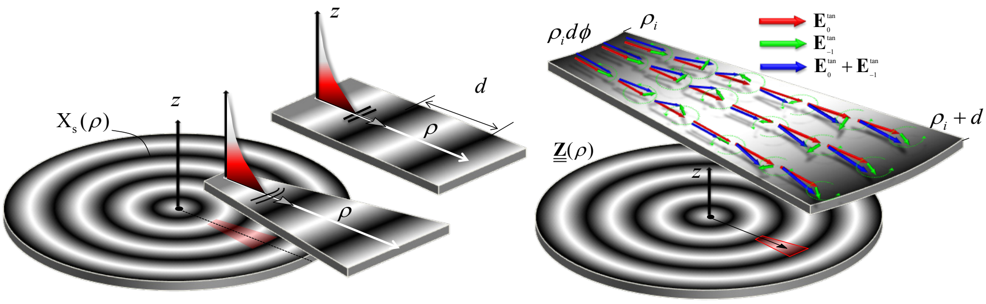
An isoflux antenna provides an homogenous power density toward the earth surface inside the visible cone. To this end, the antenna gain must compensate the power loss due to the path length by increasing the amount of power radiated toward the direction where the path is longer. By simple geometrical considerations, one can find the necessary gain diagram as a function of angle ϑ :

$$G(\vartheta,\varphi) \propto \left(1+h/R_e\right)\sqrt{1-\sin^2\vartheta} - \sqrt{1-\left(1+h/R_e\right)^2 \sin^2\vartheta} \quad (1)$$

For satellite altitudes between 500 and 2000 Km, the relevant isoflux patterns are comprised between a lower and upper limit gain masks as shown in shown in Figure 1b. Roughly speaking, the radiation pattern is conical with peak around 55°-65°, a deep roll-off outside 65°, and a broadside level around 0 dBi.

3. Radiation by Metasurface

The antenna we present here is founded on an inhomogeneous anisotropic metasurface, namely a planar surface characterized by non uniform impedance boundary conditions. The impedance surface is of reactive type, sinusoidally modulated as the one studied in [1], but here the boundary conditions are of anisotropic type as in [2]. The radiation is produced by exciting the metasurface with a TM_0 surface wave (SW) mode. The interaction of this latter with the non uniform sinusoidally modulated surface reactance, causes a complex displacement of the SW wavenumber, thus transforming it into a leaky wave (LW). In our configuration, a small electric point source provides a cylindrical SW wavefront. In order to provide the azimuthally symmetric isoflux pattern, the metasurface has a cylindrical modulation of the surface reactance. To design it, we assume that the interaction between the *cylindrical* SW and the *cylindrical* modulated reactance happens locally with the same mechanism of the interaction between a *plane* SW and a surface reactance sinusoidally modulated in *one dimension*, as in the Oliner-Hessel's problem (Figure 2). This assumption allows us to design the overall antenna by referring to the local problem as done in [3].



(a) (b)

Figure 2: (a) radial periodic modulation of impedance and identification of an elemental sector with a one dimensional sinusoidal reactance problem. (b) Behaviour of the field in one radial period of an anisotropic non-uniform periodic metasurface.

The use of an anisotropic modulation is required to control the local polarization of the aperture field and to obtain a circular polarization all over the conical beam. To understand the basic radiation phenomenology produced by the anisotropic metasurface, let us consider an elemental radial sector of the surface. A SW on the uniform surface cannot produce radiation since its phase constant β_{sw} is greater than the free space wavenumber k . However, by modulating the surface reactance it is possible to transform it into a LW. Indeed, due to the radial periodicity of the modulation, the field along the radial direction is in the form of Floquet waves series, and each *n*th-mode has wavenumber $k_{\rho n} = k_{\rho 0} + n 2\pi/d$, $n \in \mathbb{Z}$. It is straightforward to see that if the period *d* is properly set, negative indexed modes can have a wavenumber lower than *k*, thus producing a beam. The number of radiative beams and their pointing angle depends on the length of the period *d* with respect to the surface wave wavelength λ_{sw} . Each beams is referred to as *backward* or *forward* if it has the opposite or the same direction of propagation of the SW, respectively. The *unimodal* *regime*, namely the condition when only the -1 index mode is radiating, is an important condition to obtain the desired conical radiation and it is simpler to be achieved if the antenna works with the backward beam configuration. We adopted the backward-unimodal configuration to obtain a conical radiation and used anisotropic boundary conditions to locally control the polarization of the -1 Floquet mode. In our antenna, such mode is linearly polarized at each point of the surface, but while moving along the radial direction, it rotates making a complete turn in a modulation period (Figure 2b).

4. Metasurface Design and Numerical Results

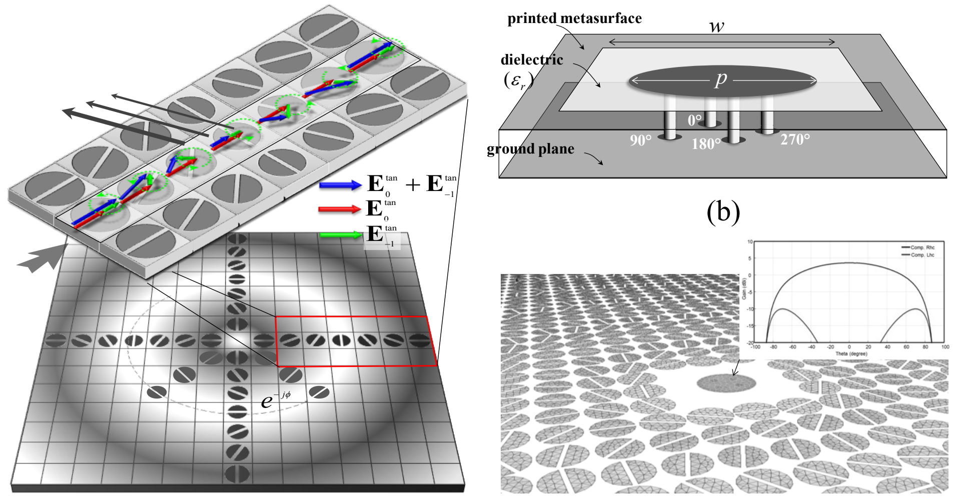
The optimum way to obtain a circular polarization antenna is to require that each point of the surface radiates a circularly polarized field. At this aim, we consider the surface as composed by circularly polarized sub-surfaces (having area smaller than $(\lambda/2)^2$) identified with a single period of sinusoidal modulation along ρ and a small angle along ϕ. Achieving such a behavior is greatly simplified if one considers an azimuthal rotating first order excitation $\mathrm{E}_0 = |\mathrm{E}_0| e^{j\phi}$. In fact, one can exploit the identity $e^{\pm j\phi}\left(\hat{\boldsymbol{\rho}} \pm j\hat{\boldsymbol{\varphi}}\right) = \hat{\mathbf{x}} \pm j\,\hat{\mathbf{y}}$ which expresses the possibility to circularly polarize the aperture in Cartesian coordinates by equalizing $\hat{\boldsymbol{\rho}}$ and $\hat{\boldsymbol{\varphi}}$ quadrature components. The two quadrature components can be obtained by realizing the following tensorial boundary conditions

$$\underline{\underline{\mathbf{Z}}} = j\zeta \begin{bmatrix} \eta_{\rho\rho} & \eta_{\rho\phi} \\ \eta_{\phi\rho} & \eta_{\phi\phi} \end{bmatrix}; \qquad \begin{cases} \eta_{\rho\rho} = \eta_s + \eta_s m \cos\left(2\pi/d\,\rho\right) \\ \eta_{\rho\phi} = \eta_s m' \sin\left(2\pi/d\,\rho\right) \\ \eta_{\phi\phi} = \eta_s - \eta_s m \cos\left(2\pi/d\,\rho\right) \end{cases} \tag{2}$$

where *m* and *m'* are modulation indexes and η_s is an average reactance level. The period *d* of the modulation is set by using a phased-array approach, namely as $d = 2\pi / (\mathrm{Re}\{k_{\rho 0}\} + k\sin|\theta_0|)$, being $|\theta_0|$ half the aperture angle of the desired conical radiation (60° for our purposes). To estimate the SW wavenumber $k_{\rho 0}$ we started by determining its value on the uniform (non-modulated) anisotropic surface. We adopted a transverse resonance approach and determined the wavenumber as a function of the tensorial components. The wavenumber on the modulated surface is found by using the tensor components (2) in the expression for the uniform surface and averaging it. Then, the values for the modulation indexes are found by requiring that the aperture field is circularly polarized.

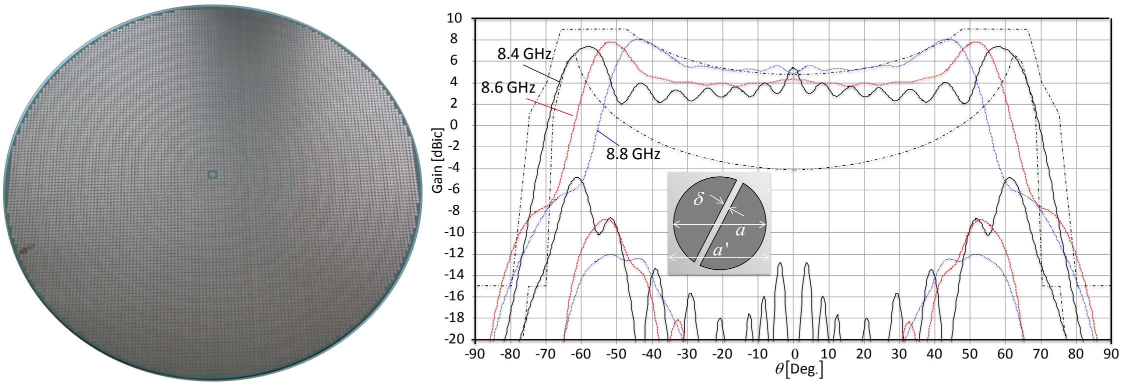
The tensorial reactance is synthesized by a dense texture of sub-wavelength metal patches printed on a grounded dielectric slab and excited by an in-plane feeder. The patches have a circular shape with a small slot cut along their diameter: the reactance tensor depends on both the area covered by the patch and the slot tilt angle with respect to the SW incidence direction of the. Roughly speaking, changing the area of the patch produce radiation, whereas rotating the slot cut control the polarization of the radiated field (figure 3a). To excite a surface wave with rotating phase, a resonant circular patch is placed at the center of the metasurface (figure 3b). The patch is printed at the same level of the metasurface and it is excited in sequential rotation by four pins displaced symmetrically with respect to the center. The role of the patch is to excite a surface wave along the metasurface and to radiate directly in the broadside direction for adjusting the radiation pattern inside the mask of figure 1a.

Figure 3c shows a sketch of the meshed structure and, in the inset, the gain pattern of the central patch feed when the metasurface is not present. Figure 4a shows a photograph of the realized prototype: about 12000 patches were printed on Arlon AR 1000 substrate (ε_r=9.8, thickness 1.575 mm). The overall structure has a weight approximately of 1 Kg. The numerical gain pattern is shown in Figure 4b for frequencies ranging between 8.4 and 8.8 GHz.



(a) (c)

Figure 3: (a) metasurface texture and field behaviour on an elementary subsurface, (b) sequential-rotation excited patch feed embedded in the metasurface and (c) sketch of the meshed structure and (in the inset) gain pattern of the central patch feed, when the metasurface is not present.



(a) (b)

Figure 4: Photograph of the realized prototype (a) and (b) simulated gain pattern (RHCP co-polar, and LHCP cross-polar components) at three frequencies. The patch is characterized by □ =0.42mm, a'=4.3mm, a ranging from 3.78 mm to 4.18 mm.

5. Conclusions

We have presented an antenna based on an anisotropic metasurface able to produce a circularly polarized isoflux pattern for LEO satellite. We summarized the basic concepts used to design the metasurface and provided numerical results for an already manufactured prototype. Experimental results will be presented during the oral session. The final device is a low cost antenna realized with the same PCB process used for printed circuits. It is flat, low profile (1.575 mm of thickness) and low weight (less than 1 Kg), thus resulting in a potentially good solution for space application.

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