METASURFACE ANTENNAS FOR USER TERMINAL

ESAA/ESTEC, NOORDWIJK, THE NETHERLANDS
3-5 OCTOBER 2012

G. Minatti (1), P. De Vita (2), S. Maci (1), M. Sabbadini (3)

(1) Department of Information Engineering, University of Siena, Via Roma 56, 53100, Siena - Italy, http://www.dii.unisi.it, {Minatti, Maci}@unisi.it
(2) Ingegneria dei Sistemi, IDS s.p.a., Via Enrica Calabresi, 24 - 56121 Pisa – Italy, p.devita@ids-spa.it
(3) European Space Agency, Keplerlaan 1, 2200 AG, Noordwijk, The Netherlands marco.sabbadini@esa.int

ABSTRACT
In this paper we discuss some results for a metasurface antenna radiating a sectorial beam with circular polarization. From numerical simulations we obtained 25 dBi of gain at around 60° off-axis angle from an antenna with 7.5λ radius. Light weight, low profile and low cost (a standard PCB process can be used to realize the metasurface) are interesting characteristics of such devices, making them suitable for several applications in particular ground terminals. Here we summarize the design process and discuss the numerical results.

1. INTRODUCTION
Recently, metasurfaces have been successfully used to realize antennas with shaped beams [1] or directive beams [2]. A metasurface is a thin layer periodically loaded in order to achieve uncommon dispersion properties of guided waves. Metasurface antennas belong to the class of leaky wave antennas. The radiation is produced by leaking energy from a surface wave propagating on a metasurface that synthesizes boundary conditions with modulated surface reactance. In [1] we studied an isoflux shaped beam antenna for LEO satellite application based on the concepts of metasurfing. 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 over a visibility cone with an apex angle of about 120°. The prototype developed in that framework showed that metasurface antennas can satisfy requirements on shaped beams, with good polarization capabilities.

In this paper we discuss some preliminary results for a metasurface antenna radiating a sectorial beam with circular polarization. The basic idea is to exploit the extreme small thickness and low mass of metasurfaces to realize a device suitable for a mechanical azimuth scanning. Such feature can be easily achieved by simply rotating the circular antenna around its symmetry axis, taking advantage from the low profile of metasurfaces (the prototype developed in [1] has less than 1 Kg of mass). Such configuration allows high gain while keeping the potential for very low production cost when coupled with a simple “turn-table” rotation mechanism. Applications of the proposed device range from antennas for satellite applications to antennas for ground terminals. An antenna with a sectorial beam could be used for a LEO satellite platform to realize an isoflux coverage of the Earth surface by means of the mechanical azimuth scanning. However the concept is quite attractive for portable ground terminal, where the light weight and low profile makes them easily transported and deployed.

Here we propose two different approaches to the design of sector beam antennas and provide relevant numerical results. The antenna radius is set around 7.5 free space wavelength at working frequency of 8.6 GHz as the demonstrator in [1]. We obtained a maximum gain of 25 dBi at around 60° off-axis angle.

The paper is structured as follow. In section 2 we provide the main radiative features of metasurfaces, discussing how to polarize the radiative field. Section 3 is dedicated to the design of a circularly polarized antenna radiating a beam tilted at around 60 degrees in the X band, while section 4 is dedicated to the anisotropic metasurfing. Numerical examples are presented and commented in section 5. Finally, conclusions are drawn in section.

2. RADIATION BY METASURFACES
The antennas we present here are founded on an inhomogeneous 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 [3], but here we make use of impedance boundary conditions of anisotropic type as in [2] and [1]. The radiation is produced exciting the metasurface with a TM0 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) [3].

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 $\beta_{sw}$ is greater than the free space wavenumber $k$. However, by modulating the surface reactance it is possible to transform it into a LW. Due to the radial periodicity of the modulation, the field along the radial direction is in the form of Floquet waves series, and each nth-mode has wavenumber $k_{rn} = k_{r0} + n2\pi/d$, $n \in \mathbb{Z}$. 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 $\lambda_{sw}$. Each beams is referred to as backward or forward if it has the opposite or the same direction of propagation of the SW, respectively.

All the beam radiated are linearly polarized if the SW mode is not modified from its TM$_0$ nature. An anisotropic modulation is required to control the local polarization of the aperture field and to obtain a circular polarization of the radiative beams. Briefly, the phenomenon can be seen as a TE phase quadrature component is added to each TM radiative Floquet mode. The resulting hybrid 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 and radiating a circularly polarized field. Figure 1 sketch this concepts for the -1 radiative mode.

![Figure 1](image1.png)

Figure 1. Behaviour of the field in one radial period of an anisotropic non-uniform periodic metasurface

3. SECTORIAL BEAM ANTENNA

In this section we aim to design a surface able to radiate a sector beam in circular polarization at 60 degrees off-axis angle. As possible scenario of application one can refers to a LEO satellite that should provide an isoflux coverage of the Earth surface. A sector beam metasurface antenna can provide the desired Earth coverage by a mechanical azimuth scanning with a simple turn-table mechanism. Also, metasurface antennas have characteristics suitable for ground terminals. Since their light weight and low profile, they are easily pointing antennas with medium-high gain. Figure 2 sketches the concept of mechanical reconfiguration of a metasurface antenna.

![Figure 2](image2.png)

Figure 2. Azimuth-elevation mechanical steering of the antenna

In our configuration, a small electric point source provides a cylindrical SW wavefront. The basic idea to design the sectorial beam is to combine the radiation from each elemental sector of the surface to produce a peak of radiation toward 60 degrees off axis angle. The pattern of the surface is designed assuming that the local interaction between the SW and the impedance pattern occurs with the same mechanism of the problem of Oliner-Hessel [3]. That is, the SW with cylindrical wavefront and a reactance modulated along the radial direction interacts in the same way of a SW with planar wavefront and a modulation of impedance in one dimension (Figure 3). This assumption allows us to design the overall antenna by referring to the local problem as done in [4].

![Figure 3](image3.png)

Figure 3. Radial sinusoidal modulation of impedance (a) and identification of an elemental modulated impedance sector with a one dimensional strip-grating problem (b)

The local periodicity of the impedance modulation is designed by using a strip-grating approach. The periodicity along $\hat{p}$ of the modulation on the azimuthal plane is such that each elemental sector produces a peak of radiation toward the desired direction $\hat{r}$. Namely, a SW propagating along $\hat{p}$ with wavenumber $\beta_{sw}$ produces a cone of radiation toward $\hat{r}$ if the modulation has a periodicity along $\hat{p}$ given by

$$d_{r}(\phi) = \frac{2\pi}{\beta_{sw} - k_{r} \hat{r} \hat{p}}$$  \hspace{1cm} (1)
This concept is sketched in Figure 4.

\[ \begin{align*}
Z &= j\varepsilon \begin{bmatrix} \eta_{\rho\rho} & \eta_{\rho\phi} \\
\eta_{\phi\rho} & \eta_{\phi\phi} \end{bmatrix} \\
\eta_{\rho\rho} &= \eta_r + \eta_m \cos \left( \frac{2\pi p}{d_r} (\phi) \right) \\
\eta_{\rho\phi} &= \eta_b + \eta_m \sin \left( \frac{2\pi p}{d_r} (\phi) \right) \\
\eta_{\phi\phi} &= \eta_r - \eta_m \cos \left( \frac{2\pi p}{d_r} (\phi) \right)
\end{align*} \] (2)

When the azimuthal rotating first order excitation \( e^{j\beta_{sw}} \) interacts with the impedance boundary conditions in (2), the aperture field is circularly polarized. In fact, the identity 
\( e^{j\beta_{sw}} (\hat{\rho} \pm j\hat{\phi}) = \hat{x} \pm j\hat{y} \) expresses the possibility to circularly polarize the aperture field in Cartesian coordinates by equalizing \( \hat{\rho} \) and \( \hat{\phi} \) quadrature components.

The tensorial reactance is synthesized by a dense texture of sub-wavelength metal patches printed on a grounded dielectric slab. The patches have a circular shape with a small slot cut along their diameter (Figure 6).

To excite a surface wave with phase \( e^{-j\beta_{sw}} \), a resonant circular patch of diameter \( p \) is placed at the centre of the metasurface (Figure 5). 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 centre.

\[ \text{Figure 5. Sequential-rotation excited patch feed embedded in the metasurface} \]

The use of an anisotropic modulation is required to control the local polarization of the aperture field and to obtain a circular polarization of the radiated beam. Two different strategies can be exploited in order to achieve such result. In [2] a spiral azimuthal variation of the sinusoidal modulation is adopted to circularly polarize the aperture field when the surface is excited by a linearly polarized source (a small dipole). Such solution is simple but has drawbacks for our purposes due to the linear polarization of the source. The feeder in fact gives rise to the surface wave and to a residual space wave. The space wave has a conical beam, linearly polarized, that cannot be combined constructively with the circularly polarized field produced by the metasurface. For this reason, as done in [1], here we made use of an azimuthal rotating first order excitation instead of the spiral variation of the sinusoidal modulation. Such a configuration allows to achieve a better polarization. Moreover, the direct feed radiation is circularly polarized and can be constructively combined with the leaky wave field produced by the modulated impedance surface.

5. NUMERICAL EXAMPLES

We propose two different strategies to design the sector beam antenna. The first one, as done by Fong et al. in [2], assumes that the surface wave propagation constant \( \beta_{sw} = k \sqrt{1 + \eta^2} \) remains invariant with respect to the azimuthal coordinate \( \phi \), despite the characteristics of the modulation are not uniform with \( \phi \). That means that the equivalent reactance value \( \eta \) is not affected by variations with \( \phi \) of the parameters of the modulation. The second one takes into account a dependence of \( \beta_{sw} \).
with $\phi$ and manage such dependence using the theory developed in [1]. In both cases, the correction term $\beta_\Delta$ to the SW phase constant that happens when dealing with modulated impedance surfaces (see [3]), has been neglected.

5.1. First example

In this first example the SW is assumed to propagate on an averaged reactance $\eta=\eta_s$ for every azimuthal observation angle $\phi$. The impedance parameters are set as $\eta=0.8$, $m=m'=0.5$ and $\beta_{sw}=220$. The periodicity of the modulation is designed to produce a peak of radiation at $r' = \sin \theta_s \cos \phi + \sin \theta_s \sin \phi \hat{x} + \cos \phi \hat{z}$ with $\theta_s=60^\circ$ and $\phi_s=0^\circ$. The antenna layout is shown in Figure 7 together with a detail of the surface.

Figure 7. Full layout of the first example of sectorial isoflux antenna (a) and (b) a detail of the layout

Figure 8 shows the gain along the x-axis resulting from the numerical simulations in the band 8.4-8.8 GHz.

Figure 8. Antenna gain resulting from numerical simulation. RHCP components are shown in solid lines, LHCP components in dashed lines. The gain is shown along the x-axis cut

Figure 9 shows a map of the gain in the theta-phi plane at the central frequency of 8.6 GHz.

5.2. Second example

In the second example we assume that the SW is propagating on an equivalent reactance given by

$$\eta \approx \eta_s \left( 1 - m'(\phi) \frac{1}{2} \frac{\eta_s^2}{\eta_s^2 + 1} \right)$$  \hspace{1cm} (3)

which is the average impedance of the modulated impedance surface with tensorial components given by (2). Equation (3) is a function of the parameters of the modulation and it is obtained by averaging an equivalent surface impedance expression with modulated impedance tensors, as explained in [1]. The radiated field is elliptically polarized with an axial ratio that depends on the ratio between the modulation indexes $m$ and $m'$. In order to have a circular polarization (unitary axial ratio), the ratio between modulation indexes must be chose as

$$m' = m \sqrt{\frac{1 + \eta_s^2(\phi)(\eta_s^2 + 1)}{1 + \eta_s^2(\phi) - \rho^p}}$$ \hspace{1cm} (4)

By combing (4)-(3) and solving the linear system, we obtain the value of $\eta(\phi)$ on the antenna surface. This latter value is used to found the wavenumber $\beta_{sw}(\phi)$ to set the periodicity of the modulation in (1).

The final antenna layout is shown in Figure 10 together with a detail of the surface.

Figure 9. Antenna gain resulting from numerical simulations on the phi-theta plane at 8.6 GHz.

Figure 10. Full layout of the second example of sectorial isoflux antenna (a) and (b) a detail of the layout
Figure 11 shows the gain along a cut on the main axis (x-axis) resulting from the numerical simulations in the band 8.4-8.8 GHz.

![Figure 11. Antenna gain resulting from numerical simulation. RHCP components are shown in solid lines, LHCP components in dashed lines. The gain is shown along the x-axis cut.](image)

Figure 12 shows a map of the resulting gain on the theta-phi plane at 8.6 GHz.

![Figure 12. Antenna gain resulting from numerical simulations on the phi-theta plane at 8.6 GHz.](image)

6. CONCLUSIONS

We have presented the main results of a study for a sector beam antenna, with circular polarization, based on an anisotropic metasurface. Metasurface antennas are light weight (around 3.5 Kg/m²), low profile (less than 1.6 mm of thickness) and low cost devices (the standard PCB process is suitable for the realization). Thanks to these characteristics, metasurface antennas are good candidates for applications where reconfigurable radiators are required. In ground terminal, a metasurface antenna can be easily deployed and mechanically set to hold the link with a satellite platform. Its low profile makes it easy to store and transport. A sector beam antenna could also be designed to provide an isoflux coverage of the Earth surface from a LEO satellite platform. In this case, an azimuthal scanning obtained rotating the antenna around its symmetry axis by means of a simple mechanical actuator, could provide the desired isoflux coverage with the benefit of a higher gain.

Here we have provided two different analytical strategies to design the impedance surface and provided relevant numerical results. Both the antennas has a radius of 7.5λ and show a peak of gain of 25 dBi at 58° off-axis angle. The angular coverage can be extended toward lower elevation at the cost of a larger antenna. Also, this technology can be extended to higher frequencies. In [5] measurements are shown for a metasurface antenna with circular polarization working in the Ku band. From the theoretical point of view, the metasurfing concept can be extended also to the Ka band, however much attention should be dedicated to the manufacturing aspects.

7. REFERENCES


