Research Networking Programmes

Short Visit Grant ☐ or Exchange Visit Grant ☒

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

PROPOSAL TITLE: *Development of metasurface antennas for satellite applications working with dual circular polarization.*

APPLICATION REFERENCE NUMBER: *5025*

1_ PURPOSE OF THE VISIT

The goal of the exchange visit of Amagoia Tellechea from Public University of Navarre (UPNA, Spain) at the University of Siena (Italy) is focused on the development of metasurface (MTS) antennas for space applications. More specifically, employment of metasurface technology for implementing satellite antennas with both right-hand and left-hand circular polarization simultaneously.

2_ DESCRIPCION OF THE WORK CARRIED OUT DURING THE VISIT

As it is well known, metasurface (MTS) technology represents low-profile low-cost solution employable for space applications. Due to the shown versatility, metasurfaces are presented as a powerful alternative to conventional satellite systems. It can be mentioned for instance antennas with different pointing beams, such as boresight solutions [1-3] or configurations providing isoflux radiation patterns [4]. Employability of this technology to provide service at more than one frequency band simultaneously also has been analysed [6]. Furthermore, feasibility to obtain very low crosspolar component of the radiated field has been corroborated [4], which represents overriding requirement for proposed solutions since most of the space applications request pure circular polarized field for communications with earth stations. Nevertheless, solutions providing circular polarization hitherto work for single hand direction, working for right hand or left hand. Therefore, two different antennas are necessary when dual polarization response is needed. Within this context, the employability of MTS to fulfill the requirements of low crosspolar component for both right-hand and left-hand directions simultaneously represents a challenge which favourable results could open up new promising horizons for this technology.

The work carried out during the exchange visit at University di Siena under the supervision of Prof. Stefano Maci was focused in the development of a single MTS antenna with boresight radiation and accomplishing simultaneously dual circular polarization behaviour.

Basic operation principle of the designed metasurface is based on the excitation of two decoupled cylindrical modes in the structure (one constituting a transversal magnetic mode (TM) and the other defined as a transversal electric (TE) mode) propagating perfectly balanced and with the same phase velocity from the feeder in the centre of the structure. When these modes interact with the surface contribute to the radiated field towards a given direction with desired circular polarization.

Metasurface antenna, composed by a thin grounded slab (thickness ~λ/20) and an appropriately modulated impedance surface constituted by sub wavelength elements on top, is fed from the centre of the structure (See Fig. 1) exciting cylindrical propagating TM and TE modes.

a) b)

Fig. 1 Metasurface composed by grounded slab and sub wavelength elements surface on top, fed from the centre of the ground plane by a magnetic dipole oriented towards a) x axis b) y axis.

A magnetic dipole oriented towards x axis (Fig.1.a) over the ground plane as a feeder of the system provides TM and TE propagating modes which tangential component(regarding the surface) is described as:

$$E^{TM} = E_\rho \sin\phi \hat{\rho} \quad (1)$$

$$E^{TE} = E_\phi \cos\phi \hat{\phi} \quad (2)$$

Equivalently, a magnetic dipole oriented towards y axis over the ground plane (Fig.1.b) provides tangential electric components for TM and TE described as:

$$E^{TM} = E_\rho \cos\phi \hat{\rho} \quad (3)$$

$$E^{TE} = -E_\phi \sin\phi \hat{\phi} \quad (4)$$

With an appropriate design of the feeding system and metasurface, equal phase velocity for perfectly balanced TM and TE decoupled propagating modes is obtained, so that electric field is linearly polarized towards $\hat{y}$ and $\hat{x}$ as:

$$E^{TM} + E^{TE} = E_\rho \sin\phi\,\hat{\rho} + E_\phi \cos\phi\,\hat{\phi} = E_o\,\hat{y} \tag{5}$$

$$E^{TM} + E^{TE} = E_\rho \cos\phi\,\hat{\rho} - E_\phi \sin\phi\,\hat{\phi} = E_o\,\hat{x} \tag{6}$$

In order to obtain circularly polarized field, 90 degrees phase shift can be introduced from the feeder between both linear polarized contributions. If designed MTS is radially symmetric, both RHCP and LHCP circular polarizations can be obtained simultaneously with the same surface configuration just depending on the introduced 90 degrees phase shift sign.

For the design of the MTS several theoretical considerations have to be taken into account: it must show inductive behaviour towards radial direction ($\hat{\rho}$) to allow the propagation of TM mode, whereas its behaviour must be capacitive in phi direction ($\hat{\phi}$) to allow propagation of TE mode. Furthermore, in order to guarantee same phase velocity for TM ($v_{ph}{}^{TM}$) and TE ($v_{ph}{}^{TE}$) modes ($v_{ph}{}^{TM} = v_{ph}{}^{TE}$), or equivalently, same surface wave phase constant for each of them at a given frequency ($k_{SW}{}^{TM} = k_{SW}{}^{TE} = k_{SW}$), the relation of surface opaque impedances have to be related with the free space (Z_0) impedance as:

$$Z_{surf}{}^{TM} Z_{surf}{}^{TE} = Z_0{}^2 \tag{7}$$

On the other hand, in order to analyse the amplitudes relation of the propagating TM and TE modes, equivalent transmission lines are studied employing the correspondent magnetic dipole as excitation of the system (See Fig.2).

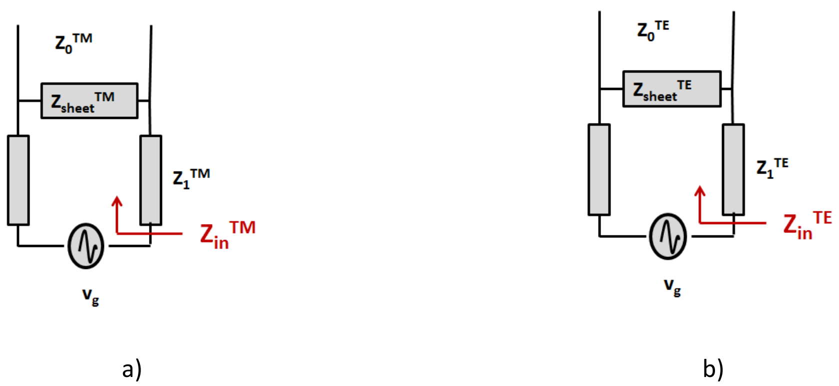


Fig.2 Equivalent transmission line for the MTS configuration fed by magnetic dipole in the center for a) TM mode and b) TE mode.

Input impedances for the TM and TE modes are defined as:

$$Z_{in}{}^{TM} = Z_1{}^{TM} \frac{Z_{||}{}^{TM} + jZ_1{}^{TM} \tan(k_{z_1} h)}{Z_1{}^{TM} + jZ_{||}{}^{TM} \tan(k_{z_1} h)} \tag{8}$$

$$Z_{in}{}^{TE} = Z_1{}^{TE} \frac{Z_{||}{}^{TE} + jZ_1{}^{TE} \tan(k_{z_1} h)}{Z1^{TE} + jZ_{||}{}^{TE} \tan(k_{z_1} h)} \tag{9}$$

where $Z_1^{TM} = Z_1 \frac{k_{z_1}}{k_1}$ and $Z_1^{TE} = Z_1 \frac{k_1}{k_{z1}}$, being k_1 the wavenumber of the dielectric ($k_1 = \sqrt{\varepsilon_r} k_0$) and k_{z_1} the transversal (to the surface) wavenumber ($k_1{}^2 = k_{z_1}{}^2 + k_{SW}^2$). Z_1 is the dielectric impedance ($\frac{Z_0}{\sqrt{\varepsilon_r}}$) and h is its thickness. Parallel impedances between sheet and free space for each mode are defined as:

$$Z_{||}{}^{TM} = Z_{sheet}{}^{TM} \,||\, Z_0{}^{TM} \tag{10}$$

$$Z_{||}{}^{TE} = Z_{sheet}{}^{TE} \,||\, Z_0{}^{TE} \tag{11}$$

where free space impedances for TM and TE modes are defined as $Z_0{}^{TM} = Z_0 \frac{k_{z0}}{k_0}$ and $Z_0{}^{TE} = Z_0 \frac{k_0}{k_{z0}}$. k_0 is the free space wavenumber and k_{z0} is the transverse wavenumber ($k_0{}^2 = k_{z_0}{}^2 + k_{SW}^2$). Based on transverse resonance equation, free space impedances and surface impedances are related as:

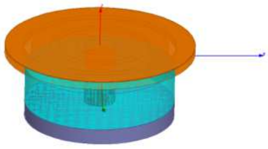
$$Z_{surf}{}^{TM} = Z_{sheet}{}^{TM} \,||\, Z_{gslab}{}^{TM} = -Z_0{}^{TM} \tag{12}$$

$$Z_{surf}{}^{TE} = Z_{sheet}{}^{TE} \,||\, Z_{gslab}{}^{TE} = -Z_0{}^{TE} \tag{13}$$

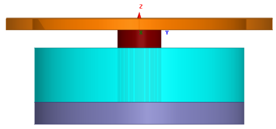
Taking these expressions into account, residuals for TM and TE modes propagating in the system are calculated as the inverse of the derivatives of the input impedances:

$$res = \lim_{k_{SW} \to k_{SW}^{'}} \left(\left(k_{SW} - k_{SW}^{'} \right) f\left(k_{SW} \right) \right) = \frac{1}{\left(Z_{in} \right)^{'}} \tag{14}$$

In the studied cases, residuals of TM and TE show that the contribution of the TM mode is more important than the one of the TE mode, thus it is concluded that a feeding system capable to balance appropriately both modes contribution is necessary for the proposed solution. Hence, circular waveguide providing TE11 mode as excitation is employed, as the correct balance of the TE and TM modes can be obtained as function of the radius of the waveguide taking into account also theoretical surface wave wavenumber at desired working frequency. Besides, in order to control the direct radiation contribution of the waveguide to the desired boresigth radiation pattern, corrugated hat has been introduced in the system (Fig.3).



a)



b)

Fig.3 Details of the employed feeding system: circular waveguide providing TE11 excitation mode with corrugated hat on top. a) Top View b) Lateral View

[1] Gabriele Minatti, Francesco Caminita, Massimiliano Casaletti, and Stefano Maci, "Spiral Leaky-Wave Antennas Based on Modulated Surface Impedance", IEEE Trans. Antennas and Propag., vol. 59, no. 12, pp4436-4444 2011

[2] S. Maci, G. Minatti, M. Casaletti, and Marko Bosiljevac,"Metasurfing: Addressing Waves on Impenetrable Metasurfaces", Trans. Antennas and Wireless Propag. Letters, vol. 10, pp1499-1502 2011

[3] G. Minatti, M. Casaletti, F. Caminita, P. De Vita and S. Maci, "Planar Antennas Based on Surface-to-Leaky Wave transformation", Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP) ppp1915-1918 2011

[4] G. Minatti, S. Maci, P. De Vita, A. Freni and M. Sabbadini "A Circularly-Polarized Isoflux Antenna Based on Anisotropic Metasurface", IEEE Trans. Antennas Propag., vol. 60, no. 11, pp.4998 -5009 2012

[5] G. Minatti, S. Maci, P. De Vita, A. Freni, M. Sabbadini, "A Metasurface Antenna for Space Application", Proceedings of ISAP2012, Nagoya (Japan), ppp870- 873 2012

[6] A.Tellechea, E. Martini, D. Gonzalez-Ovejero, M. Faenzi, G. Minatti, S. Maci, "Dual Band Isoflux Ultraflat Meta Antennas", Eucap 2015, Lisboa, Portugal

3_ DESCRIPTION OF THE MAIN RESULTS OBTAINED

Based on aforementioned operation principle, ideal metasurface has been implemented to radiate boresight (θ=0°) at 13.5GHz, providing both Rigth Hand and Left Hand circular polarizations simultaneously. Ideal surface impedances have been defined as:

$$Z_{surf}{}^{TM} = Z_{ave}{}^{TM}\,(1+m^{TM}\,\cos(\frac{2\pi}{d^{TM}}\rho)) \tag{15}$$

$$Z_{surf}{}^{TE} = Z_{ave}{}^{TE}\,(1+m^{TE}\,\cos(\frac{2\pi}{d^{TE}}\rho+\varphi)) \tag{16}$$

where m is the modulation index, d the periodicity and Z_{ave} the average value of opaque impedances defined for each propagating mode. φ describes the shift introduced to the definition of the surface impedance for the TE mode regarding TM to compensate possible undesirable phase velocity differences due to the presence of the corrugated hat over the feed in the final configuration. ρ describes radial direction from the feeding system situated in the center.

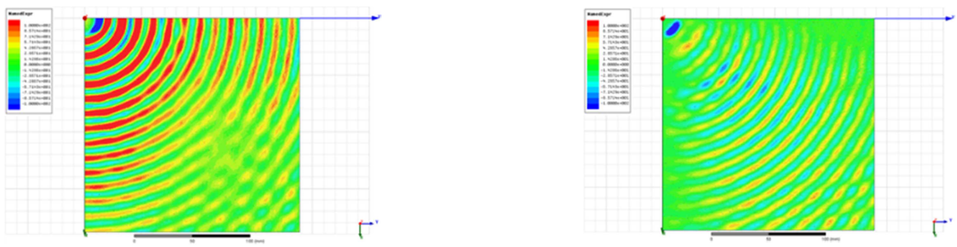
Ideal MTS structure has been simulated using ANSYS HFSS simulator (Fig.4):

a) b)

Fig. 4 Details of the simulated ideal MTS. a) Top View b) Details of the feeding system.

Only quarter of the structure has been simulated employing appropriate symmetry boundary conditions. Structure is excited with a circular waveguide with corrugated hat on top providing linearly polarized TE11 mode oriented towards y axis. In this example,unitary cell dimension is 3.14mm (~λ/ 7) and radius of the structure 8.2λ.

Fig.5 shows copolar and crosspolar electric field components close to the surface at 13.25GHz.

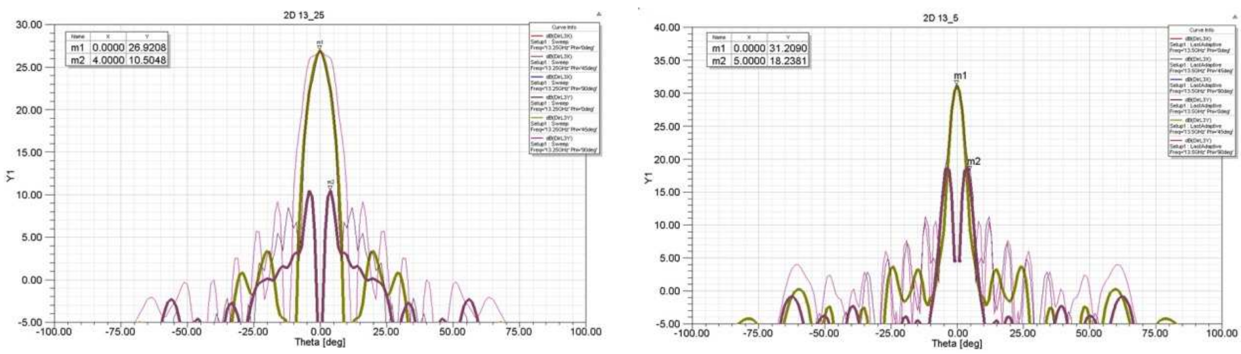


a) b)

Fig.5 CO (a) and XP (b) components of the electric field close to the MTS at 13.25GHz.

Good balance between TM and TE modes with same phase velocity can be appreciated and consequently low crosspolar component level is obtained.

Radiation patterns at 13.25GHz and 13.5GHz are shown at Fig.6 for phi 0°, 45° and 90° cuts. Based on Ludwig third definition for BOR1 structures, information of radiated CO and XP components at phi=45° give information of circular polarization.



a) b)

Fig.6 CO and XP components of radiated field at phi=0°,45° (bold),90° at 13.5GHz.

Maximum directivity of 27dB and 30dB with crosspolar components of -17dB and -13dB are shown for 13.25 GHz and 13.5GHz, in concordance with previously established theoretical premises.

In practice, metasurface is composed by subwavelength elements which geometrical properties are modified appropriately providing necessary surface impedance values. In this case, dispersion properties of elliptical shaped pixels with cross shaped hole in the center have been analyzed and selected as best candidates.

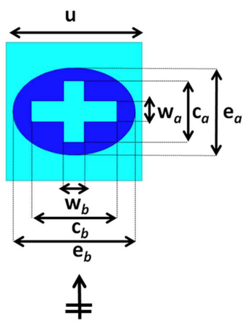
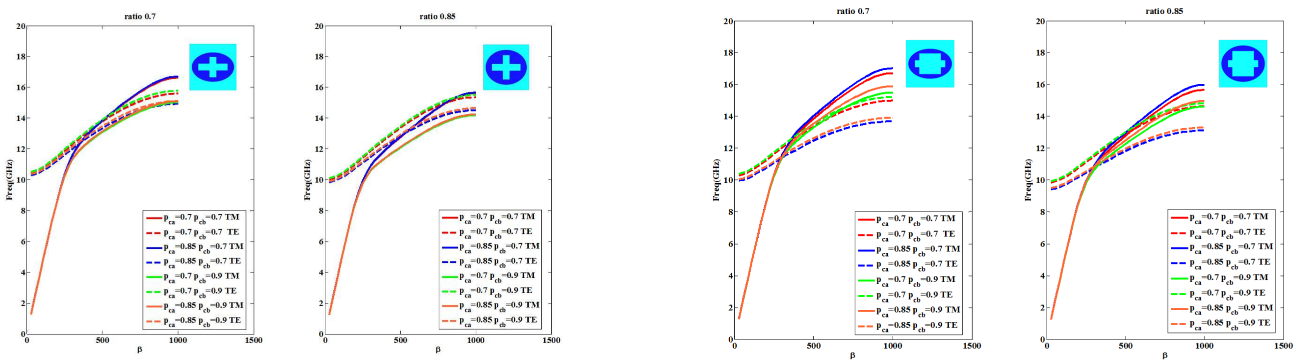


Fig.7 Elliptical shaped metallic subwavelength element with cross shaped hole in the center selected as best pixel for the practical implementation of the MTS.

Parameters of the pixel are related as: $e_b = p_e \cdot u$, $e_a = ratio \cdot e_b$, $c_a = p_{ca} \cdot e_a$, $c_b = p_{cb} \cdot e_b$, $w_a = p_{wa} \cdot u$, $w_b = p_{wb} \cdot u$. Dispersion analyses (Fig.8) for several parametric values ($ratio$, p_{ca}, p_{cb}, p_{wb}) have been realized to obtained complete information of pixels:

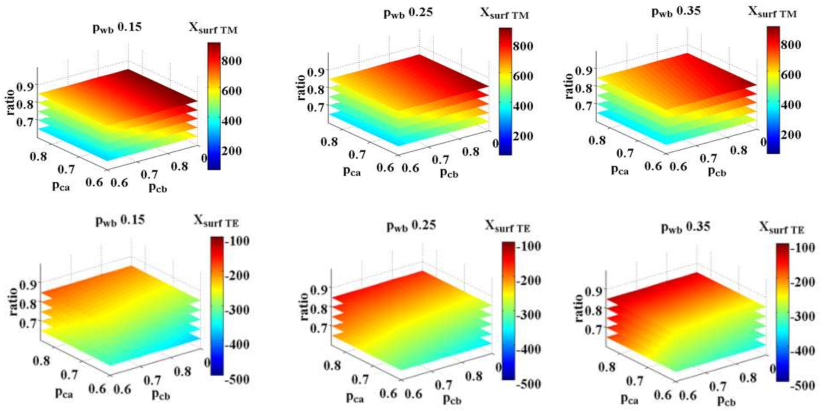


a) b)

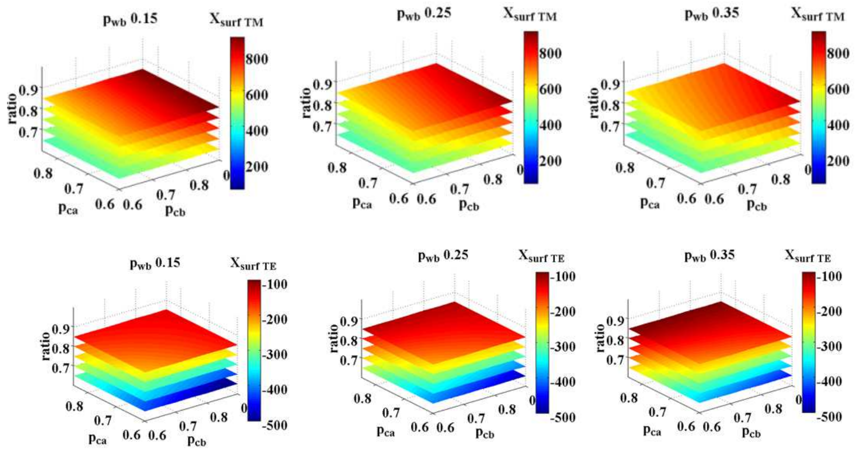
Fig.8. Dispersion analysis for several parametric values of the pixel:
u =3.14mm, p_e =0.9, $ratio$=0.7, 0.85
(p_{ca}, p_{cb})=(0.7,0.7 red), (0.85,0.7 blue), (0.7,0.9 green), (0.85,0.9 orange) and p_{wb} = 0.15 (a), 0.45 (b). TM mode (continuous) and TE mode (dashed). Rotation and impinging angle of the pixel is towards x axis.

It can be shown that variations of p_{wb} parameter mostly affects to TE mode which enables independent control of dispersion characteristic and consequently surface impedance properties for TM and TE propagating modes.

Based on dispersion information of the surface wave (SW) phase velocity, opaque impedance information at desired working frequency (13.5GHz) can be extrapolated for each geometric modification of the pixel. Information for several impinging angles (phi=0°, 15° and 45°) has been gathered at Fig.9. The pixel is always rotated with the impinging angle.



a)



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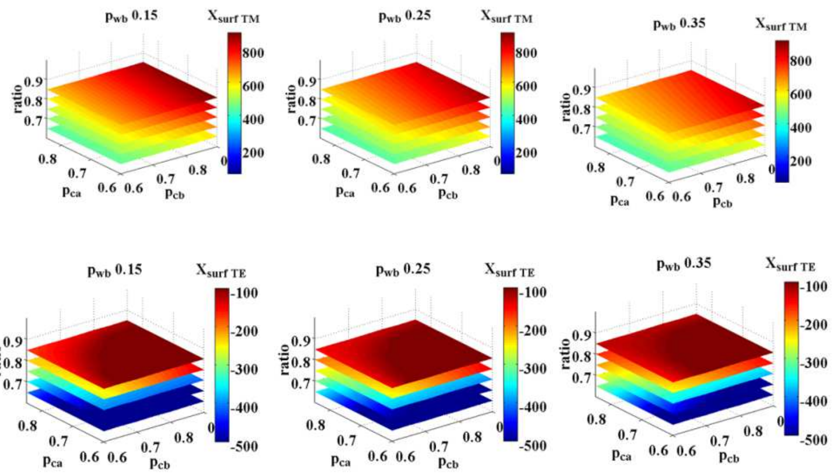


c)

Fig.9 Opaque surface impedance values for TM(up) and TE(down) modes for several parameterization of the geometric properties of the pixel and SW impinging angles (a) 0° b)15° c)45°.

Once the pixel is characterized, complete metasurface is implemented with the same impedance parameters as for the ideal MTS case. Details of the implemented metasurface can be shown at Fig. 10:

a) b)

Fig.10 Main view of the complete implemented MTS, composed by elliptical pixels with cross type hole inside. a) Top View. b) Zoom out of the center.

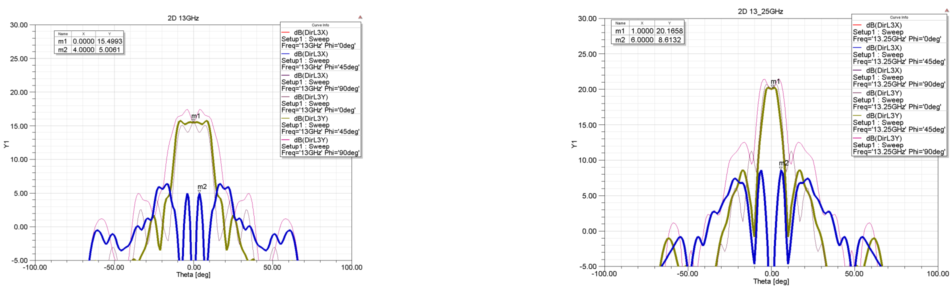
Copolar and crosspolar components of the electric field close to the aperture at 13GHz are shown at Fig. 11:

a) b)

Fig. 11 Copolar (a) and Crosspolar (b) component of the field close to the aperture at 13GHz.

Frequency shift regarding theoretical working frequency (13.5GHz) is seen and balance between TE and TM modes is not as good as for the ideal case.

Radiation patterns at 13GHz and 13.25GHz are shown at Fig.12.



a) b)

Fig.6 CO and XP components of radiated field at phi=0°,45° (bold),90° at 13GHz and 13.25GHz

It can be seen that maximum achievable directivity with the metasurface composed by pixels is around 20dBs at 13GHz and 13.25GHZ. Present frequency shift makes that contributions of TM and TE modes shift radiation direction, so that total contribution is shifted from desired boresight radiation inappropriately. Crosspolar level is around 15dBs. Better circular polarization behavior and consequently increment of the achievable maximum directivity can be obtained by adjusting appropriately balance and phase velocities of both TM and TE modes at the correct working frequency.

It has to be mentioned that these are preliminary results and no optimization processes have been performed for feeding system, surface impedance implementations, pixels design etc., so better results are expected for future realizations. For instance, Fig.10 shows predictable metasurface implementation error (%) when elliptical pixels are employed as subwavelength elements instead of ideal unitary cells:

a) b)

Fig.10 Implementation error (%) predictable at the implementation of the MTS with pixels for a) TM mode b) TE mode.

Incorporation of pixels for the composition of the MTS introduces errors in the theoretical surface impedances, which are more important around phi=45° plane for TM mode and phi=30°and 60° planes for TE mode, achieving around 15% of error in the implementation. These effects can be avoided optimizing the implemented pixels.

To conclude, it can be highlighted that potential of MTS technology to accomplish the required dual polarization at boresight has been demonstrated. Better results are expected for future realizations after adequate optimization processes are performed.

4_ FUTURE COLLABORATION WITH HOST INSTITUTION

The visit realized at University di Siena has been very positive experience for both involved institutions. As optimization of the preliminary results presented in this document is still necessary, future collaboration between both institutions is expected. Fabrication and measurements will also be done in common.

5_PROJECTED PUBLICATIONS / ARTICLES RESULTING OR TO RESULT FROM THE GRANT

Currently we are writing an article summarizing the entire job realized during this stay. ESF will be acknowledged in this publication.