Characteristic Modes Theory Exploitation for Wideband Circularly Polarized Metasurface Antenna Design

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Abstract

A novel compact and low profile Circularly Polarized (CP) antenna operating in the whole X-band for satellite communications is proposed. A suitable radiative performance is achieved by resorting to the Characteristic Modes Theory (CMT). More in detail, the wideband operation and CP radiated field are achieved by a proper excitation of two orthogonal current modes (J_n) supported by the investigated metasurface (MTS) antenna. Measurements on a realized prototype provide a satisfactory agreement with simulations, confirming the reliability of the proposed approach.

1. Introduction

Over the past years nanosatellites are becoming more and more important into space industry market, providing a more versatile as well as affordable solution than traditional satellites, which are very expensive and typically involve a more complex engineering process [1]. Earth observation, internet of things, disaster monitoring, deep space as well as a seamless and ubiquitous 5G connectivity represent just few examples of the multiple applicative scenarios within which satellites can play a crucial role [2]–[5]. Among the several onboard equipment, radiators represent a key component affecting the overall wireless communications performance. To be space compliant, antennas are prone to stringent requirements, not only concerning the radiative performance but also the mechanical and aerodynamic aspects. In the past, different solutions have been proposed for the design of CP antennas, spanning from microstrip patch antennas [6], spirals [7], helix antennas [8], to dielectric resonators [9]. More recently, CP radiators based on metasurfaces (MTSs) have been proposed. For example, [10], [11] show two designs of CP antennas by resorting to artificial magnetic conductors. Other recent radiators are illustrated in [2], [12] confirming the great interest in finding better solutions to face the overwhelming growth of the satellite applications.

A novel and fruitful approach that has been used for the design of CP antennas is represented by the Characteristic Modes Theory (CMT) [13]. The modal analysis allows achieving insightful physical information about the radiative performance that can profitably exploited during the antenna design. The usefulness of the CMT approach has been highlighted in several recent publications spanning from pattern reconfigurable antennas [14]–[16], Multiple-Input-Multiple-Output (MIMO) antenna [17], 3- D platforms [18]–[21] as well as MTSs [22]–[24].

The purpose of this paper is to propose a low-profile CP antenna based on MTS operating in whole satellite communications X-band, namely from 7.25 GHz to 8.4 GHz. The breakthrough approach relies on exploiting a MTS superstrate based on loops elements capable of converting the feeder linearly polarized field into a CP radiated field. Measurements, which are in good agreement with simulations, confirm the proposed design approach as well as the benefits of adopting CMT for designing CP radiators based on MTS superstrate.

2. CMT of Loops Elements MTS

Modal analysis allows achieving orthogonal current modes (J_s) that the investigated structure can support. These characteristic modes depend solely by the geometrical structure and shape regardless of the external feeding arrangement.

According to the CMT, the total current distribution on the investigated object (J_{tot}) can be decomposed as a linear superposition of infinite characteristic modes:

$$J_{tot} = \sum_n \alpha_n J_n \qquad (1)$$

where J_n represents the characteristic modes obtained by solving the generalized eigenvalue equation [13] whereas α_n, known as Modal Weighting Coefficient (MWC), represents the complex amplitude related to each mode that expresses the modal excitation degree on the platform due to the presence of an external exciter. The current modes (J_n) inspection and their correspondent far field provide useful guidelines to control the radiation performance of the examined object by an appropriate tune of the MTS elements.

A sketch of the proposed MTS along with the corresponding geometrical dimensions is reported in Figure 1. The proposed MTS consists of a rectangular loop arranged in a 4 × 4 array configuration placed at a distance h from the ground plane.

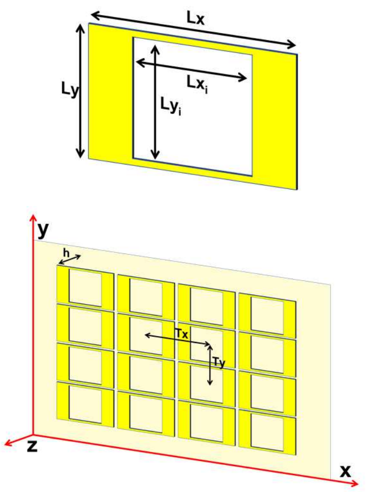
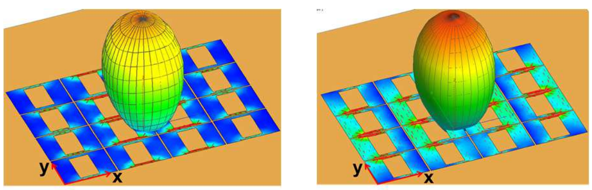


Figure 1. Geometry of the proposed loops based MTS superstrate placed on an infnite ground pane. Lx = 9.5mm, Lx_i = 3.5mm, Ly = 6.5mm, Ly_i = 3.5mm, Tx = 9.75mm, Ty = 6.75mm and h = 3.5mm.

The MTS geometrical dimensions have been accurately tuned through a thorough Characteristic Mode Analysis (CMA) with the purpose of supporting two orthogonal current modes (J_n) whose Characteristic Angles (CAs) differ 90° on average within the considered bandwidth. In fact, the CA describes the phase difference between the current mode (J_n) and the related electric field mode (E_n). Moreover, to guarantee a good CP purity, the identified couple of modes must have a broadside radiation pattern with orthogonal linearly polarized electric field. Among all characteristic modes supported by the MTS shown in Figure 1, just two current modes, namely Mode#1 and Mode#2, can satisfy the latter condition about the modal radiation field. Indeed, the other supported current modes show a less focused radiation pattern or present a pattern null at broadside. The modal current distribution and the related radiation patter concerning the selected couple of modes (Mode#1 and Mode#2) are shown in Figure 2. As it is visible, they have a broadside radiation pattern with the current mode distribution mainly along *x* axis (Figure 2a) and *y* axes, respectively (Figure 2b).



(a) (b)

Figure 2. Surface current mode distribution and the related modal radiation pattern of (a) Mode#1 and (b) Mode#2.

The CA phase difference between Mode#1 and Mode#2 as a function of the frequency is reported in Figure 3 for different values of the thickness *h*. As it can be drawn, the identified couple of modes can support a phase lag close to 90° within the working bandwidth (*i.e.* 7.25 GHz-8.4 GHz). Moreover, with the increase of the distance between the MTS and the ground plane the CA phase difference undergoes a slight down shift of the frequency response as well as to provide a mild decrease of the CA phase difference around central frequencies.

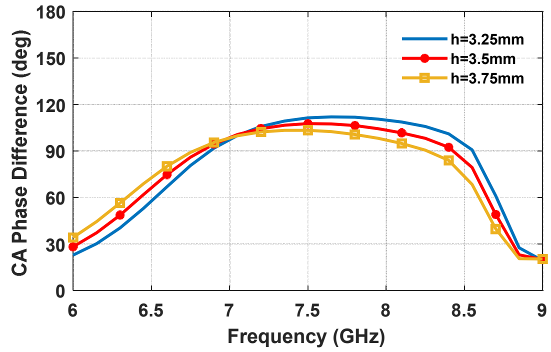


Figure 3. CA phase difference between Mode#1 and Mode#2 as a function of the frequency.

Under the assumption that the selected couple of current mode, Mode#1 and Mode#2, are equally excited on the finite MTS comprising 4×4 rectangular loops, the Axial Ratio (AR) at broadside direction as a function of the frequency is illustrated in Figure 4. It can be interpretated as the AR potential supported by the proposed MTS superstate structure. More in detail, Figure 4 highlights two AR peaks around 6.75 GHz and 8.25 GHz with a remarkable AR bandwidth capable to cover whole satellite communications X-band. Moreover, the CA phase difference downshift with the increase of the thickness underlined in Figure 3 provides the same behaviour in the AR response.

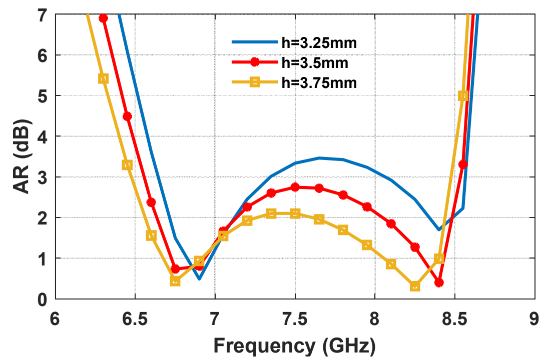


Figure 4. Potential AR of the proposed MTS as a function of the frequency for different air thickness *h* under the assumpion of uniform excitation of Mode#1 and Mode#2 .

3. CP X-band Antenna with MTS Superstrate

CMA of the proposed MTS based on loops elements highlighted the noteworthy radiative performance making it a good candidate for realizing a wideband CP antenna. However, for finalizing the antenna design it is necessary a feeding structure capable of stimulating the identified pair of modes (*i.e.* Mode#1 and Mode#2). To this end, a rectangular slot is etched on the ground plane centre of the MTS which, in turn, it is excited by the underneath microstrip line as displayed in Figure 5.

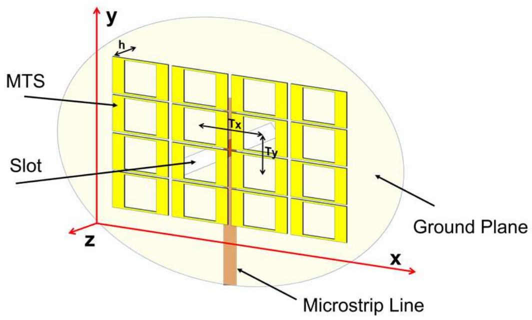
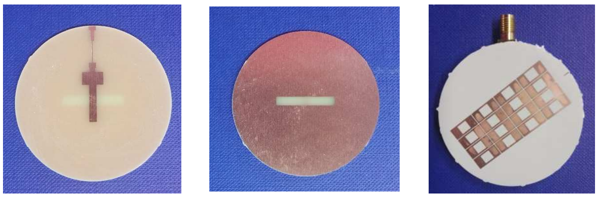
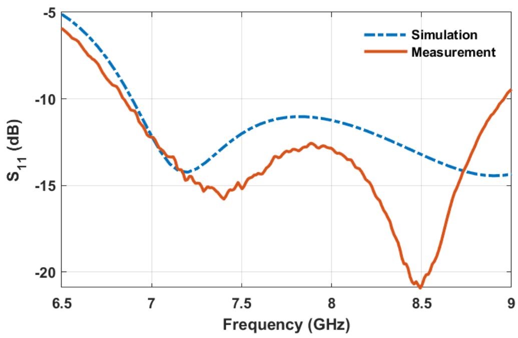


Figure 5. Excitation scheme of the proposed MTS based on loop elements.

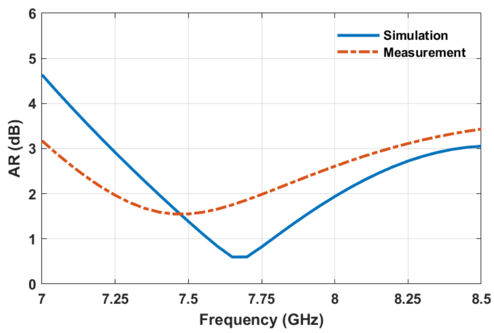


(a) (b) (c)

Figure 6. Manufactured prototype: (a) microstrip line, (b) top view of slot exciter and ground plane and (c) MTS superstrate.



(a)



(b)

Figure 7. Comparison between simulation and measurement (a) S11 parameter and (b) AR at broadside direction as a function of the frequency.

A prototype of the proposed antenna has been fabricated in order to assess the performance and it is shown in Figure 6. It comprises two separate Printed Circuit Boards (PCBs). In the first PCB (FR-4) was printed both the microstrip line and the rectangular slot in the opposite side (Figure 6a-b), whereas in the other one (thin kapton) has been printed the proposed MTS superstate. Then these two PCBs have been assembled by employing a spacer to keep the ground plane and the MTS at the desired distance (h = 3.5 mm).

Comparison between simulations and measurement in terms of impedance matching and AR are shown in Figure 7 and their satisfactory agreement validates the reliability of the design approach as well as confirm the remarkable performance.

4. Conclusion

A novel wideband CP antenna based on MTS loops element superstrate has been proposed. The individuation of the most promising supported current modes and their tuning have been carried out through insightful CMA. A prototype was fabricated, and the measurement campaign confirms the reliability of the design approach.

5. Acknowledgements

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References

[1] M. N. Sweeting, ‘Modern Small Satellites-Changing the Economics of Space’, *Proc. IEEE*, vol. 106, no. 3, pp. 343–361, Mar. 2018, doi: 10.1109/JPROC.2018.2806218.

[2] N. Chahat *et al.*, ‘Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review’, *IEEE Antennas Propag. Mag.*, vol. 61, no. 5, pp. 37–46, Oct. 2019, doi: 10.1109/MAP.2019.2932608.

[3] Z. Qu, G. Zhang, H. Cao, and J. Xie, ‘LEO Satellite Constellation for Internet of Things’, *IEEE Access*, vol. 5, pp. 18391–18401, 2017, doi: 10.1109/ACCESS.2017.2735988.

[4] F. A. Dicandia and S. Genovesi, ‘Exploitation of Triangular Lattice Arrays for Improved Spectral Efficiency in Massive MIMO 5G Systems’, *IEEE Access*, vol. 9, pp. 17530–17543, 2021, doi: 10.1109/ACCESS.2021.3053091.

[5] F. A. Dicandia and S. Genovesi, ‘Spectral Efficiency Improvement of 5G Massive MIMO Systems for High-Altitude Platform Stations by Using Triangular Lattice Arrays’, *Sensors*, vol. 21, no. 9, p. 3202, May 2021, doi: 10.3390/s21093202.

[6] S. D. Targonski and D. M. Pozar, ‘Design of wideband circularly polarized aperture-coupled microstrip antennas’, *IEEE Trans. Antennas Propag.*, vol. 41, no. 2, pp. 214–220, Feb. 1993, doi: 10.1109/8.214613.

[7] H. Nakano, K. Nogami, S. Arai, H. Mimaki, and J. Yamauchi, ‘A spiral antenna backed by a conducting plane reflector’, *IEEE Trans. Antennas Propag.*, vol.

34, no. 6, pp. 791–796, Jun. 1986, doi: 10.1109/TAP.1986.1143893.

[8] J. M. Tranquilla and S. R. Best, ‘A study of the quadrifilar helix antenna for Global Positioning System (GPS) applications’, *IEEE Trans. Antennas Propag.*, vol. 38, no. 10, pp. 1545–1550, Oct. 1990, doi: 10.1109/8.59766.

[9] R. Chair, S. L. S. Yang, A. A. Kishk, K. F. Lee, and K. M. Luk, ‘Aperture fed wideband circularly polarized rectangular stair shaped dielectric resonator antenna’, *IEEE Trans. Antennas Propag.*, vol. 54, no. 4, pp. 1350–1352, Apr. 2006, doi: 10.1109/TAP.2006.872665.

[10] F. Yang and Y. Rahmat-Samii, ‘A low profile single dipole antenna radiating circularly polarized waves’, *IEEE Trans. Antennas Propag.*, vol. 53, no. 9, pp. 3083–3086, Sep. 2005, doi: 10.1109/TAP.2005.854536.

[11] T. Nakamura and T. Fukusako, ‘Broadband Design of Circularly Polarized Microstrip Patch Antenna Using Artificial Ground Structure With Rectangular Unit Cells’, *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 2103–2110, Jun. 2011, doi: 10.1109/TAP.2011.2143656.

[12] M. J. Veljovic and A. K. Skrivervik, ‘Aperture-Coupled Low-Profile Wideband Patch Antennas for CubeSat’, *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3439–3444, May 2019, doi: 10.1109/TAP.2019.2900428.

[13] R. F. Harrington and J. R. Mautz, ‘Theory of characteristic modes for conducting bodies’, *IEEE Trans. Antennas Propag.*, vol. 19, no. 5, pp. 622–628, Settembre 1971, doi: 10.1109/TAP.1971.1139999.

[14] F. A. Dicandia, S. Genovesi, and A. Monorchio, ‘Null-Steering Antenna Design Using Phase-Shifted Characteristic Modes’, *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2698–2706, Jul. 2016, doi: 10.1109/TAP.2016.2556700.

[15] F. A. Dicandia, S. Genovesi, and A. Monorchio, ‘Advantageous Exploitation of Characteristic Modes Analysis for the Design of 3-D Null-Scanning Antennas’, *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 3924–3934, Aug. 2017, doi: 10.1109/TAP.2017.2716402.

[16] F. A. Dicandia, S. Genovesi, and A. Monorchio, ‘Efficient Excitation of Characteristic Modes for Radiation Pattern Control by Using a Novel Balanced Inductive Coupling Element’, *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1102–1113, Mar. 2018, doi: 10.1109/TAP.2018.2790046.

[17] D. Manteuffel and R. Martens, ‘Compact Multimode Multielement Antenna for Indoor UWB Massive MIMO’, *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2689–2697, Jul. 2016, doi: 10.1109/TAP.2016.2537388.

[18] A. Narbudowicz, R. Borowiec, and S. Chalermwisutkul, ‘No-Need-To-Deploy UHF Antenna for CubeSat: Design Based on Characteristic Modes’, *IEEE Antennas Wirel. Propag. Lett.*, vol. 20, no. 4, pp. 508–512, Apr. 2021, doi: 10.1109/LAWP.2021.3055418.

[19] R. F. M. D. Castillo, R. Ma, and N. Behdad, ‘Platform-Based, Electrically-Small HF Antenna With Switchable Directional Radiation Patterns’, *IEEE Trans. Antennas Propag.*, pp. 1–1, 2021, doi: 10.1109/TAP.2021.3060013.

[20] F. A. Dicandia and S. Genovesi, ‘A Compact CubeSat Antenna With Beamsteering Capability and Polarization Agility: Characteristic Modes Theory for Breakthrough Antenna Design’, *IEEE Antennas Propag. Mag.*, vol. 62, no. 4, pp. 82–93, Aug. 2020, doi: 10.1109/MAP.2020.2965015.

[21] T. Shih and N. Behdad, ‘Bandwidth Enhancement of Platform-Mounted HF Antennas Using the Characteristic Mode Theory’, *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2648–2659, Jul. 2016, doi: 10.1109/TAP.2016.2543778.

[22] F. A. Dicandia and S. Genovesi, ‘Characteristic Modes Analysis of Non-Uniform Metasurface Superstrate for Nanosatellite Antenna Design’, *IEEE Access*, pp. 1–1, 2020, doi: 10.1109/ACCESS.2020.3027251.

[23] K. E. Kedze, H. Wang, and I. Park, ‘A Metasurface-Based Wide-Bandwidth and High-Gain Circularly Polarized Patch Antenna’, *IEEE Trans. Antennas Propag.*, pp. 1–1, 2021, doi: 10.1109/TAP.2021.3098574.

[24] F. H. Lin and Z. N. Chen, ‘Low-Profile Wideband Metasurface Antennas Using Characteristic Mode Analysis’, *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1706–1713, Apr. 2017, doi: 10.1109/TAP.2017.2671036.