Electrically Thin VHF Array Elements for Satellite Applications Using Artificial Magnetic Material

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Abstract — **The application of large antenna arrays for space missions in VHF band is hindered by the dimension and weight of the single radiating element from a conventional design approach. Satellites used for this kind of applications are typically micro/mini platforms and cannot accommodate large antennas. To this purpose, element volume minimization and mass reduction are considered performance drivers, even considering the array deployment and satellite mass requirements. The important size reduction properties of Artificial Magnetic Materials (AMM) / Meta Materials (MM) made this approach a natural choice for the development of miniaturized antennas. A multipurpose, dual polarized array element with highly reduced dimensions and weight was developed to overcome these obstacles. This paper describe the design, manufacturing and testing of a dual polarized array element considering application in a low orbit Automatic Identification System (AIS) mission.**

Keywords—Artificial Magnetic Materials, miniaturization, metamaterial, cross dipoles, VHF band.

I. INTRODUCTION

The Automatic Identification System (AIS) is a ground-based coastal tracking system operating at VHF and detecting messages sent by vessels for maritime traffic monitoring purposes. The SAT-AIS European initiative aims at providing a space-based complementary system to extend the range of the existing system to high seas via a satellite constellation. The objective of the AISMAN activity, funded by ESA/ASI in the frame of the ARTES 5.1 program, is to design, manufacture and test a miniaturized space array antenna suitable for the SAT-AIS initiative. The system requirements for high performance payload are met with a 5-element array antenna synthesizing five beams per polarization in receive mode (162 MHz) through digital beam forming [1]. The work has then been further concentrated on a mini-satellite class platform of 300 kg having a volume of 1m × 1m × 1m, conceived in line with the one studied in the Phase B1 of the ESA ARTES21 SAT-AIS project. In the following steps of the activity, a detailed design of the array element has been carried out, focusing on downsizing and mass reduction, preserving the radiation efficiency and pattern symmetry.

The design cycle of the radiating element has included preliminary tests on a single element breadboard to validate the proposed approach, followed by manufacturing and testing of a metallic version of the antenna. Electrical validation campaigns have been carried out with the development of ad-hoc testing methodologies and the application of cutting-edge post-processing techniques. Therefore, a further iteration on the mechanical and electrical design of the element has been conducted, improving topics such as materials and manufacturing process, so to get one-step closer to the flight model. Result of this iteration has been a new version of the antenna, manufactured according to a sandwich technology, particularly suitable for space application.

II. ANTENNA ELEMENT DESIGN

The crossed dipoles over an Artificial Magnetic Conductor have been chosen as the baseline for the antenna design. In fact, they offer very satisfactory performances while requiring relatively low manufacturing complexity. In their conventional structure, cross-dipoles are placed close to a quarter of wavelength over a perfect electric conductor. Working at VHF frequencies, that will lead to an antenna thickness of 450 mm about, which is clearly not compatible with a mini-satellite class platform. The solution has consisted in the replacing of the PEC plane by an AMM [2]. In this last configuration, contrarily to the configuration based on a PEC, the crossed dipoles can be placed close to the surface of the

AMM without creating a short circuiting effect and a strongly mismatched antenna. The selected AMM layout consists in a periodic structure based on 16 metallic square rings. These cells are in electrical and mechanical contact with a ground plane by means of metallic posts placed on the corner of each ring. The folding effect produced by the geometry of the structure increases the currents path length leading to a more compact AMM structure. The general operating principle of the AMM cells can be described as current loops (Fig. 1) originating from the extremity of the center square ring (A), flowing to the ground plane through the metallic post (B), running on the ground plane surface (C) and finally reaching the neighboring rings through the metallic posts (D).

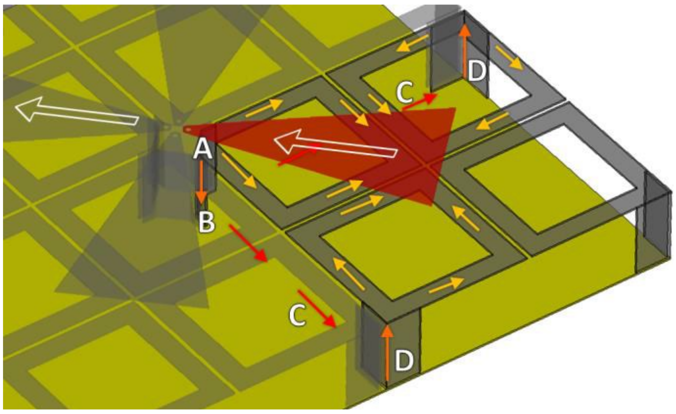

Fig. 1. Current loops in the AMM structure (hollow white arrows represent the dipole excitation currents, while all others refer to induced currents).

The design of the low profile AMM at VHF band has been quite challenging. This general behavior of the AMM structure is partially affected by the very close presence of the crossed dipoles. The crossed dipoles and the AMM structure form in fact a tightly coupled ensemble and their standalone working frequencies are modified by their respective presence. The resulting AMM structure is very compact, the rings have a size of 0.07 λ and its thickness is only 0.04 λ, which represents a drastic thickness reduction compared to a conventional crossed dipoles structure placed on PEC. The crossed dipoles feeding scheme is based on a folded coaxial line, providing a self-balanced excitation. Moreover, the dipoles have been rotated by 45°, leading to a dual slant linear polarization, in order to minimize the interaction with the platform, which hence appears symmetric with respect to the RF axis. The only weak point of the crossed dipoles over AMM surface radiating element is a low front-to-back ratio, deteriorated by the profile reduction. In order to improve this performance parameter, folded slots have been introduced inside the ground plane to concentrate the surface currents in the center of the panel. Therefore, the amount of currents flowing on the panel edges and corners (Fig. 2) and reaching the bottom face of the ground plane has been considerably reduced. In addition, balanced currents running in opposite directions on each slot cancel their residual spurious radiation and further improve the front-to-back ratio of the antenna (see close-up in Fig. 3). The layout of the final optimized element is shown in Fig. 4. The overall element envelope is 500 $mm \times 500\ mm \times 39\ mm$, considering a 1.5 mm thick ground plane. The resonance of the final element is tuned at 162 MHz and a good level of S_{11} was achieved without the need of an external matching network. Radiation efficiency has also been computed taking into account realistic properties of the antenna materials. The element has been manufactured using high precision machining techniques with the objective of validating the design cycle at early stage.

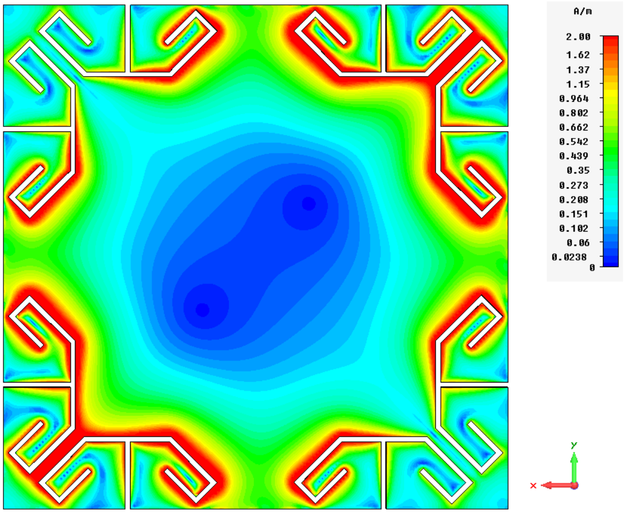

Fig. 2. Current distribution on the bottom-face of the slotted ground plane.

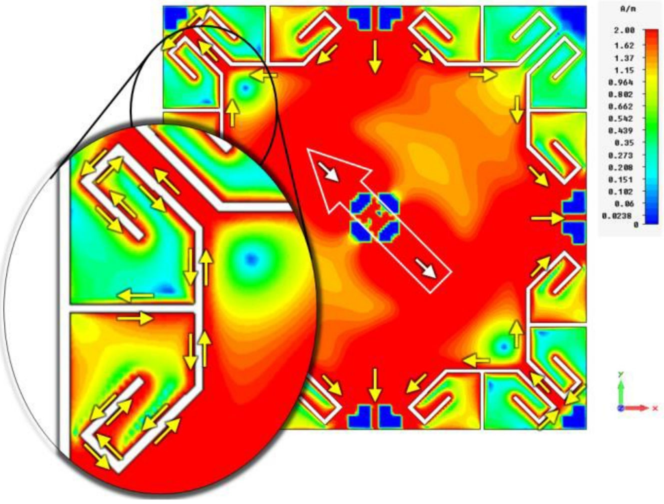

Fig. 3. Currents flowing on the top-face of the slotted ground plane (hollow white arrows represent the dipole excitation currents, while all others refer to induced currents).

All the metallic parts have been made from aluminum and coated with Alodine 1200 surface treatment. The vertical grounding of the AMM has been manufactured from a solid blocks of aluminum with precision CNC machining, while the square cells and the dipoles have been cut out from a thin aluminum by means of precision laser cut.

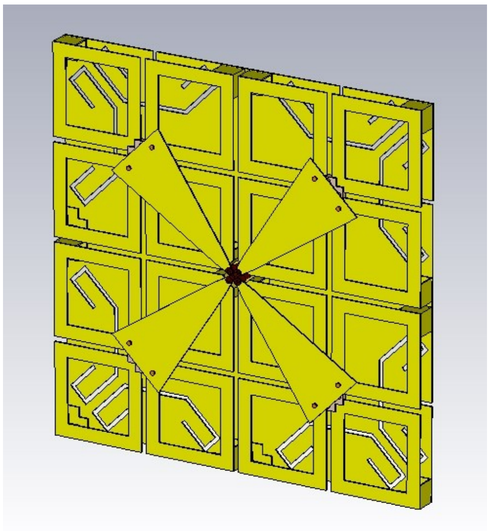

Fig. 4. Crossed dipoles over AMM surface on slotted ground plane.

III. VALIDATION CAMPAIGNS

The verification testing of the AIS array element has been carried out at the automotive measurement facility sited in the Renault Technical Centre at Aubevoye, France (Fig. 5). The range is an hemispherical multi-probe near-field system. Data acquisition is performed according to a regular sampling of 3.21° with a truncated area of ±105° in elevation [3] [4]. The measurement speed derives from the use of the MV multi-probe technology (MV-Scan^{TM}). A complete antenna measurement comprising 21 frequencies can be performed in approximately 35 minutes [5].

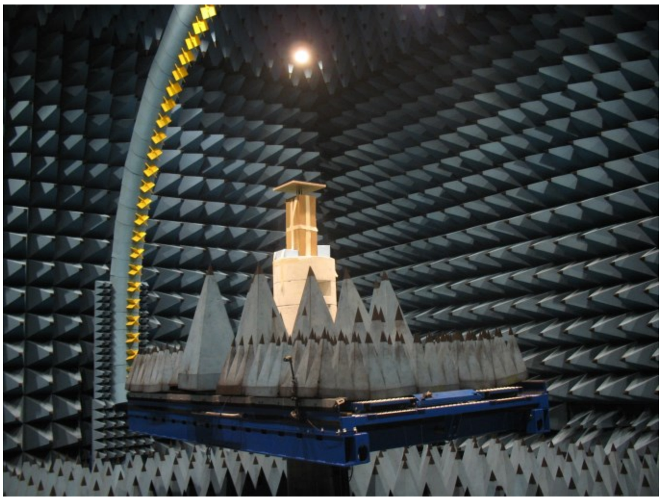

Fig. 5. AIS array element during measurement in Renault Technical Centre hemispherical range.

The geometry of the facility – being an automotive range - is truncated, meaning that data acquisition of field samples is limited to the θ range [0-105°] (when considering the lower frequency probe array), with a solid angle slightly larger than the forward hemi-sphere. According to the standard measurement procedure of such a range, the collected truncated data set is then interpolated in order to reconstruct a full near-field spherical data set, which can be then expanded to far-field by standard NF to FF transformation algorithm.

It is common knowledge that the abrupt discontinuity in the field values at the edge of the scan area may lead to erroneously large values of the higher order spherical harmonic coefficients and, in particular, may have a strong impact on low directivity AUT's. Several techniques of data interpolation and filling have been considered for automotive ranges to reduce the truncation error, but for the specific AIS application, the method based on equivalent currents has shown outstanding accuracy [6] [7] [8]. Based on the measured data samples, the equivalent electric and magnetic currents have been reconstructed on a box closely surrounding the antenna using MV-INSIGHT™ software [9].

The E-plane directivity comparison is shown in Fig. 5. The improvements obtained by the EQC expansion are appreciable. In fact, the FF ripple caused by the truncation of the scanning area and stray signals present in the measurement environment are strongly attenuated by the data processing. It is worth noting that the agreement between simulated and measured data obtained with MV-INSIGHT software is satisfactory even out of the reliable visible region of the measurement sphere, meaning that the equivalent current method has very good extrapolation capabilities. Due to this feature, it is possible to appreciate the improvements deriving from the design characteristics of the elements with slotted ground plane. In fact, as highlighted by the pattern cuts, the front-to-back ratio has been significantly increased.

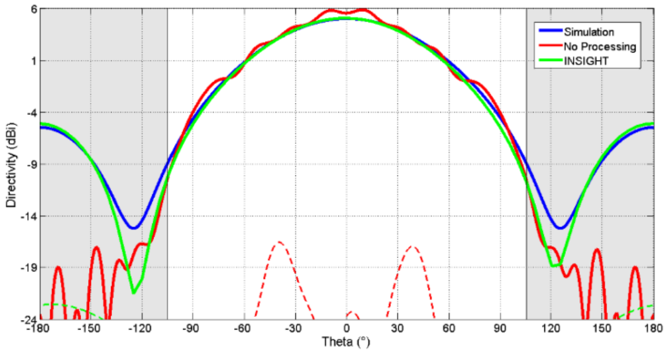

Fig. 6. E-plane directivity pattern comparison of simulation, raw measured data and processed data.

IV. MANUFACTURING EVOLUTION

A further iteration on the mechanical and electrical design of the element has been conducted, improving topics such as material and manufacturing process, so to get one-step closer to the flight model. In particular, target of the evolved model have been improving the element mechanical robustness, accounting for environmental conditions (mechanical constraints, thermal stresses) and further reduce the antenna element weight using specific light-weight materials. Therefore, upgrade of the designed antenna has been conducted considering a multi-layer sandwich assembly, with the metallic parts printed on a composite substrate bonded to a core material made from RF transparent honeycomb. This new design has been submitted to a preliminary coarse electric tuning, in order to compensate for the deviations due to the introduction of new materials. In particular, AMM cells (side, width and relative distance) were re-tuned with the target to compensate for the effect of upper dielectric skin and to improve the coupling with the dipoles. Finally, the obtained design has been submitted to a fine tuning activity in order to optimize the overall performance of the antenna. Being an electromagnetically small antenna, with narrow and AMM coupled dipoles, an isolation of the effects induced by the tuning of the parameter was not possible. Indeed, each parameter does not have an isolated impact on a specific performance, but on all the performance of the antenna. Therefore, the final model is the result of a global optimization conducted at the same time on many parameters. Target of this optimization has been matching the antenna to the desired resonance frequency, align it with respect to the front-to-back ratio trend and provide an as much as possible Gaussian shape to the far-field pattern.

The antenna has been manufactured considering a sandwich structure composed by a honeycomb core closed by sheets of E-GLASS. Metallic parts are manufactured as a thin copper layer of thickness 0.1 mm about for AMM cells and slotted ground planes (made by a galvanic growth) and as aluminum sheets of thickness 1.5 mm for cross-dipoles (made by laser cut). Skins are made by an autoclave curing of pre-preg materials (resin impregnated fibers).

V. CONCLUSIONS

A very compact VHF array element, suitable for dual-polarization narrow band space applications, has been achieved placing crossed-dipoles over an electrically-thin (λ /25) AMM. This design combined with a slotted ground plane has allowed a significant reduction in size and mass, maintaining high efficiency and low back radiation. The design cycle, manufacturing techniques and testing methodologies have been validated by breadboards at early stage, enhancing the overall confidence and reducing the development risks. Moreover, a further iteration on the mechanical and electrical design of the element has been conducted in order to get one-step closer to the flight model. Sandwich antennas have been manufactured and the testing and validation process is currently in progress.

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