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TOWARDS PLANAR SCANNING ANTENNA ARRAYS AT ONERA: A REVIEW

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Abstract – Several activities of ONERA are presented with a focus on printed planar antenna arrays. First, attention is given on wideband arrays comprising tightly coupled dipoles covered by wide angle impedance matching dielectric layers. Primarily, a SAR multi-layered antenna is shown allowing -10 dB matching in the band 13.1 – 18.4 GHz, with single linear polarization and a broadside beam. This opens towards a dual-linearly-polarized array targeting scanning angles up to 60 degrees. Another antenna array configuration with circular polarization based on stacked patches is then proposed in Ka-band for satellite connectivity. Finally, some other activities related to narrow-band active beamformers for antenna arrays are also shown, providing a scanning range from -60 to +60 degrees.

I. INTRODUCTION

This paper aims to present a review of ONERA studies dealing with various topologies of printed scanning antenna arrays. Indeed, this past decade a special consideration has been put on the investigation of several configurations through PhD theses, internal research activities and industrial projects, in order to target the realization of large scanning range antenna arrays.

Intensive research activities are now dedicated to the design of active electronically scanned arrays (AESAs) as these systems procure versatility via direct control of each radiating element both in phase and magnitude [1]-[3]. A first specific set of works done at ONERA considers wideband planar arrays that may be exploited for multifunction AESAs. In addition to the versatility procured by the active AESA beamformer, the exploitation of wideband radiating elements enables using the system for multiple applications as radar, electronic warfare and communications. Within this frame, the authors propose wideband planar antenna arrays based on tightly coupled dipoles covered by wide angle impedance matching (WAIM) dielectric layers [4]. Exploiting the early principles proposed by Munk [5], ONERA has developed additional procedures to optimize in an effective way both the radiating element and its associated WAIM [4], [6]. These studies focus on structures allowing a large field of view, up to 60 degrees, while maintaining good matching and gain within wide bandwidth ratios. Such concept has been recently used for designing a Ku-

band antenna with a broadside beam for synthetic aperture radar (SAR) and ground moving target identification (GMTI) applications [6]. In this paper, we present a novel antenna comprising a wideband feed network. Provided its experience, ONERA is currently implied in the CROWN European project which targets the development of an AESA with wideband and dual-linear polarization capabilities [3]. More specifically, ONERA is working on the design of a 6-18 GHz dual-polarized printed antenna array.

Recently, the authors also developed another AESA configuration in Ka-band for satellite connectivity up and downlinks on airborne platforms. Such antenna arrays still aim a wide field-of-view up to 60 degrees. However, instead of targeting a wideband capability, the antennas should now procure dual-circular polarization with low axial ratio (< 2 dB) on the whole scanning range. The proposed radiating elements are based on circular stacked patches [7]-[10]. Two pins are exploited to feed the main patch, which allows controlling the polarization purity and its left or right-handed property by choosing the proper magnitude and phase on each port. To increase the bandwidth, slots have been etched in the patches. The optimization of the unit-cell also implies several new structures to lower coupling effects: a cavity to prevent inter-cell couplings, and metallic vias to prevent intra-cell couplings. Two antennas have been designed and manufactured in both receiving and transmitting bands [10].

To go further, other studies focusing on active metasurfaces have been carried out. The technology presents an alternative to phased array antennas. It is based on the use of cascaded composite right left handed (CRLH) cells that are reconfigured with varactor diodes [11]-[12]. With this technique, it is possible to control the phase of the transmission line and scan the beam in various directions.

In this paper it is proposed to give a particular focus on the different structures, especially showing the realizations and measurement results. Section II presents the activities that are related to wideband arrays and the proposed tightly coupled dipoles. The second AESA configuration based on stacked patches with circular polarization is described in section III. Section IV is dedicated to ONERA studies dealing with active beamforming networks. Finally, conclusions are given in section V.

II. WIDEBAND ANTENNA ARRAYS

Tightly coupled dipole arrays are well-known for their ultra-wideband (UWB) performance associated to a wide scanning range [5]. The main challenge is thus now to combine this UWB property together with multiple polarizations while keeping high isolation between the polarizations and a wide field-of-view.

A. Antenna Topologies

A stepped investigation was done on this topic during the past decade. The initial topologies studied at ONERA are illustrated in Fig. 1. by their concept view together with the realized prototypes [4], [6]. They all consist of printed dipoles covered by WAIM dielectric layers. The main originality brought by ONERA relies on the development of a joined optimization procedure for both the radiating element and the WAIM layers.

Fig. 1. (a) presents a linearly-polarized unit-cell. The dipole is fed with coaxial cables using a thin and compact transition. Each element is thus independently accessible. Thanks to the interdigital capacitors and the WAIM layers, an active VSWR < 2 is achieved from 6 to 16 GHz while scanning up to 60 degrees in all planes [4].

Fig. 1. (b) shows a first evolution of the previous case, where the radiating element is pixelated within the optimization procedure [6]. The fabricated array shows an active VSWR < 2 from 5 to 18 GHz while scanning up to 60 degrees in the E-plane.

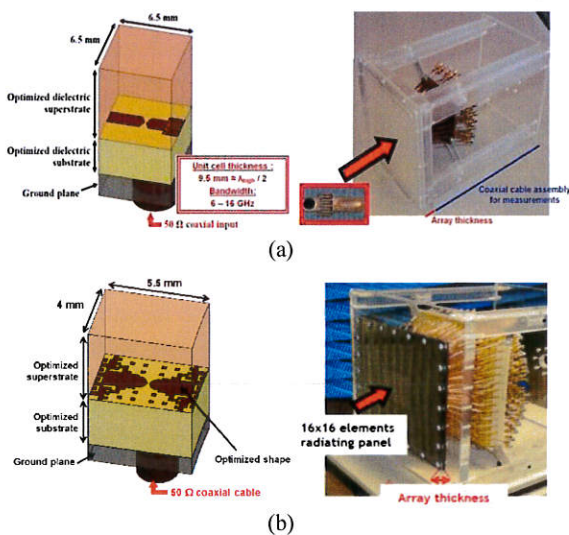


Fig. 1. Tightly coupled dipoles topologies. (a) Linearly-polarized antenna, with the unit-cell on the left and the prototype on the right. (b) Linearly-polarized pixelated antenna, with the unit-cell on the left and the prototype on the right.

B. Linearly-Polarized Array with Broadside Beam

This section presents an antenna specifically designed for SAR and GMTI applications in Ku-band (13.5 GHz – 17.5 GHz).

At the start of this development project, an important specification was to design an operational antenna that fits the SETHI pod mounted on board of ONERA's platform for in-flight tests [13].

Due to space limitations inside the pod, 400 mm \times 200 mm is the maximum size allowed for the antenna aperture. Moreover, the antenna thickness must be as small as possible, with a maximum acceptable value of 50 mm with connectors and cables, to provide sufficient moving amplitude inside the pod to the mechanical beam pointing.

The antenna comprises eight subarrays in a 4 \times 2 configuration. Each subarray contains 64 radiating elements in an 8 \times 8 configuration, and includes a 1:64 corporate feed network that is shown in Fig. 2. (a). Eight SMPM connectors provide access to the eight subarrays. The 1:64 corporate feed network fits into a one-layer PCB topology and provides a compact and wideband solution.

The thickness of the PCB (radiating elements and the feed network) is 5.45 mm. By taking into account the thickness of the ground plane, the overall antenna thickness is 10 mm.

Antenna tests were performed using a 140 mm long cable connected to each SMPM connector. Fig. 2. (b) shows the antenna with the cables and the support frame.

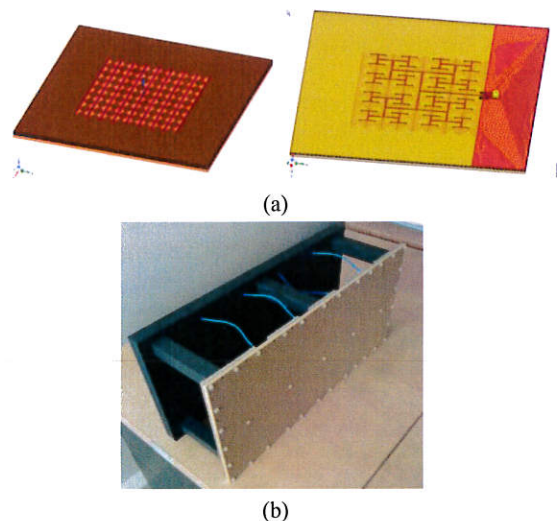


Fig. 2. Linearly-polarized SAR antenna array. (a) Front (left) and rear (right) views of the sub array. (b) Photo of the manufactured 4 x 2 antenna with its mechanical support.

The reflection coefficients of the 8 subarrays are depicted in Fig. 3. (a). The measurements show good

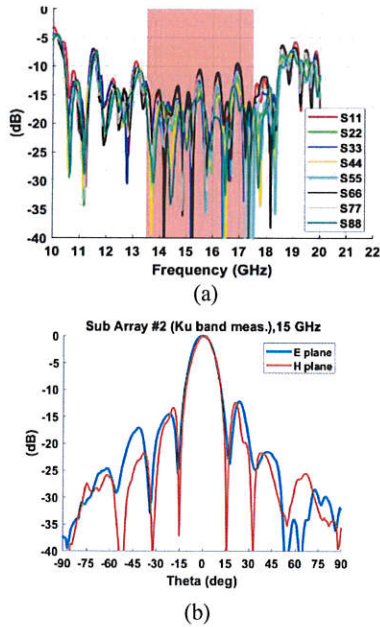


Fig. 3. Measured performance of the SAR antenna array. (a) Reflection coefficients (dB) of each subarray (from 1 to 8) with the operational bandwidth being highlighted in red. (b) Normalized radiation patterns (dB) of the subarray #2 at 15 GHz.

similarity whatever the subarray, with a matching level being below -10 dB from 13.1 to 18.4 GHz. The radiation patterns of E- and H-planes are presented in Fig. 3. (b). The results are similar for all the subarrays, therefore only one of them is presented here. The measured gain ranges from 18.5 to 20.5 dBi between 13.5 – 17.5 GHz. Losses are mainly attributed to the 140 mm long feeding cables.

C. Dual-Linear Polarization and Scanning Beam

To go further, the CROWN project consists in the design and manufacturing of a multifunction AESA system [3]. To reach this goal, it is required to provide an antenna array with dual-linear polarization and a scanning range of 60 degrees within the largest possible bandwidth such as 6 – 18 GHz.

Previous works at ONERA [4] proposed by simulation a pixelated unit cell allowing for these performances, as an extension of the case of Fig. 1. (b). A new element has been developed and optimized, see Fig. 4. (a). Two orthogonal tightly coupled dipoles are printed on a double-sided PCB to generate H- and V-polarizations. The interdigital capacitors are replaced by face-to-face metallization on both sides of the substrate, equivalent to standard capacitors made of two conductors separated by an insulator.

The manufactured antenna is an array of eight elements surrounded by 90 dummy elements connected to 50-ohm loads (Fig. 4. (b)). So as to perform the AESA

function, each dipole is independently fed with a coaxial cable. Due to the small periodicity of the array, a mesh expander (bundle of cables) is needed. In practice, the fabrication of such component is complex. Measurements of the antenna are currently in progress.

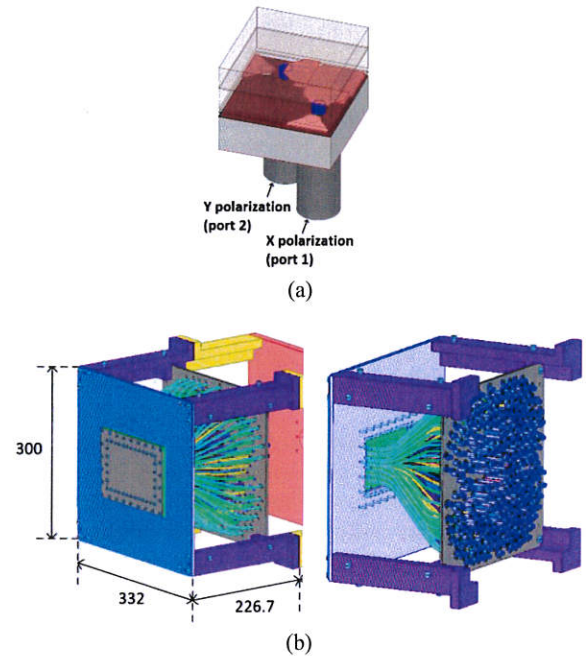


Fig. 4. Illustration of the dual-linearly-polarized CROWN antenna. (a) Unit-cell of the array. (b) Prototype including the antenna array, its mechanical structure and the feeding cables. Dimensions are in mm.

III. CIRCULARLY-POLARIZED ANTENNA ARRAYS

A second type of antenna array topology is also studied by the authors for an AESA application in the CHOSE project. To procure connectivity between airplanes/helicopters and satellites, the dedicated antennas must be circularly-polarized and should be able to scan space with large steering angles. On the other side there is not anymore need for a large bandwidth as compared to the previous cases.

A. Antenna Structure and Working Principle

The proposed unit-cell is presented in Fig. 5. It is composed of two circular patches that couple together to enlarge the bandwidth and match with standard satcom frequency bands. For the same reason, the bottom patch is cut with 4 symmetrical slots. This latter is directly fed with two coaxial cables, whose positions are optimized for a good input impedance. They are placed orthogonally so that one port provides H-polarization while the other gives a V-polarization. In such a way, the combination of the two ports with the proper phase and magnitude enables either a left or

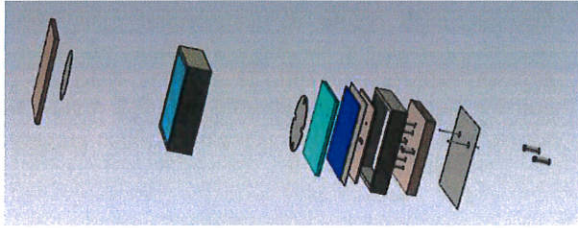


Fig. 5. Circularly-polarized unit-cell.

right-handed circular polarization. The symmetrical properties of this unit-cell further allow a pure circular polarization thanks to the expected similar behaviours from the two inputs. Metallized holes are placed within the feeding layer in order to prevent coupling between the two access ports. The same idea is applied to the unit-cell scale with a cavity shield.

The design phase consists in optimizing two distinct unit-cells: a first one with periodicity 7.5 mm for the 18 – 20 GHz receiving band, and a second one with period 5.5 mm for the 28 – 30 GHz transmitting band. The optimized parameters are mainly substrate and superstrate heights, patches sizes, cavity dimensions, and coaxial positions. The process is accomplished considering an infinite array environment with a triangular lattice to achieve a wider scanning range. The unit-cell detailed performances are available in [10], with further simulations of the finite 8x8 elements arrays.

B. Antenna Prototypes

A major challenge here is to fabricate an antenna array compatible with standard VNA and anechoic chamber measurements.

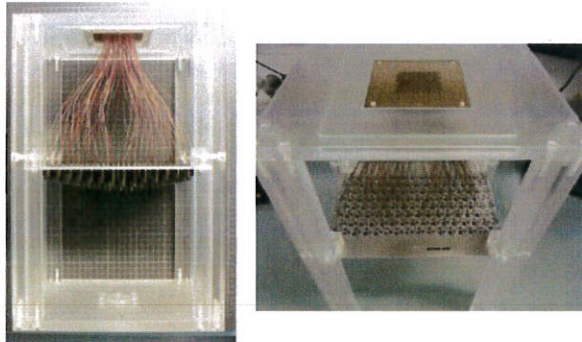


Fig. 6. CHOSE transmitting and receiving prototypes.

In comparison with the antenna presented for CROWN, the complexity is different here by the higher frequency bands considered that lead to two cables to be soldered either in a 7.5 mm or 5.5 mm lattice. Those cables are therefore thinner, with a fragile K-connector, which requires a solder procedure under binocular loupe. Furthermore, high precision manufacturing with electro-erosion is exploited to fabricate the cavities, that should then be perfectly aligned with both patches

layers to prevent short-circuits. The realized prototypes with the mechanical structures are shown on Fig. 6. For the sake of conciseness, the results are not presented here but are detailed in reference [10].

IV. ACTIVE BEAMFORMING NETWORK FOR SERIES ARRAYS

Section II and section III are dealing with AESAs where each radiating element and polarization should be fed independently, with the power and phase being tuned with active amplifiers and phase shifters. This section proposes an alternative approach where the radiating elements are connected to a common beamforming network, which is itself reconfigurable.

For this purpose, a research study was conducted through a PhD thesis on active metasurfaces [11]-[12]. The solution relies on the exploitation of cascaded active composite right left handed (CRLH) cells. The unit-cell is depicted in Fig. 7. by its equivalent circuit and its coplanar waveguide realization. When tuning the varactors, whose effect is evidenced in the equivalent circuit model, it is possible to control the phase shift between the input and output of the unit-cell. As a consequence, one may cascade several cells and generate a desired phase law along the propagating line.

This reconfigurable phasing line can be used as a beamforming network to feed radiating elements. With this approach, all kinds of complex beamforming networks can be envisaged. As depicted in [11], an active metasurface was designed and used to feed a large array of 45×45 patches arranged in a 10.8 mm \times 10.8 mm square lattice. The proposed antenna architecture provides beam scan capabilities ranging from -60° to $+60^\circ$ at 14 GHz. Further studies are required to assess losses, especially in the varactors.

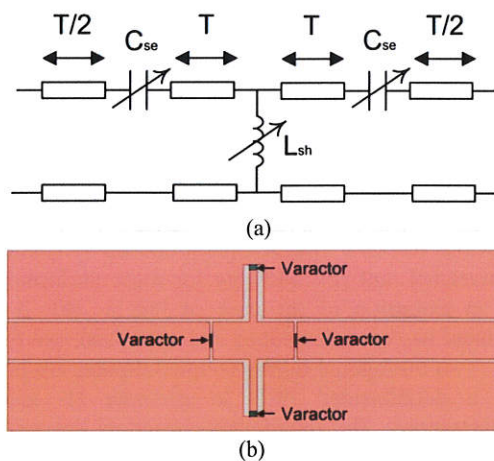


Fig. 7. (a) Equivalent circuit representation of a reconfigurable CRLH cell, (b) CRLH cell with varactor diodes tuning in coplanar waveguide technology.

V. CONCLUSION

In this paper the authors present three different research activities currently developed at ONERA.

The first case concerns printed planar arrays formed by tightly coupled dipoles covered by WAIM layers to perform wideband performance. Different topologies are presented, exploiting interdigital or parallel plate capacitors, as well as classical dipoles or pixelated versions. A specific set of optimization procedures has been developed to achieve linear or dual-linear polarization with scanning up to 60 degrees. A SAR multi-layered antenna array is demonstrated with a large bandwidth beamformer, with good matching from 13.1 to 18.4 GHz. The CROWN project goes further with dual-polarization, generating a complex device as presented in this paper.

The second topology presented relates to connectivity of airborne platforms by using Ka-band up and downlinks. The designed and fabricated AESA antennas procure now a pure circular polarization with wide angle scanning capability. It is shown here that such small and complex prototypes are very sensitive to precision and quality of the manufacturing and alignment steps.

Finally, a concept based on active reconfigurable beamformers is presented. CRLH cascaded unit-cells may be controlled by varactor diodes to get a reconfigurable phase shift between inputs and outputs. This is demonstrated here with a patch array that scans from -60 to +60 degrees when it is excited by the active beamformer.

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