

DUAL-FREQUENCY PHASED ARRAY ANTENNAS WITH OPTICAL BEAMFORMING FOR AIRBORNE SATELLITE COMMUNICATION

H. Schippers⁽¹⁾, J. Verpoorte⁽¹⁾, P.Jorna⁽¹⁾, A. Hulzinga⁽¹⁾,
A. Meijerink⁽²⁾, C. G. H. Roeloffzen⁽²⁾, L. Zhuang⁽²⁾, D. A. I. Marpaung⁽²⁾, W. van Etten⁽²⁾,
R. G. Heideman⁽³⁾, A. Leinse⁽³⁾, A. Borreman⁽³⁾, M. Hoekman⁽³⁾, M. Wintels⁽⁴⁾

⁽¹⁾ National Aerospace Laboratory NLR, Anthony Fokkerweg 2, 1006 BM Amsterdam, the Netherlands,
Email: schipiw@nlr.nl

⁽²⁾ University of Twente, P.O.Box 217, 7500 AE, Enschede, the Netherlands, Email: A.Meijerink@IEEE.org

⁽³⁾ Lionix bv, P.O. Box 456, 7500 AH Enschede, the Netherlands, Email:A.Leinse@lionixbv.nl

⁽⁴⁾ Cyner Substrates, Savannahweg 60, 3542 AW Utrecht, the Netherlands, Email: m.wintels@cyner.nl

INTRODUCTION

For enhanced communication on board of aircraft, novel antenna systems with broadband satellite-based capabilities are required. So far existing L-band satellite based systems for communications are used primarily for passenger application (APC) or administrative communications (AAC); initially analogue voice and now data are tending to evolve towards broadband digital applications. Many studies are going on worldwide to employ Ku-band TV geostationary satellites for communication with mobile terminals on aircraft. For a short period broadband internet was available on aircraft via Connexion by Boeing (CBB) services. Lufthansa installed the CBB system on some of their long-haul aircraft.

In the EC Sixth Framework Programme ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) existing and planned aeronautical SATCOM services, systems and technology have been analysed. It has been concluded that for cockpit services, L-band systems (namely Inmarsat, MTSAT, Iridium and Globalstar) are clearly most suitable, whilst Ku-band systems have appeal for passenger services.

In order to decrease the cost of communication avionics and to provide SATCOM services for both cockpit crew and passengers, in the ANASTASIA project technology is being developed for a conformal dual frequency airborne antenna. This means that only one antenna is needed instead of two because it will provide access to two frequency bands (L-band and Ku-band). Being conformal will decrease installation and exploitation costs. The objective of this paper is to present research results of two key topics: the development of a dual frequency phased array antenna and beam steering capabilities for the Ku-band part of the antenna.

The antenna front-end consists of a broadband faceted phased array antenna. The antenna elements in Ku-band are stacked patch antennas with dual linear polarization (bandwidth ≥ 2 GHz in Ku-band). Each tile of 8x8 Ku-band antenna elements contains on a separate layer two radiating L-band slots (dual linear polarized). Special attention is paid to the manufacturability of the antenna by selecting specific materials and appropriate fabrication techniques.

For the steering of the beam of the conformal phased array a squint-free, continuously tunable mechanism is proposed that is based on a fully integrated optical beam forming network (OBFN) using cascades of optical ring resonators (ORRs) as tunable delay elements.

The technology development is carried out partly in the Dutch FlySmart project, under contract with SenterNovem, an agency of the Dutch Ministry of Economic Affairs, and partly in the European project ANASTASIA (<http://www.anastasia-fp6.org/>).

SYSTEM ASPECTS

In the Dutch FlySmart project, technology is developed for a conformal phased array antenna having an instantaneous bandwidth of 2 GHz, covering the whole frequency range of 10.7 to 12.75 GHz. Satellites operating in this band are geostationary satellites spaced 2° apart in the United States and 3° in Europe. In order to be able to receive these satellites also at high latitudes (e.g. during inter-continental flights) the antenna system should have sufficient performance at low elevation angles. Therefore the antenna system is required to have a small beamwidth (to discriminate between the satellite signals) and a high gain (>30 dB) also at low elevation angles. Since gain of the antenna is related to the effective aperture of the antenna in the direction of the satellites, a conformal antenna also covering side parts of the fuselage could be an advantage. The phased array antenna shall maintain the proper (linear) polarization during all attitudes and at all positions of the aircraft (also at high latitudes).

An antenna to be used on aircraft has to be able to operate in severe environmental conditions concerning temperature, pressure, vibration and humidity. The environmental requirements for civil airborne equipment are given in RTCA DO-160 or EUROCAE ED-14 [1].

In general, the antenna system consists of a phased array antenna, electrical-to-optical conversion, optical beam forming (or beam steering) and optical-to-electrical conversion (Figure 1).

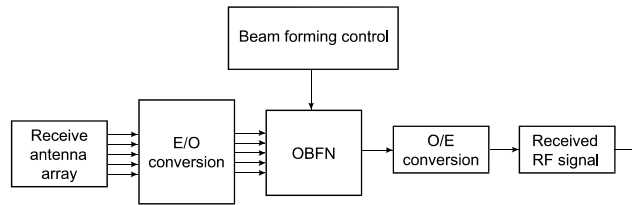


Figure 1 System design of Ku-band receive antenna with Optical Beam Forming Network (OBFN)

The phased array antenna will be a conformal (singly-curved) 2-D array of dual linear polarized broadband antenna elements. Each antenna is followed by a Low Noise Amplifier (LNA) and down-converter (together a Low Noise Block converter, LNB). The Local Oscillator (LO) signals of the LNBS are synchronised to maintain an appropriate phase relation between the OBFN channels. The Intermediate Frequency (IF) signal from the LNB is subsequently fed to optical modulators which perform the electrical-to-optical conversion. In the Optical Beamforming Network (OBFN) each individual signal is attenuated and delayed in order to shape and direct the antenna beam. The sum of all signals is converted back from the optical to the electrical domain. The tracking algorithm will use the aircrafts position and attitude to determine the appropriate polarization and azimuth and elevation of the antenna beam.

To reach the objective of a 2 GHz bandwidth, both the antenna front-end and the beamforming network should have broadband characteristics. Therefore, the antenna front-end consists of an array of stacked patch antennas. The beamforming network consists of an optical network with True Time Delays (TTD) which have inherently large bandwidth. To have a 2° beamwidth and high gain antenna (approx. 36 dB), a large array antenna is needed. The current design is based on an array of 40 by 40 antenna elements (1600 in total).

PRELIMINARY DESIGN OF DUAL-FREQUENCY BAND ANTENNA

The dual-frequency band antenna for future SATCOM should operate at L-band and Ku-band. At L-band, the polarization should be circular and the frequency range should be about 1.3 GHz – 1.5 GHz. At Ku-band, the polarization should be linearly adjustable and the frequency range should be ~ 10.5 GHz - ~14 GHz. Hence the ratio between the L-band and Ku-band antenna elements is about eight. The L-band antenna elements should be about 8 times larger than the Ku-band antenna elements. In the case of such a wide separation between the two frequency bands the concept of interleaved array appears to be a promising approach. In other words, different elements can be used for L and Ku-band, which both exhibit their own feed network. The elements are arranged in an interleaved way, where extra attention should be paid to the positioning of the elements. In a tight grid, mutual coupling will have an impact on the radiation pattern and may give rise to an increase of the cross-polarized component.

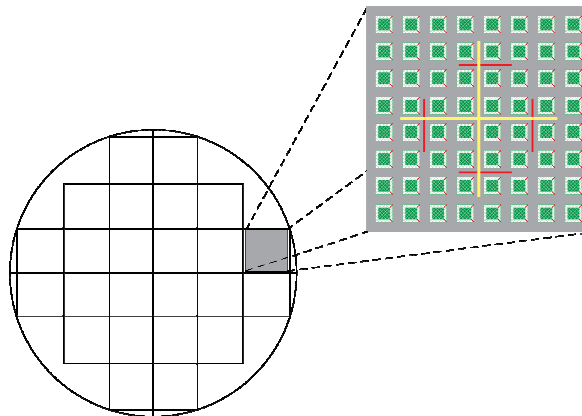


Figure 2 A large antenna array composed of 24 square 8x8 Ku-band building blocks crudely approximating an antenna array with circular boundary.

In the 64 element array (as displayed Figure 2) the distance between the centres of the patches is a half wavelength for the maximum frequency of 12.7 GHz, that is the element centres are 11.8 mm separated from each other. Both height and width of the tile are $8 \times 11.8\text{mm} = 94.4\text{mm}$ and hence the overall size of the tile is 94.4mm by 94.4 mm. The square tile can be used as the building block of a much larger array as is shown in Figure 2. The array shown in Figure 2 crudely approximates a circularly shaped array with radius $R_a = 4\sqrt{10}\lambda$. It is clear from the figures that the relatively large tiles are not very well suited for conformal installation. The array built with square tiles contains $24 \times 64 = 1536$ elements.

Design of L-band antenna

Some of the dimensions of the antenna are defined by the Ku-band element. These constraints result in less flexibility for designing the L-band element. Given the fact that a ground plane with slots is used for the Ku-band antenna a possible design for a L-band antenna is a radiating slot with or without parasitic elements.

The use of a parasitic element did not lead to a design with an acceptable return loss and an acceptable radiation pattern. Also the integration of the parasitic elements with the Ku elements gave some problems. Therefore the L-band antenna was designed as two orthogonally crossed slots in the ground plane (see Figure 3). Each slot is symmetrically excited by two feed lines. The resonance frequency depends on the length of the slot. Optimisation for the bandwidth was found by small changes in the length and width of the slot.

As each slot is symmetrically fed by two feed lines a power divider is needed to split the antenna connection into two parts with equal phase and amplitude.

The initial dimensions of the L-band element were designed in Ansoft designer. The element was optimised in Ansoft HFSS. The vertical feed lines were also added in HFSS. Initially the required space between the two Ku patches was filled with Rohacell foam. During the manufacturing process it became clear that due to gluing the different layers of the antenna the glue was penetrating the foam. This led to an uncontrolled value for the resulting permittivity of the foam layers. A solution was found for this problem. The foam was replaced with the same material as the patch substrates were made off. However on specific places holes were made in this so-called foam replace material. This process was completely done in HFSS. Due to the relatively small distance between the slotted ground plane and the support ground plane of the antenna a new optimisation was required. However due to this relatively small distance the antenna properties were influenced in a negative way. Figure 4 displays the computed return loss. The figure implies that a small adjustment of the slots may be needed. The resonance peak may need to be shifted to a somewhat higher frequency. Further optimization for bandwidth is limited to the length and width of the slot.

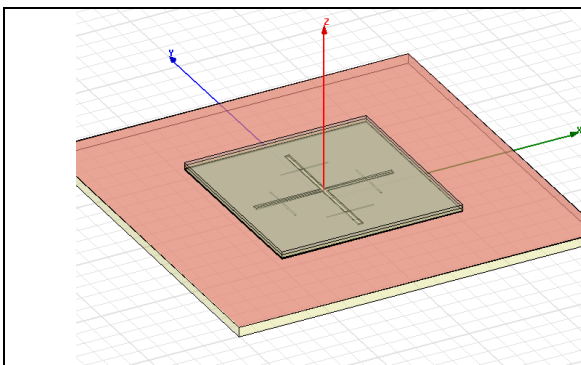


Figure 3 Ansoft HFSS model of the L-band antenna only

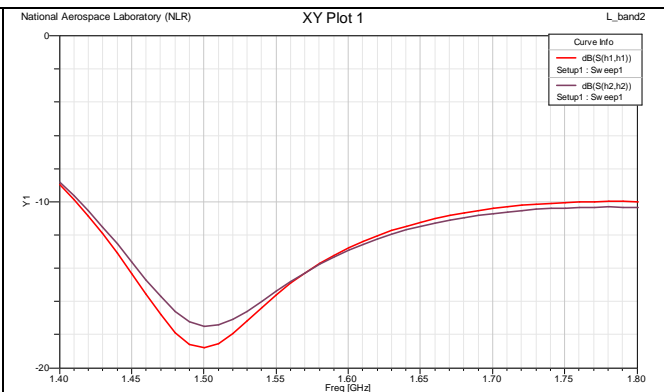


Figure 4 Return loss L-band element

Design of Ku-band antenna elements

A common approach for increasing the bandwidth is to add parasitic elements to the antenna structure (e.g. a stacked patch). This reduces the impedance variation of the antenna with the frequency, thus enhancing bandwidth performance. Various arrangements of stacked structures have been considered in the literature. In practice, it is difficult to optimise the bandwidth of these structures due to their sensitivity with respect to many physical parameters (patch sizes, substrate thicknesses, and feed-point position). Research has focused on the choice of the materials for the dielectric layers in the stacked configuration. Thick laminates of low-dielectric constant provide the largest bandwidth and surface wave efficiency (see [2]).

Figure 5 shows the design of the present Ku-band antenna element consisting of a multilayer structure where the parasitic and radiating patches are mounted on commercially available Duroid substrates. The space between the patches is filled with typical space filler that is being developed for this purpose. The lowest patch is being fed by an aperture in a lower ground plane, again mounted on a substrate. On the lower side of this substrate are horizontal feed lines, which are connected to shielded vertical feed lines to provide connections with the beam forming network on a lower layer.

The dimensions of the Ku-band antenna design have been optimised by using ANSOFT HFSS simulation software. The ANSOFT HFSS model for the design is shown in Figure 6. The dimensions of the patches, dog bone aperture and thicknesses of foam layers have been optimised with the aim to get an antenna which could span the frequency-band from 10.7 to 12.75 GHz. The computed gain of this stacked patch antenna is about 9dBi. Figure 7 displays the reflection coefficients of the antenna element. Notice that the return loss is below -10 dB in the frequency range between 10.7 to 12.75 GHz as aimed, which indicates that this element has sufficiently large bandwidth for broadband data transmission.

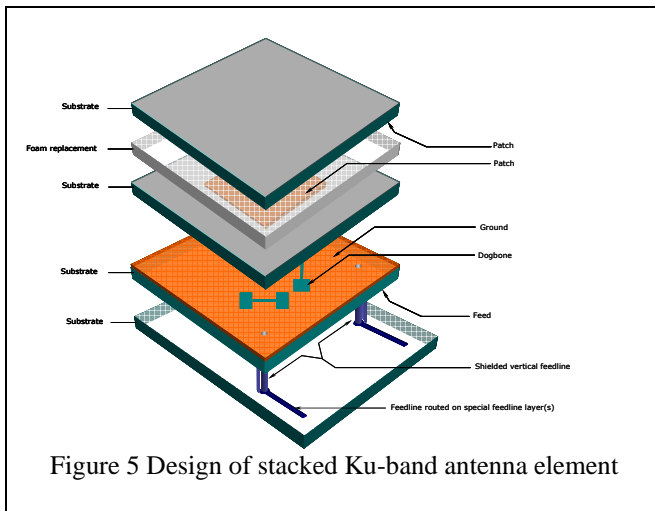


Figure 5 Design of stacked Ku-band antenna element

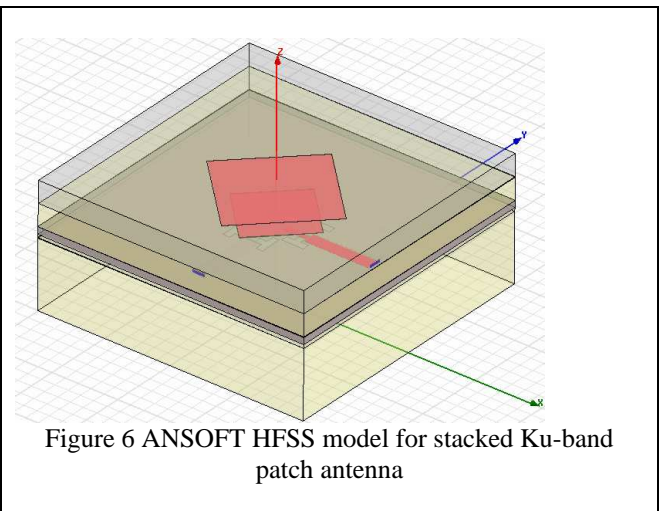


Figure 6 ANSOFT HFSS model for stacked Ku-band patch antenna

Due to the integration of the Ku and L-band antennas some dimensions of the Ku-band antenna had to be changed. Also the final decision to use 5mm of distance between the support ground layer and the feed traces influenced the properties. These two changes led to an antenna with less good performance. A further optimisation was performed. The return loss is displayed in Figure 7. It is clear that the antenna shifts down in frequency.

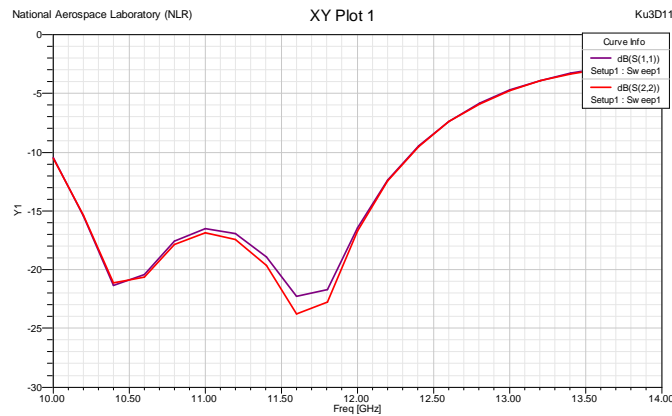


Figure 7 Return loss Ku-band antenna

OPTICAL BEAMFORMING

For the steering of the beam of the conformal phased array a squint-free, continuously tunable mechanism is proposed that is based on a fully integrated optical beam forming network (OBFN) using cascades of optical ring resonators (ORRs) as tunable delay elements. A narrowband continuously tunable optical true time delay (TTD) device can be realized as a recirculating waveguide coupled to a straight waveguide. This straight waveguide can behave as an all-pass filter with a periodic, bell-shaped tunable group delay response. The maximum group delay occurs at a tunable resonance frequency. A larger delay-bandwidth product can be achieved by cascading multiple ORR sections. A complete OBFN can be obtained by grouping several delays and combining elements in one optical circuit. Such an OBFN can be realized on a single-chip. Electrical/Optical (E/O) and Optical Electrical (O/E) conversion are realised by means of filter based single-sideband modulation (suppressing the carrier) and balanced coherent optical detection. Further details of the optical beamforming network have been presented in Ref. [3]

REFERENCES

- [1] EUROCAE ED-14E; Environmental Conditions and Test procedures for Airborne Equipment, March 2005.
- [2] R. B. Waterhouse, "Design of probe-fed stacked patches", IEEE Transactions on Antennas and Propagation, vol. 47, no. 12, Dec. 1999, pp. 1780-1784.
- [3] H. Schippers et. Al, Broadband Conformal Phased Array with Optical Beamforming for Airborne Satellite Communication, Paper presented at IEEE Aerospace Conference, Big Sky (US), March, 2008.