HIGHLY INTEGRATED RF-MODULES FOR KA-BAND MULTIPLE-BEAM ACTIVE PHASED ARRAY ANTENNAS

J. Butz, M. Spinnler, J. Christ*, U. Mahr*

Bosch Satcom GmbH, D-71522 Backnang / Germany
*Marconi Communications, D-71522 Backnang /Germany

Abstract — **This paper describes design and measurement results of RF modules intended for a proposed spaceborne multimedia Ka-Band multiple-beam transmit phased array antenna. The developed modules include a four-beam RF Control Module (CM) for amplitude and phase shaping, a Solid State Power Amplifier Module (SSPAM) for power amplification as well as a Radiating Module (RM). The CM is realised on a multilayer LTCC substrate with custom-designed 6-bit phaseshifter MMICs and 5-bit attenuator MMICs. The SSPAM is realised on thin-film substrates with GaAs MMIC amplifiers. The modules were designed to meet the electrical, mechanical and thermal requirements of the proposed antenna. Using the developed modules, a subarray demonstrator consisting of four radiating patches was realised. The measurement results show that specified key performance parameters are met and prove the feasibility of the antenna concept.**

These activities are co-funded by the European Space Agency (ESA) in the frame of the ARTES 3 Multimedia Programme.

I. INTRODUCTION

Satellite communication systems must meet the rapidly growing demand of tomorrow's high-speed multimedia services. The ESA ARTES-3 Program has identified in particular Ka-Band Tx/Rx antennas and frontends designed for variable traffic patterns as immediate development objectives. Reported development activities point in the same direction [1][2]. Bosch SatCom derived the target performance parameters of such an antenna from a reference LEO satellite scenario. The concept of a modular phased array antenna was developed and a subarray consisting of four radiating patches with all necessary active modules was realized. To our knowledge, this is the first reported multi-beam Ka-Band Phased Array with four independantly steerable beams.

II. ANTENNA DESIGN AND TARGET PERFORMANCE

The block-diagram of the proposed antenna is shown in Fig. 1. Operating in the Ka-Band downlink frequency range at 18.8-19.3 GHz, the Tx-Antenna is specified to have a scan range of 41.5° vs. boresight.

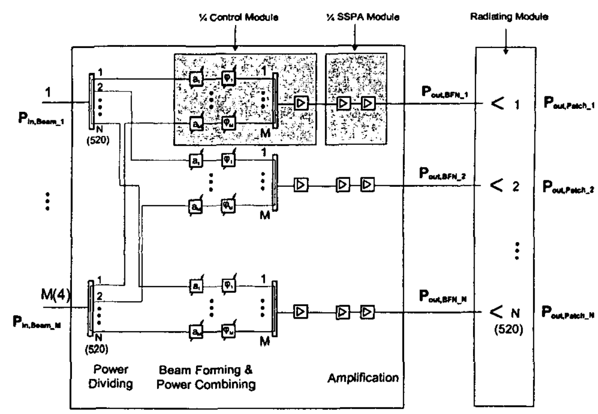

Fig. 1. Block Diagram of Multibeam Phased Array Antenna

The mechanical design of the antenna is such that all active circuit modules responsible for one row of radiating patches are located within one module tray. The trays in turn are stacked on top of each other. RF input divider, DC-Supply, DC distribution and antenna controller are located on the four sides of the resulting antenna block.

In total, one Tx-Antenna drives 520 radiating patches which are arranged in 27 module trays, each containing the active modules for up to 24 patches. Not all trays are fully populated for a circular arrangement of the radiating patches. Table 1 summarizes the characteristics of the Tx-Antenna.

TABLE I
SUMMARY OF ANTENNA CHARACTERISTICS

Frequency Range	18.8 – 19.3 GHz
Steerable Beams	4
Radiating Patches	520
Active Module Trays	27 (each containing 6 CM and 6 SSPAM)
3dB Beamwidth	7° boresight, 4° x 5° EOC
Scan Range	0° ... 41.5° vs. boresight
EIRP	30 dBW boresight
Power Consumption	430 W
Mass	25 kg
Dimensions	440 x 470 x 250 mm^3

The performance requirements for the active modules described in the following paragraphs were derived from this frontend concept.

III. Module Design and Performance

A. Control Module

A Control Module (CM) including all phase shifters and attenuators for four independently steerable beams and driving four independant antenna radiators was developed. The CM requirements are summarized in Table II.

TABLE II
SPECIFICATION REQUIREMENTS OF CONTROL MODULE

Independant Beams	4
RF Inputs	16 (4 identical circuits with 4 beam inputs each)
RF Outputs	4
Phase Shift Range	0 ... 360 deg
Phase Accuracy	<7 deg
Attenuation Range	0 ... 8 dB
Attenuation Accuracy	0.5 dB
On/Off Switch	>40 dB isolation
3rd Order Intermodulation	ICP3 > +5 dBm
Power Consumption	< 400 mW
Mass	<8 g (assembled substrate)
Dimensions	49.9 mm x 39 mm x 1.3 mm

Size is one of the most challenging parameters for a direct radiating antenna at Ka-Band. Thus, one major development focus was on a high integration level for both active circuits as well as interconnection substrate.

Both phase shifters and attenuators were realized as monolithic GaAs MMIC devices of 2 x 3 mm^2 size each. The phase shifter is of the series type with six dicrete, cascaded phase shift bits (5.6°, 11.2°, 22.5°, 45°, 90°, 180°). The 180° bit is realized as a FET switched highpass/lowpass filter while all other bits are reflection-type phase shifters using Lange couplers with FETs as switching devices. The attenuator uses the same circuit configuration, but the individual bits are tuned for nominal attenuation with minimal phase variation between the states, while the phaseshifter bits are tuned for nominal phaseshift with minimal attenuation variation. Both MMIC are controlled by digital inputs.

The specified multibeam capability, phaseshift and attenuation resolution require a very high number of RF and DC interconnections within the antenna, down to the substrate level. The specifications in Table II result in a total number of 32 Control MMIC, having >200 digital DC and >50 RF interconnections. The CM design approaches this task by means of a monolithic LTCC multilayer substrate, which carries both DC and RF interconnections. Fig. 2 shows a picture of the substrate surface with mounted RF components.

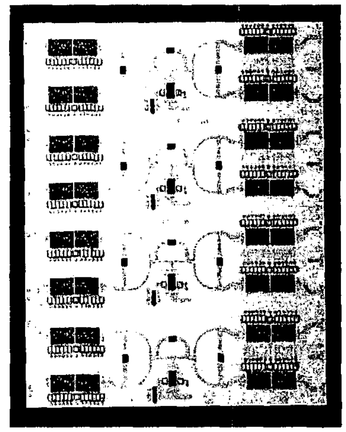

Fig. 2. CM Substrate with RF Components (Size approx. 49.9 mm x 39 mm)

The LTCC is based on the FERRO A6M substrate system and consists of 12 ceramic layers with screen-printed external Au and internal Ag conductors. Apart from the internal DC signal routing, the LTCC carries buried RF striplines and RF microstrip lines as well as Wilkinson-type RF power combiners on the surface [3]. All RF components are mounted on the frontside while the backside of the substrate is foreseen to carry a control ASIC. For this demonstrator, however, the ASIC was not realized and the control inputs on the substrate backside are connected to an external interface.

B. SSPA Module

A Solid State Power Amplifier Module (SSPAM) was developed which provides the necessary amplification for driving the radiating patches. The performance requirements are summarized in Table III.

TABLE III
SPECIFICATION REQUIREMENTS OF SSPA MODULE

Small-Signal Gain	36 dB
1 dB Compression	P_{1dB} >21dBm
Return Loss	>15 dB
PAE @ P1dB	>27%
3rd Order Intermodulation	>13 dBc @ P_{1dB}
Power Consumption	4 x 475 mW
Mass	1.2 g (assembled substrate)
Dimensions	49.9 mm x 15 mm x 0.4 mm

Due to the large number of amplifier circuits confined to a compact volume in the complete antenna, the dissipated heat poses a major design challenge. The problem was addressed by using very power-efficient amplifier MMICs and an appropriate substrate technology.

A commercially available high-gain (21dB), power-efficient (PAE=21%) amplifier MMIC with moderate output power (P_{1dB}=13dBm) was chosen as a first stage amplifier, followed by a power-amplifier with high efficiency (PAE=32%) and high output power (up to 26 dBm, depending on bias). The overall power-added efficency of the SSPAM at 1dB gain compression was measured at 27%.

The MMICs are soldered directly onto a 10 mil thin alumina substrate which incorporates Au-filled vias directly below the heat sources. The temperature rise from substrate backside to FET junction was calculated to 29 K. Fig. 3 shows a picture of the assembled substrate.

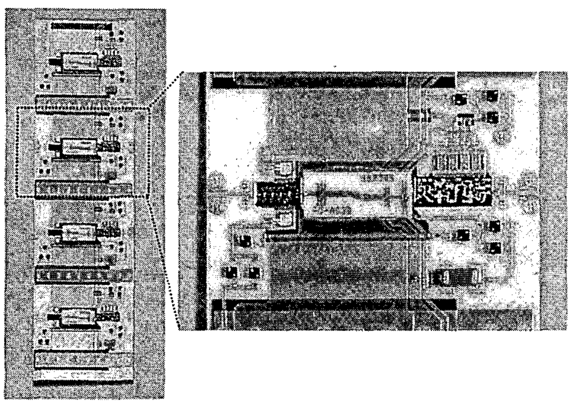

Fig. 3. SSPA-Module Substrate (left); One of the four identical SSPAM-Channels (right)

C. Radiating Module

A novel planar radiating element was designed, where the aperture of a double ridge waveguide above cutoff feeds the patch radiator and serves as electrical transformer as well as mechanical support [4]. The radiating element consists of a square patch on a substrate without ground metallization. For circular polarisation, the resonant frequencies of the two orthogonal modes are slightly shifted from the center frequency f_0 due to notches in the patch. A Radiating Module (RM) consisting of eight radiating elements was realized. The picture in Fig. 4 shows the RM as part of the subarray demonstrator, where four elements are fed by the active modules and two elements on either side are used to model the antenna environment

IV. Subarray Demonstrator

In order to verify the antenna performance, the developed modules were packaged into individual test fixtures and integrated into a subarray demonstrator. Since no control ASIC was realized for the CM, all control signals were made available by external connectors. In order to keep the external interfacing reasonable, only a one-beam subarray was measured. The active modules incorporate all circuits of a complete four-beam subarray, however. Fig. 4 shows the integrated subarray demonstrator.

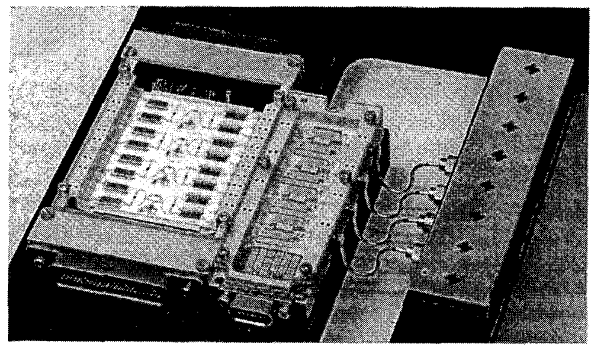

Fig. 4. Subarray Demonstrator with Test Fixture (from left to right: CM, SSPAM, RM)

V. Measurement Results

Fig. 5 shows the attenuation control performance of one of the 16 individually controllable paths of the subarray, normalized to the state with lowest attenuation. The dynamic is −11.5 dB with a resolution of 0.8 dB. This reflects the attenuator MMIC performance, which did not meet the exact specified values of 8 dB dynamic with 0.5 dB resolution.

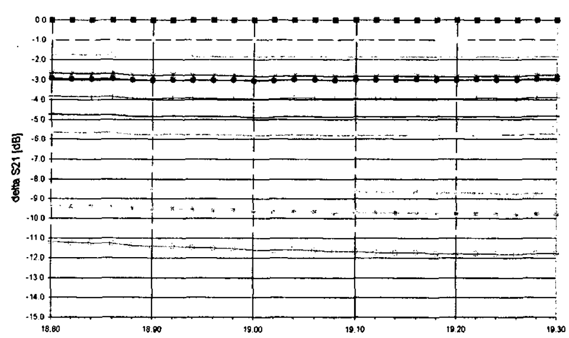

Fig. 5. Subarray Attenuation Performance. Shown are all 16 Attenuator States at Tamb (Beam 1/Path2)

Shown in Fig. 6 are all 64 possible phase shifter states of the same individual path as above. Relying on the same circuit topology as the attenuator MMIC, the phase shifter MMIC also did not meet the exact phase values. However, using a lookup-table for the measured values, full 360° are covered with an accuracy <15 deg. The specified requirement of <21deg accuracy for the integrated antenna is achieved.

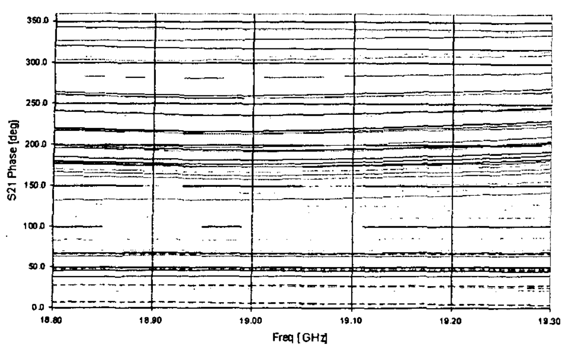

Fig. 6. Subarray Phase Shift Performance. Shown are all 64 Phase Shift States at Tamb (Beam1/Path2)

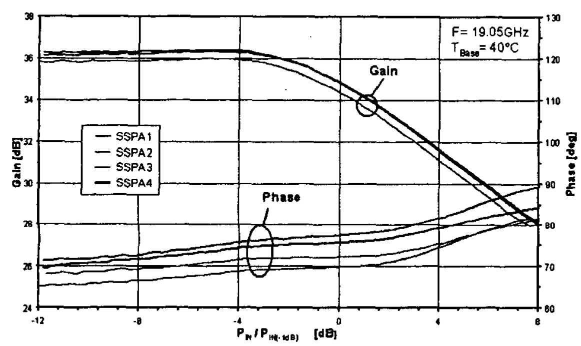

Fig. 7. SSPA-Module Large Signal Insertion Gain, Phase

Fig. 7 shows the large signal performance of the SSPA Module. All four SSPA deliver the required +21dBm output power. Gain variation between SSPAs at 1dB compression is below 0.5 dB while the phase expansion relative to small-signal conditions is below 10 deg.

Fig. 8 shows the beam scanning performance of the 4-element subarray. The measured results in terms of side-lobe level, appearance and position of grating lobes, 3dB beamwidth and co-cross-polar discrimination show good agreement to the simulated and expected ones.

More detailed measurement results will be presented at the conference presentation.

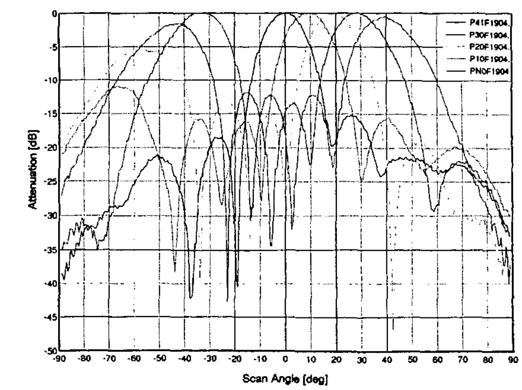

Fig. 8. Measured Scan Performance of the Demonstrator

VI. Conclusions

A Ka-band 4-beam subarray antenna demonstrator consisting of a Control Module, an SSPA Module and a Radiating Module was developed. The electrical, mechanical and thermal constraints of a full-scale antenna were taken into consideration. Output power and efficiency requirements are met. Phase shift accuracy and attenuation accuracy of the MMICs exceed the specified values. By using a lookup-table, the demonstrator accuracies are within specification, nevertheless. With an improved MMIC design, the specification could be met without using a lookup table. The radiation measurements showed good agreement with the specified and simulated values.

Acknowledgement

This work has partially been funded by the European Space Agency in the frame of the ARTES 3 Multimedia Programme.

References

[1] J. D. Warshowsky, J. J. Whelehan, R.L. Clouse, "High rate user phased array antenna for amall LEO satellites," *1998, 4th Ka-Band Util. Conf. Dig.*, pp. 539-546.

[2] D. Michel, B. Cogo, D. Roques, G. Raguenet, T. Dusseux, G. Caille, M. Belfort, "Active Ku-band spaceborne antennas: Design, technology and testing," *1996 COST ESA Workshop on Active Antennas Proc.*, pp. 341-347.

[3] F.J. Schmückle, A. Jentzsch, W. Heinrich, J. Butz, M. Spinnler, "LTCC as MCM substrate: Design of strip-line structures and flip-chip interconnects," *2001 IEEE MTT-S Int. Microwave Symposium Dig.*, vol. 3, pp. 1903-1906

[4] U. Mahr, J. Christ, M.Munk, "Planar Phased Arrays of Aperture Coupled Microstrip Patches with Novel Feeding Technique," *Millenium Conf. on Antennas and Propagation,* AP 2000, Davos, Dig. p. 198