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A low-profile user terminal antenna for mobile bi-directional Ka-band satellite communications

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A LOW-PROFILE USER TERMINAL ANTENNA FOR MOBILE BI-DIRECTIONAL KA-BAND SATELLITE COMMUNICATIONS

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ABSTRACT

This paper presents a low-profile user-terminal antenna for mobile bi-directional Ka-band satellite communication networks for emergency scenarios. We have devised an antenna with a circularly polarised radiation pattern and dual-band capability, which addresses a hybrid tracking. The principle of operation of a rectangular antenna panel applying a dual-band partially reflective surface (PRS) of 60 mm by 200 mm was manufactured and successfully verified. This publication describes the design of the panel and analyses measurement results. Furthermore, our first low-profile antenna demonstrator is presented, intended to be evaluated at a testbed for satellite communications in Ilmenau.

1. INTRODUCTION

In emergency scenarios the communication of rescue forces and public authorities would no longer be feasible due to overstrained or damaged terrestrial networks. But in the initial relief phase of rescue operations, current situation reports, voice communication and the transmission of positioning and geographical data are of key relevance. This communication can be established via satellite links, even on the move and with high reliability. This alternative to terrestrial infrastructure provides the connection of vehicles by nomadic or mobile satellite user-terminals operating favourably at Ka-band frequencies (downlink: 20 GHz, uplink: 30 GHz). Ka-band frequencies permit a satellite spot-beam architecture, which relaxes the link budget and permits even moderate antenna gain of on-the-move user-terminals. These considerations lead to the development of a mobile low-profile multi-panel antenna for heterogeneous Ka-band satellite communication networks. Our antenna concept involves a hybrid mechanical-electronic tracking method and addresses circular polarisation, well suited for mobile applications. The presented work contributes to the public R&D project *MoSaKa* (Mobile Satellite Communications in the Ka-band [1]) with partners from Fraunhofer IIS Ilmenau, DLR Oberpfaffenhofen, and IABG Ottobrunn.

2. LOW-PROFILE ANTENNA CONCEPT

The *MoSaKa* low-profile antenna has a compact outdoor-unit with an antenna height below 15 cm. The antenna concept [2] is based on a low-complexity approach using just a small number of feeding points and on differently tilted antenna panels located on a high-precision mechanical azimuth positioner as depicted in Fig. 1. A leaky-wave antenna principle [3,4] employing 2D-periodic structures was chosen to be used for the panels, which provide a reconfigurable circularly polarised radiation pattern and dual-band capability. This dual-band behaviour is realised by interlaced radiating apertures for the widely separated downlink- and uplink frequency bands around 20 and 30 GHz. The tracking in the elevation plane is accomplished electronically by *maximum ratio combining* (MRC) of the signals received from the antenna panels acting as sub-apertures. Furthermore the detected MRC-coefficients can be used to create the right distribution of the transmitting sub-apertures and to realise a closed-loop tracking in the elevation plane. A step-tracking procedure is used to achieve the signal acquisition in the azimuth plane and the mechanical tracking itself is stabilised by GPS-information and an inertial sensor-unit comprising a gyro compass, an accelerometer, and a magnetometer. Furthermore the antenna panels are providing monopulse-tracking information in the azimuth plane, which can be used to enable a closed control loop even in this plane.

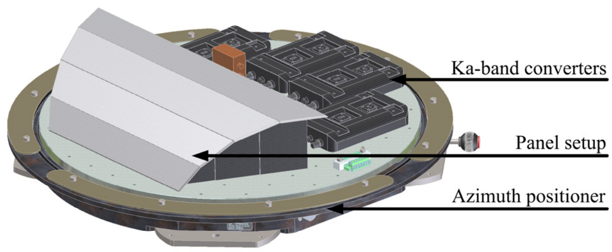

Figure 1. Sketch of the low-profile user-terminal antenna intended for mobile Ka-band satellite communications.

3. DESIGN & IMPLEMENTATION OF THE LEAKY-WAVE ANTENNA PANEL

The leaky-wave antenna panel based on 2D-periodic cell structures applies a 2-layer partially reflective surface (PRS) to enable the functionality at 20 and 30 GHz at the same time. A top- (20 GHz PRS) and a bottom-layer (30 GHz PRS) of 2D-periodically arranged unit cells are printed on a suitable microwave substrate, e.g., *Rogers* laminate. Depending on the effective permittivity of the substrate and air, both are located at approximately a half guided wavelength over a ground-plane with an integrated slot radiator array operating as primary source of the leaky-wave antenna. The intention is to create a 2-layer arrangement, where only one PRS layer offers its partially reflective behaviour at one frequency band while it does not influence the radiation pattern at the respective other frequency too much. The general layer build-up of the dual-band leaky-wave antenna panel is shown in Fig. 2 and further design information were already published in [5,6].

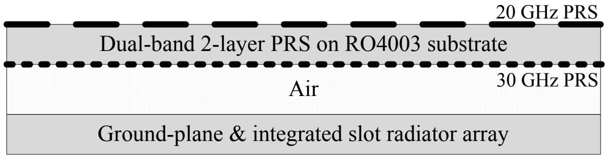

Figure 2. Layer build-up of the dual-band leaky-wave antenna panel.

The geometry designs of the top- and bottom-layer unit cells with a lattice constant of 2.32 mm are depicted in Fig. 3. The frequency selective behaviour [7] of that cells used as 2D-periodic cell surface is important to create a band-pass filter characteristic with the required frequency response respectively bandwidth and the needed reflection values for the operational frequency range.

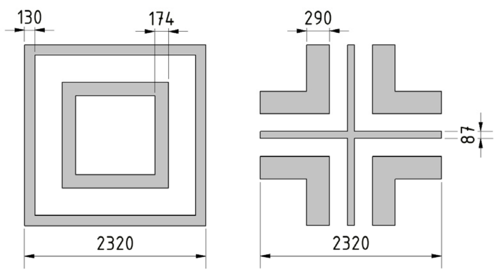

Figure 3. Unit cells of the 20 GHz (left-hand side) and 30 GHz (right-hand side) PRS-layers (all dimensions in µm).

Fig. 4 shows the realised aluminium ground-plane with feeding waveguides and a hybrid T-junction (magic-T) milled into it. The travelling guided wave excites the circularly polarised radiation of the laser-cut slot antenna array, located above [8].

In the case of the 20 GHz excitation a 10-slot array with differing slot lengths from 6.8 mm to 7.25 mm was implemented and as 30 GHz source an array of 14 slots with lengths from 4.45 mm to 4.775 mm was realised. The magic-T, with its post and iris used for the matching, provides a sum and a difference radiation pattern at its E- and H-waveguide ports guided to the backside of the antenna panel. The evaluation of magnitude and phase of both signals provides monopulse-tracking information in the azimuth plane.

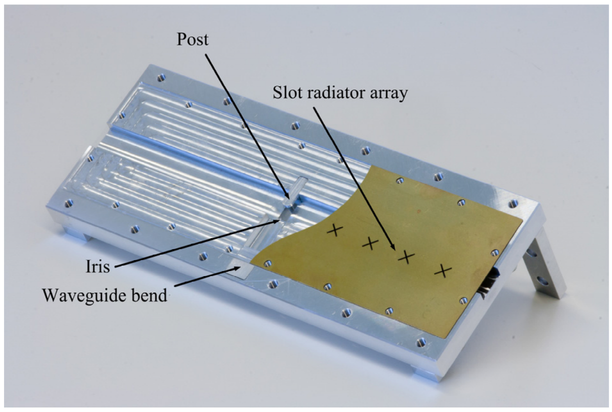

Figure 4. Antenna panel ground-plane with integrated waveguide feeding structure and 20 GHz slot radiator array (sectional representation) used as primary source below the dual-band PRS.

The 2-layer PRS was etched on 1.52 mm thick *Rogers RO4003* (ε_r = 3.55) circuit board (Fig. 5) and the copper-layer has a height of 18 µm. The aperture size amounts 60 mm by 200 mm respectively 25 by 86 unit cells with a periodicity of 2.32 mm. That size corresponds to 4 by 13.3 free-space wavelengths at the downlink frequency of 20 GHz and 6 by 20 at the uplink frequency of 30 GHz. The bottom PRS-layer is located exactly 5.2 mm above the slot radiator array. The complete implementation of the circularly polarised Ka-band antenna panel for the low-profile user-terminal is depicted in Fig. 6, connected to the measurement equipment in our anechoic chamber.

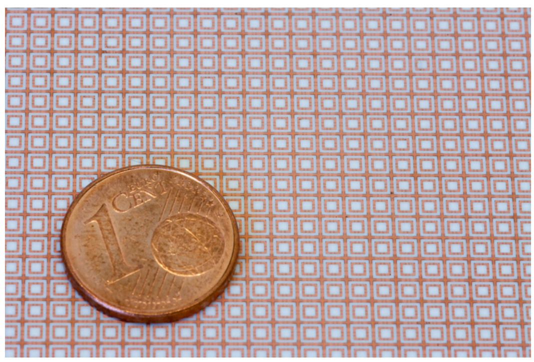

Figure 5. Copper top-layer PRS manufactured on Rogers laminate with a unit cell periodicity of 2.32 mm.

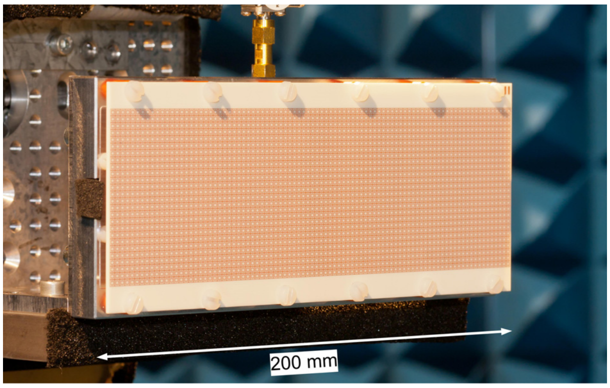

Figure 6. Realisation of the circularly polarised Ka-band leaky wave antenna panel intended for the low-profile user-terminal outdoor-unit.

4. ANTENNA DEMONSTRATOR

To evaluate the general operation performance and to identify further research and development necessities, a low-profile antenna demonstrator was built (Fig. 7), which aims to implement aspects of the developed antenna concept as a first realisation of the complete terminal outdoor-unit. Besides the validation of general functionalities and the tracking algorithm, the tracking with respect to the mechanical azimuth positioner and its achievable positioning accuracy, velocity, and acceleration can be examined. The antenna demonstrator is intended to be evaluated primarily at the *Fraunhofer IIS* testbed for satellite communications located in Ilmenau, which comprises an antenna mast carrying Ka-band satellite payload, a land-mobile channel simulator for different propagation conditions and a motion emulator where the device under test can be installed. Herewith a comparison between measurement data and the expectation of link budget parameters like channel capacity, carrier-to-noise ratio, and gain-to-noise temperature ratio is enabled. Furthermore field trials and outdoor measurement campaigns are conceivable to assess the robustness of communication by testing with a geostationary Ka-band satellite.

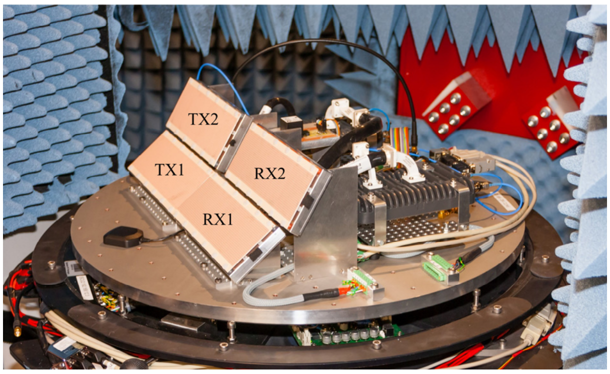

Figure 7. Outdoor-unit demonstrator of the low-profile user-terminal for Ka-band satellite communications.

The demonstrator assembly consists of two differently tilted antenna panels for each band, down- and uplink (RX1/2 and TX1/2), located on the payload-plate of the azimuth positioner. At the current development state the circularly polarised slot radiator array used as illumination for the presented dual-band PRS in the section before, is just implemented as a mono-band version. In a further implementation step the feeding structure of receiving and transmitting antenna parts will also be interlaced in a single antenna panel ground-plane. The panels have different inclinations, which cover an elevation range of 15° to 65° with respect to the measured 3-dB antenna beamwidth. In principle this range is modifiable due to the modular antenna concept, which accepts a differing number and alignment of antenna panels, e.g. suitable for different operational regions with differing needed elevation angles. For this implemented arrangement the maximum payload height is 13.9 cm. The used converter modules (*ViaSat Ka-band transceiver* [9]) are connected to the backsides of the panels by low-loss flexible waveguides and at the IF-band (L-band) coaxial cables lead to a 6-channel rotary joint, enabling the IF connection to the indoor-unit of the mobile user-terminal. The block up-converter offers a transmitting power of 3 W and the used low-noise block has a noise figure of 1.4 dB. Furthermore, a GPS receiver module, several inertial sensors, and a motor control unit are part of the outdoor-unit payload. All terminal outdoor-unit components had to be manufactured and mounted in sufficient quantities for the demonstrator. For instance, the four antenna panels, whose measurement results are presented in the following section.
The mechanical azimuth positioner was developed and manufactured especially for the presented antenna concept and application. At this time, the design focus was on the dynamic parameters of the positioner: It is easily able to operate at velocities and accelerations of 300°/s respectively 300°/s^2. The positioning repeatability amounts 5’’ and it is construed for a maximum payload weight of 12.5 kg. The height of the positioner measures 8 cm and the diameter of its payload plate amounts 60 cm. Especially the positioner compactness can be optimised within further implementation steps.

5. MEASUREMENT RESULTS

After the manufacturing of two RX and two TX antenna panels intended for the demonstrator the measurement of the antenna parameters of all panels in the anechoic chamber was necessary to ensure the functional capability of the entire outdoor-unit. The measurement of several antenna panels is also a good opportunity to evaluate the reproducibility of the desired antenna parameters after the manufacturing process. The figures below present the measured realised gain of the four panels over the downlink respectively the uplink frequency band.

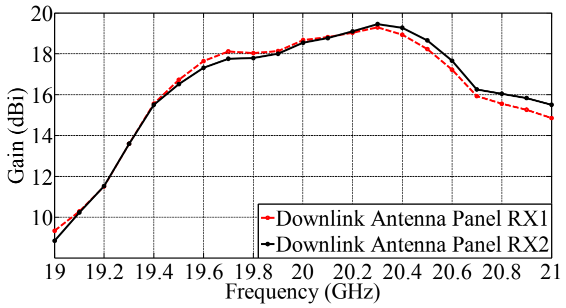

Figure 8. Realised gain measurement over the frequency downlink band of both demonstrator RX antenna panels.

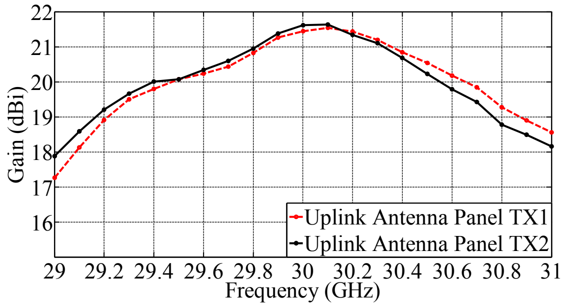

Figure 9. Realised gain measurement over the frequency uplink band of both demonstrator TX antenna panels.

Fig. 8 shows a good agreement between the spectral gain behaviour of both downlink antenna panels. The maximum gain amounts to 19.3 dBi (panel RX1) respectively 19.5 dBi (panel RX2) at 20.3 GHz, what is slightly shifted compared to the target frequency at 20.0 GHz. But even at 20.0 GHz the gain measures 18.5 respectively 18.7 dBi. A main-beam gain above 17.5 dBi could be measured over a bandwidth of about 1.0 GHz, from 19.6 to 20.6 GHz.

Fig. 9 also shows a good agreement of the gain over the frequency for the two versions, which are intended for the uplink. The maximum gain was determined by the measurement at 30.1 GHz and it was found to be 21.5 dBi (panel TX1) and 21.6 dBi (panel TX2). The main-beam gain in that case could be observed above 20.0 dBi within a bandwidth of about 1.0 GHz, from 29.5 to 30.5 GHz.

Fig. 10 shows the left-hand circular polarisation (LHCP) realised gain pattern of one of the downlink antenna panels across both, the elevation and azimuth at 20.3 GHz, where the gain has its spectral maximum. A broad lobe in the elevation plane, enabling easy and fast tracking, and a narrow main lobe in the azimuth plane, for precise pointing to the satellite with enhanced gain, is observed. The right-hand circular polarisation (RHCP) realised gain pattern for the uplink frequency of 30.1 GHz is depicted in Fig. 11. This measurement was done using the same dual-band PRS and located with the same height over its excitation, realised by the presented slot radiator array.

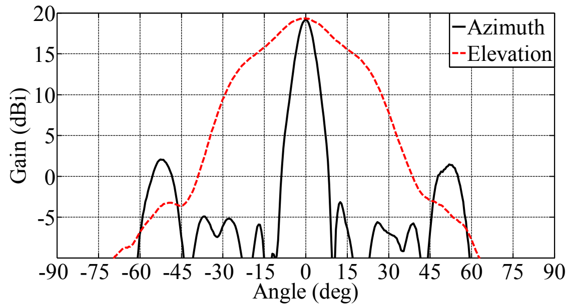

Figure 10. Measurement of the realised gain pattern at 20.3 GHz in both, azimuth and elevation plane.

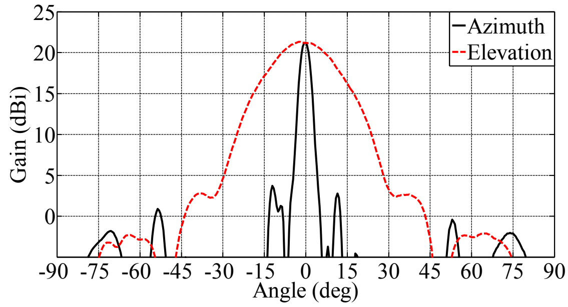

Figure 11. Measurement of the realised gain pattern at 30.1 GHz in both, azimuth and elevation plane.

The measured sum and difference radiation patterns at the downlink frequency of 20.0 GHz are depicted in Fig. 12. These patterns are created by the two ports of the hybrid T-junction integrated in the antenna panel ground-plane as part of the waveguide feeding structure. The sum pattern corresponds to the conventional azimuth radiation pattern of the Ka-band antenna panel. The difference pattern has two main lobes in the azimuth tracking plane with a deep null on the boresight axis. As already mentioned, this behaviour provides monopulse-tracking information [10] in the azimuth plane. The deviation from the target position can be indicated by the amplitude difference of both patterns, and the phases lead to the direction of deviation. A tracking range of about +/-4 degrees is offered by the low-profile antenna panel.

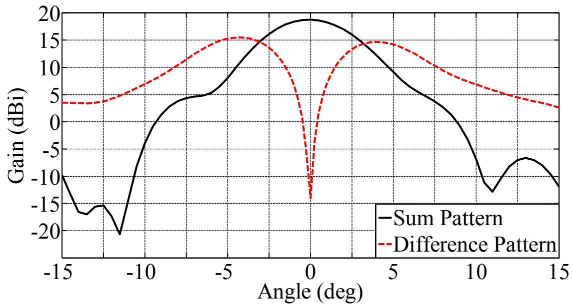

Figure 12. Sum and difference radiation pattern measurement over the azimuth plane at 20.0 GHz provided by the E- an H-port of the ground-plane integrated hybrid T-junction.

6. SUMMARY

The design and measurement results of a Ka-band leaky-wave antenna panel intended to be used for an antenna demonstrator representing the outdoor-unit of our low-profile user-terminal concept are presented in this publication. The low-profile antenna demonstrator is presented and described in detail. The antenna panel applies a 2-layer dual-band PRS, which is excited by a 20 and 30 GHz slot radiator array above a waveguide feeding structure, which is integrated into the ground-plane of the panel. The measured maximum gains at the boresight axis resulted in 19.5 dBi for 20.3 GHz and 21.6 dBi for 30.1 GHz. A downlink bandwidth of 1.0 GHz with a realised gain above 17.5 dBi was achieved, while the associated uplink bandwidth amounts to 1.0 GHz with a realised gain of more than 20.0 dBi. Furthermore a ground-plane integrated hybrid T-junction provides monopulse-tracking information in the azimuth plane, which could be verified by measurements.

Next steps are extensive tests and measurements of the low-profile antenna demonstrator at the *Fraunhofer* SatCom Test Facility in Ilmenau and further developments leading to a lower height respectively an increase of compactness, which can be achieved for instance by multiple IF-signal converter modules that are mounted directly on the backside of the antenna panels. Further developments considering an optimisation of the compactness are related to an improved rotary joint and signal transmission based on optical components, which are connecting multiple channels between the outdoor- and indoor-unit of the mobile user-terminal.

7. ACKNOWLEDGEMENTS

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