

LTCC Ka-Band Switch Matrix Experiment for On-Orbit Verification

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Abstract

We have developed a compact, high-performance, mechanically robust reconfigurable microwave switch matrix in combination with diode driver, voltage controlled oscillator, and power detector modules for satellite applications using the low temperature co-fired ceramics technology (LTCC).

During an on-orbit mission aboard a German test satellite to be launched in the end of 2010, the correct operation and reliability of the entire switch matrix system will be analyzed. Therefore, additional circuitry is required such as biasing and a digital interface. The system design had to account for power consumption, mass, overall geometrical dimensions, mechanical robustness, and space qualification. All components are mounted onto a polymer substrate attached to a Kovar[®] carrier board. A double-sided hybrid integration of ICs into the ceramic module enabled the simultaneous achievement of very promising microwave properties and mechanical robustness. Accordingly, the qualification tests revealed no problems. The contribution summarizes our technological approach in terms of both electronic and mechanical performance and describes the layout and the control of the remote experiment to be conducted on-orbit.

Key words: on-orbit verification, satellite communications, Ka-band, 3D-hybrid-integration, LTCC

Introduction

The low temperature co-fired ceramic technology (LTCC) offers multilayer design capabilities, hermetic hybrid integration, passive circuit elements, good microwave performance, excellent thermal stability, and cost efficiency [1].

Space applications take advantage of reduced volume, mass, and footprint area, but require a careful design and analysis of the mechanical robustness. The launch of satellite hardware into space is accompanied by severe mechanical vibrations and shocks, and temperature changes during the operational lifetime may cause deterioration, too. Developing ceramic modules for space applications hence requires an accurate qualification to prove the resistance against these influences. In the case described here, our experiment intends to qualify a reconfigurable 4x4 microwave switch matrix for the Ka-band downlink (17-22 GHz) including all peripheral components required for remote digital control and operation. The

switch matrix would require significantly more space and mass when built using standard coaxial waveguide technologies. Due to the passive design the module can be used for bidirectional signal routing. We have devised a complete space experiment to qualify the function the described switch matrix during the on-orbit verification (OOV) space mission aboard the technology evaluation carrier (TET) launched presumably at the end of 2010. The payload contains two further experiments of partners of the KERAMIS R&D consortium [2].

In this paper we describe the LTCC-optimized design of the individual modules, the latest results achieved in the course of different development stages, and the concept of the remotely controlled space experiment.

Manufacturing the LTCC-components

All LTCC-modules considered here were manufactured using the DuPont DP-951 AX/PX Green-

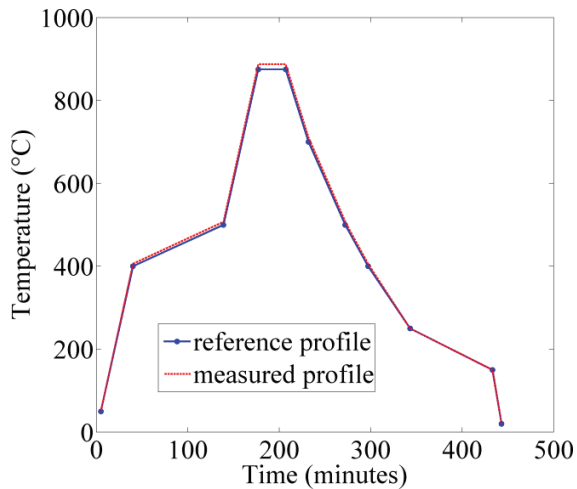


Fig. 1. Applied temperature profile for sintering the green tapes (reference and measured).

Tape system. For the solderable pads, the Pd/Ag paste 6146 was used. The transmission lines and bond pads were processed with the gold paste 5734, while for the overglaze the 9615 paste was used. According to Fig. 1, the measured temperature variation during the sintering process corresponded closely to the reference profile, thus assuring a high degree

of reproducibility. With respect to the established screen printing process, minimum line widths and spaces of 50 μm were applicable, while the standard via diameters were 150 μm .

LTCC-components for the space experiment

The reduction of volume and mass with simultaneously increased functionality and mechanical robustness is the main aim in developing space components. The LTCC-technology is well suited because of the potential for multilayer layouts, integration of passive structures, good microwave performance, and the hybrid integration of surface mounted devices (SMD) and bare die ICs. The LTCC-components developed specifically for the space experiment are shown in Fig. 2 as mounted on the carrier board, with detailed descriptions of the individual modules following below.

A. Diode driver

The configuration of the 4x4 switch matrix requires the control of 32 bipolar currents. These are provided by two diode drivers located close to the switch matrix module (see number 1 in Fig. 2), delivering currents of ± 5 mA. The applied current

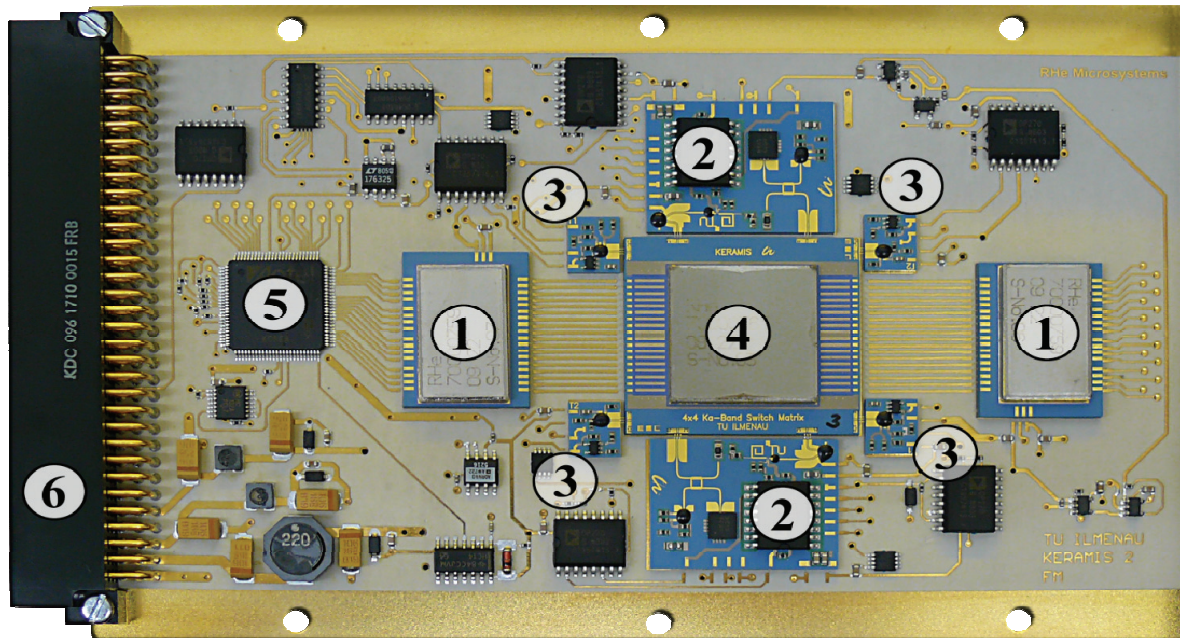


Fig. 2. Photograph of the proto-flight-model (PFM) of the switch matrix space experiment. Numbers indicate the individual modules: 1 - diode-driver, 2 - VCO-module, 3 - power detector, 4 - switch matrix, 5 - FPGA, 6 - 96-pin-connector to the satellite bus.

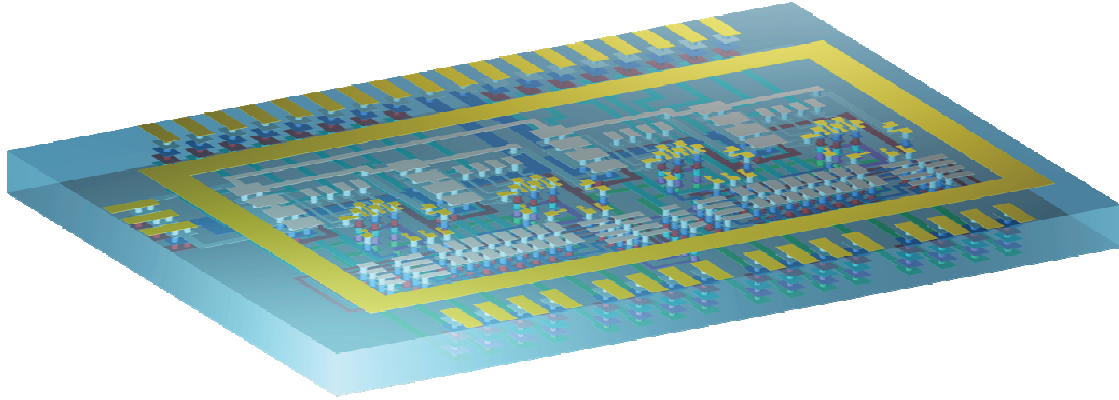


Fig. 3. Schematic of the diode driver module, including the power supply (left-hand side), the digital input (bottom), and the current pads (top). All surface mounted parts as well as the ICs are mounted within the solder frame. The size of the module is 24 mm × 18 mm and incorporates seven layers for routing.

influences the microwave performance of the module. Insertion loss and matching improve at higher magnitudes of current [2]. Adjustable currents could therefore be used beneficially to control the insertion loss, to achieve a constant attenuation over the entire operational frequency band. However, higher currents cause higher dissipation losses and are not suitable for the experiment.

The complexity of the diode driver module is indicated by Fig. 3. Further downsizing is limited by the dimensions of the SMD-components used for the passive microwave circuit elements. Buried resistors and capacitors could be used instead of discrete elements to circumvent this limitation.

B. VCO-module

The voltage controlled oscillator (VCO) module (number 2 in Fig. 2) includes two microwave sources with output frequencies between 17.2 - 19.2 GHz (IHP T208) and 23.8 - 24.8 GHz (Hittite HMC 533) with output power levels of 2 × 2 dBm and 12 dBm, respectively. The actual level of the output power is monitored by detectors (see also Sec. C. below). The microwave signal is transmitted using coplanar waveguides and bond ribbons, to keep parasitic inductances at a tolerably low level.

Applying control voltages or switching digital inputs, depending on the two different types of VCO-IC, tunes the oscillators and therefore sweeps the frequency, in order to analyze the insertion loss and isolation of the switch matrix over the broad frequency range corresponding to the Ka-band (downlink).

The size of the module measures 27 mm × 20 mm and is mainly determined by fixed positions of the connections to the switch matrix.

C. Microwave power detector

The size of the detector modules (number 3 in Fig. 2) measures 8.5 mm × 7.5 mm. These modules deliver an amplified DC-signal according to the incident microwave power (-30 to +10 dBm) over the broad frequency range from 10 to 40 GHz. A power detector CHE 1270a (United Monolithic Semiconductors) and the operational amplifier OPA347 were selected because of their small size.

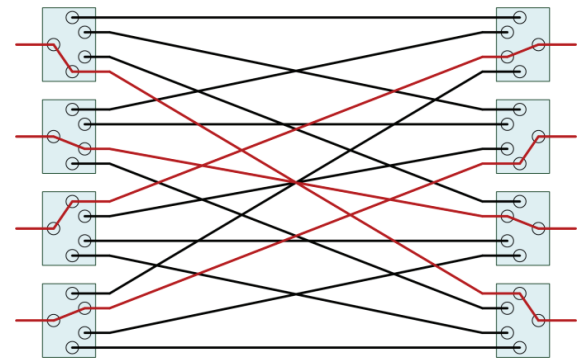


Fig. 4. Schematic view of the signal routing capability of the switch matrix with four microwave ports on both sides, incorporating eight SP4T-switch-ICs. One possible configuration is the transmission along the red colored lines, black lines indicate isolated paths for this case.

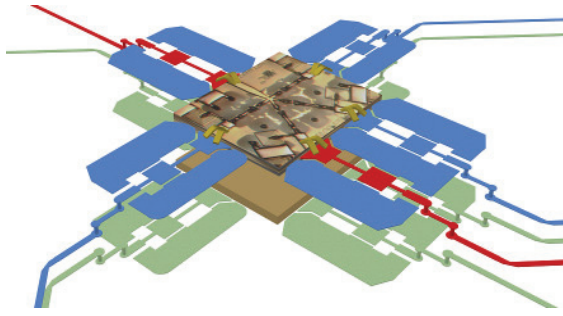


Fig. 5. Schematic view of the switch matrix module with matching networks, bond ribbons, and double sided switch-IC mounting. The blue area indicates the top layer, the green area the bottom layer.

D. The 4x4 switch matrix

The topology of the switch matrix (module 4 in Fig. 2) is based on a single-pole four-throw (SP4T) switch-IC (M/A-COM MA4SW410B-1) which leads to 16 possible transmission paths (see

Fig. 4). Simple $50\ \Omega$ connections between the switches using transmission lines would cause reflections and a strongly limited operational frequency bandwidth. Therefore, impedance matching networks were developed and arranged between the switch ICs and the ports (see Fig. 5), improving the matching over a broad frequency range [3]. Typical scattering parameters of a complete transmission path, incorporating two switch ICs and approx. 5 cm of coplanar

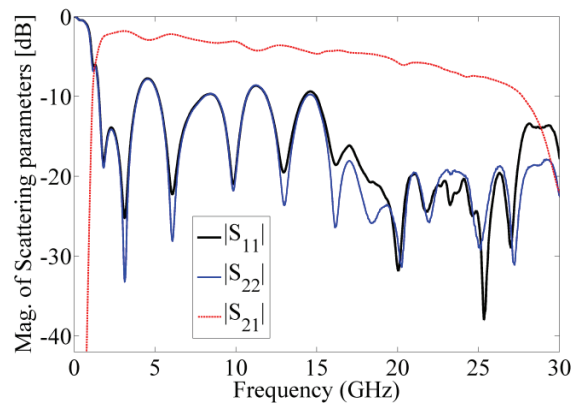


Fig. 6. Typical scattering parameters of the switch matrix module measured for a complete switching path. The operational frequency band is between 15.6 and 27.7 GHz (S_{ii} better -15 dB) with an insertion loss between -4.3 and -10 dB (-6 dB at 22 GHz).

transmission lines, are shown in Fig. 6. The achieved matched -20 dB- bandwidth is around 5 GHz, hence covering the complete Ka-band for the satellite downlink. A slight shift of the operating band towards higher frequencies is caused by manufacturing tolerances and can be compensated by design adjustments. The insertion loss increases for higher frequencies according to the dielectric and ohmic contributions to the attenuation constant. The insertion loss at the center of the operational frequency range varies by a maximum of about 6.5 dB considering all possible switching paths. For applications where a constant insertion loss is important, the gain flatness could be improved with controlled attenuators respectively amplifiers, or by controlling the PIN-diode currents.

This module takes advantage of a double-sided IC-mounting technology [4,5]. Fig. 5 gives an impression of the arrangement of the switch ICs, the bond connections, and the matching networks. Eight cavities house the bare dies, and two frames and covers are used to seal the module hermetically. Due to the sealing, the mounting of this module requires an aperture in the carrier board. The switch matrix is connected with $25\ \mu\text{m}$ round gold wire bonds for the control signals, while the microwave connections are composed of $20\ \mu\text{m} \times 60\ \mu\text{m}$ bond ribbons, to reduce the parasitic inductances. A microscopic image of such a transition is shown in Fig. 7.

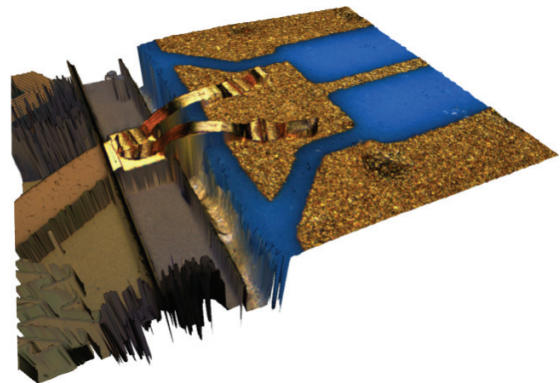


Fig. 7. Three-dimensional image acquired with the focus variation profilometer Alicona Infinite Focus. The bond ribbon connects the switch IC in a cavity (left-hand side) with the matching network on the top layer of the switch matrix module (right-hand side).



Fig. 8. Switch matrix module with mounted switch ICs and frame for hermetical sealing (top view). The coplanar microwave ports are located close to the corners, and the diode currents are applied through the left-hand and right-hand side pads.

As an alternative to bond ribbon connections, flip-chip and LGA contacts have been developed by the KERAMIS consortium [6]. The actual version of the switch matrix module would allow the use of connectors with 1 mm pitch. The solder pads indicated in Fig. 8 are close to the golden DC-bond-pads on the left- and right-hand sides of the module.

Space Qualification

Participating in a space mission requires to pass the qualification procedures including mechanical and thermal stress and, in general, exposure to radiation depending on the application, the requested life time and the orbit. Our mission aims at the qualification of the LTCC-technology, in particular the switch matrix, during a one-year mission in a 550 km low earth orbit. Therefore, the requirements would be lower compared to geostationary communication satellite systems. However, with respect to a maximum reusability in further satellite systems, the requirements were raised to a level comparable to those applicable for commercial satellite subsystems.

The first tests were performed with a preliminary switch matrix module developed for the technology model TM1. A heavy cover and the large outer dimensions (56 mm × 56 mm) of the TM1-module caused cracks in the mechanical tests and prohibited the further use of this module. Changes in the assembly and choice and mounting of different materials became necessary [7].

The improved technology model TM2 required significantly less area (34 mm × 32 mm). It also included a Kovar frame and a soldered lid making the module smaller and more lightweight. In addition, a multilayer substrate (Rogers RT/duroid 6002) was glued onto a Kovar carrier board of 2 mm thickness

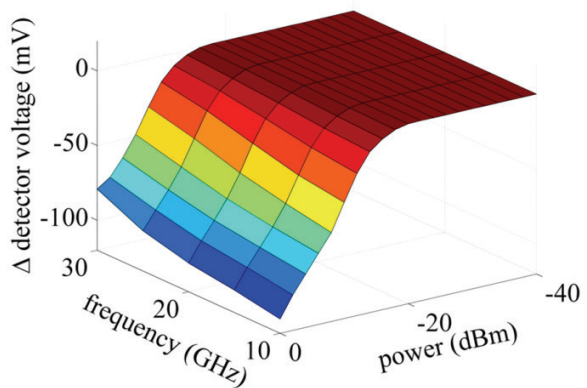


Fig. 9. Measurement setup for the characterization of environmental influences on the microwave performance of the LTCC-modules. A computer controls the temperature, the pressure in the wafer prober chamber (left-hand picture, center part) and the supply voltage. Several parameters were monitored, e.g. the detector output voltage vs. frequency, power, temperature and pressure. The diagram on the right-hand side shows the change of the detector voltage at -10°C compared to a reference measurement at +10°C.

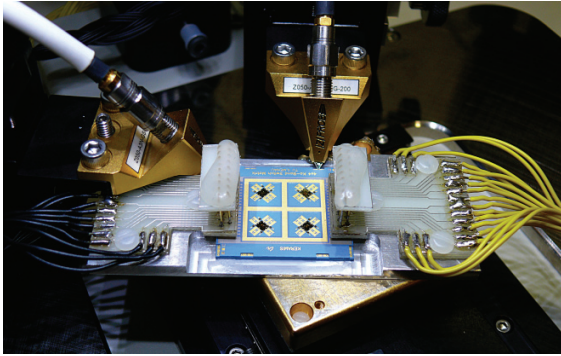


Fig. 10. Fixture for measuring the scattering parameters of the switch matrix during an early stage of the integration process, when the frame is not yet mounted. Two coplanar probe tips are used to contact the microwave ports, while metal contact probes are used for the DC-pads.

instead of the 1.5 mm aluminum plate used for TM1. The LTCC-modules were glued and bonded onto the substrate, following a space-qualified procedure [2].

Laboratory tests of environmental effects caused by changes of pressure and temperature were per-

formed with a vacuum wafer prober and coplanar probe tips, as illustrated by Fig. 9 and Fig. 10. The mechanical stress tests were performed at *Astro- und Feinwerktechnik Adlershof GmbH*, Germany, with sinusoidal, noise, and random excitations creating different accelerations up to 20 g at frequencies between 5 and 2,000 Hz. The shock test induced accelerations up to 3,000 g with a frequency spectrum reaching up to 10,000 Hz. The resulting resonance spectra of the TM2 were found to exceed 1,000 Hz, and therefore uncritical. Thus the module required no further mechanical improvements.

After the TM qualification all subsequent tests were performed with a complete experimental board incorporating all modules (see Fig. 2).

The On-Orbit Experiment

A. The experiment and the scheduled control

The switch matrix itself is not capable of being tested without the peripheral components such as described above. A field-programmable gate array (FPGA) controls the active components like the

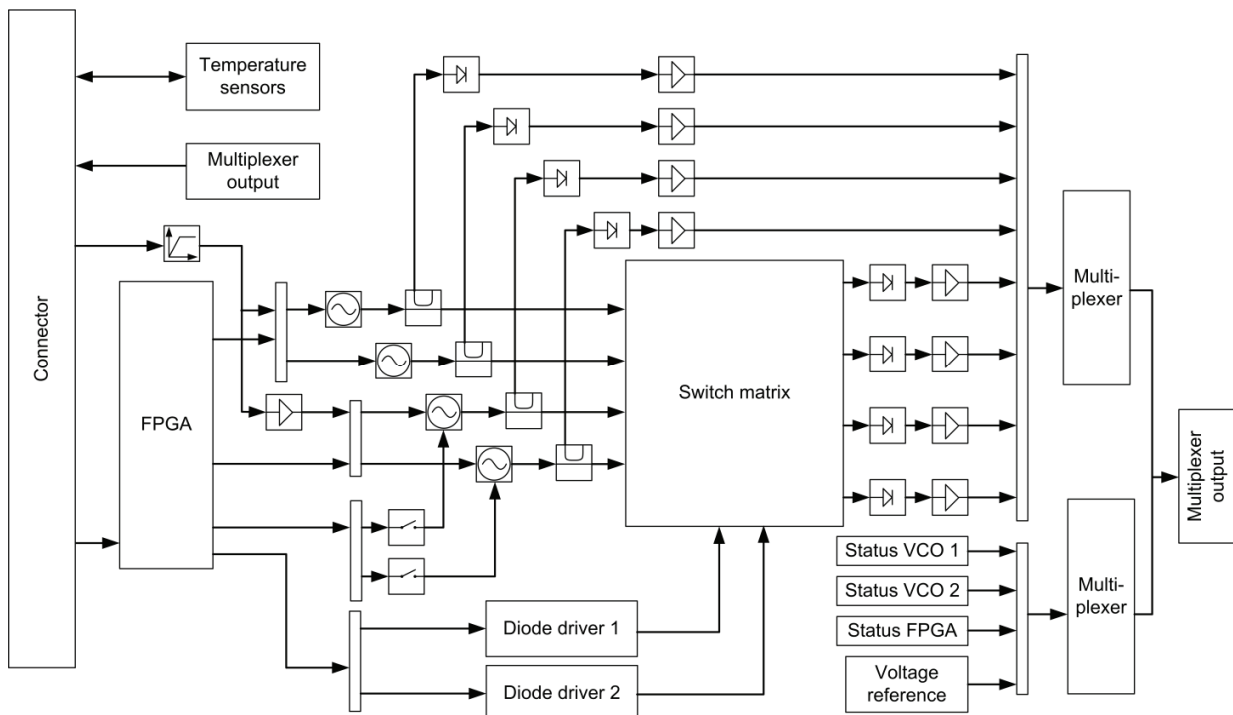


Fig. 11. Block diagram of the space experiment. The FPGA controls the microwave sources and diode drivers, to supply and configure the switch matrix. Detectors are used to measure the microwave power at several positions. Their outputs are combined using multiplexers.

switch matrix, by setting the input values for the diode drivers. Furthermore, it measures voltages and temperatures. Fig. 11 shows a block diagram of the space experiment. The microwave power is measured before and after passing the switch matrix by correspondingly arranged microwave power detector modules. Measurements are performed for all possible path configurations using four VCOs and eight detectors. The temperatures, status information and housekeeping data complete the measurement data. The FPGA employed (Actel A54SX32A) controls the experiment and communicates with the satellite bus. The anti-fuse technology used for programming the FPGA implies high-reliability and prevents therefore single-event effects.

Autonomous measurements will be performed in the course of the on-orbit verification during assigned time slots. A sequence of operations and measurements is executed, to perform measurements with different configurations and boundary conditions. A list of configurations is defined as well and accessed by references. Different programs enable the analysis of single configurations with several measurements over an extended time period, e.g., the influence of temperature, or different switch matrix paths for given values of temperature, position, and time.

B. Calibration of the components

In order to enable a quantitative analysis of the measurements, the general behavior influenced by power supply voltage, temperature, pressure, microwave frequency and power for each of the LTTC-components needs to be known. A vacuum wafer prober was used to control the ambient pressure between $1 \cdot 10^{-3}$ and $1 \cdot 10^5$ Pa and temperature between -20 and 150 °C (Fig. ??). Probe tips with 200 µm pitch were used together with DC-pins to contact the modules without the need to use solder or bond connections (Fig. ??). The frequency was swept between 10 and 40 GHz while the microwave power was varied between -40 and 10 dBm.

Analyzing the housekeeping data of the satellite mission and the temperatures of the experiment, the conditions under which the data will have been acquired can be reconstructed, and the data can be corrected using the calibration curves acquired previously. As an example, Fig. 9 (right-hand side) illustrates the difference of the detector voltages for 10 °C (reference) and -10 °C ambient temperature. Such influ-

ences clarify the need to calibrate all components and to process the measured data accordingly. Because two identical boards will be used for the space experiment, the measurement data can be analyzed by comparing both space boards with each other as well as with data of reference boards available on the ground. In case of malfunction, the redundancy enables the localization of the error and the adjustment of the measurement program, in order to avoid further measurements involving damaged components.

Conclusion

Within the KERAMIS-project we have developed fully space qualified ceramic multilayer components and, based on these modules, a space experiment for the validation of the used technology during a one-year mission aboard the German TET-satellite. The sequentially optimized switch matrix as the key component was described together with the required peripheral modules in terms of the design and microwave performance, leading to promising results, and achieving compact size and mechanical robustness.

Latest results of the status of the space experiment will be presented at the conference; first space measurements will be available only after the launch of the satellite at the end of 2010.

The use of the modules developed in this work for commercial satellite applications, like the German Heinrich Hertz mission, requires further reductions in size and an extension of functionality. Special attention will be given to equal insertion loss for all switching paths, and to a defined back-off configuration in the event of power supply loss. A modification of the switch technology could possibly further improve the power consumption, life time, and radiation hardness.

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