LTCC Antenna Array with Integrated Liquid Crystal Phase Shifter for Satellite Communication

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Abstract

Low Temperature Cofired Ceramic (LTCC) is used as a substrate material for microelectronic devices in satellite communication. Its dielectric properties and excellent variability allows a good compactness and a high level of integration. An LTCC antenna array for microwave signals operating at 30 GHz is presented. All components such as radio frequency distribution network, four waveguide phase shifters and horn antennas are integrated in one ceramic module. The phase shifters are implemented as high volume cavities in the LTCC. A tailored mixture of liquid crystal can be stored inside the cavities. By applying an electric field, the anisotropic LC-molecules are aligned. The field is provided through a biasing network with four electrodes and screen printed resistive layers with resistance values in the MΩ/□ range. The alignment and with it the phase shifting is nearly seamless. The antenna module is manufactured in multilayer technology and consists of more than 40 layers. Lamination is carried out by thermocompression in two steps. A water based adhesive is used in the second. The cofiring is done in a sintering press. Temperature and pressure profile are chosen carefully, considering the high volume of the laminate and the buried cavities inside the module. After sintering, the horn antennas are milled into the front side of the ceramic body, which is about 5 mm in height.

Keywords: LTCC multilayer, Liquid crystals, Cavities, Pressure assisted sintering

Introduction

Liquid Crystals (LC) consist of anisotropic rod-like molecules and posses properties both of a liquid and a crystal. An entire bulk of liquid crystals can be aligned by an external electrical field. Thereby the effective permittivity is changing. Using this mechanism is the basic idea behind a tunable LC phase shifter for radio frequency signals. The functionality of such a device has already been shown [1]. The LC to be used for the antenna described here is a tailored mixture with optimized molecular structure and radio frequency properties. With it a continuous shifting of full 360° is possible. To use the LC for phase shifting, it has to be stored in a leak proof container with defined geometry. Metallization has to be added around the container to create an integrated waveguide. Low temperature cofired ceramic (LTCC) is a suitable class of material for this purpose. It is commonly used as packaging material for integrated circuits in microelectronics due to its advantageous dielectric properties. It is often used in combination with thick film processes like screen printing to apply required metallization structures. Additionally it is possible to integrate customized three dimensional microstructures like channels and cavities in LTCC. This leads to various applications in microfluidics, sensors and related micro- and mesosystems [2, 3]. Tick et al. presented a LTCC integrated waveguide for high frequency signals [4]. In contrast to the LC phase shifter this waveguide was air-filled.

The manufacturing of high volume cavities inside a LTCC body is rather challenging. Lamination of green tapes, which is usually done by thermocompression in an uniaxial or isostatic press, cannot be done in a single step. There would be a difference in density above and below the cavity compared to the rest of the laminate. That would probably lead to inhomogeneous shrinkage or microstructural defects during sintering. Another problem often reported is sagging of the LTCC material into the cavity caused by softening of the organic phase at elevated temperature. To keep the cavities geometry as accurate as possible, subparts are laminated first and then joined, still in green state. Different joining techniques for green laminates are known. Small channels and cavities can be provided by progressive lamination without additional adhesives [5]. For larger structures it is more promising to reduce pressure and/or temperature and support the joining by some kind of adhesive. Different organic liquids [6, 7] or adhesive tapes [8, 9] can be used. However, in this work we applied a liquid adhesive based not on organic solvent but on water, containing a dissolved cellulose derivate.

The sintering process is the next critical step for the integrity of complex three-dimensional structured modules. Delamination and cracks are the most common reasons for failure. By applying uniaxial pressure on the laminate during sintering, delamination can be prevented. Temperature range as well as the amount of applied pressure has to be chosen carefully in order to avoid damage on the integrated structures.

Antenna array Layout

Fig. 1 and 2 show the design of an antenna array. Central elements of the array are four phase shifters, implemented as liquid crystal filled cavities. The geometry of the rectangular cavities is adjusted to the targeted operating frequency of 30 GHz. The cavities are 48 mm in length, 2.6 mm in width and 1 mm in height. The center to center distance of the cavities in lateral direction must be exactly 5 mm, which is half of the wave length. This would be very difficult to manufacture in one plane, thus the cavities are staggered stacked in two levels (Fig. 3). Each is connected to the nearest surface by a hole with 0.5 mm in diameter, which is for the LC filling. The cavities are surrounded by two large planar metallization, one layer below and one above their inner surface. Together with via-fences along the side walls, these metal structures build up a substrate integrated waveguide. Directly on the inner bottom and top surface, striped resistive layers with resistances in the MΩ/□-range are designed. Connected to a DC voltage supply by four electrode lines, these provide the electrical field for the alignment of the liquid crystal. The radio frequency signal, coming from a connector on the surface, is distributed by a Wilkinson divider to the four phase shifters. The signal is emitted at the front side of the module, by four cylindrical horn antennas. The antennas are 1.6 mm deep and 1.95 mm in diameter. At the opposite end of the module, a cut out next to the connectors allows to stack several arrays upside down on each other. In this way, a multiple antenna array can be created in a modular approach.

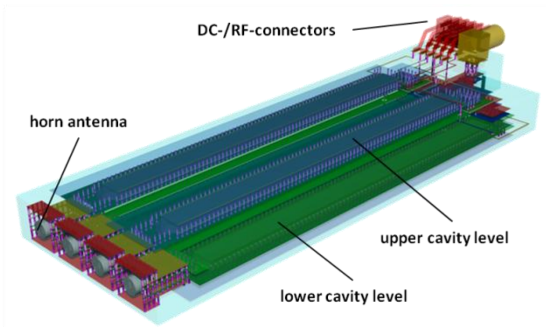

Fig. 1: Layout of the antenna array module

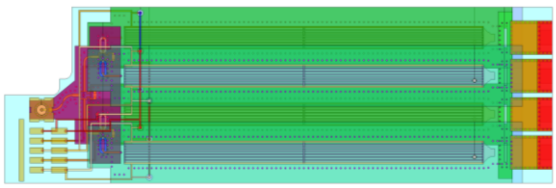

Fig. 2: Top view of the antenna array module

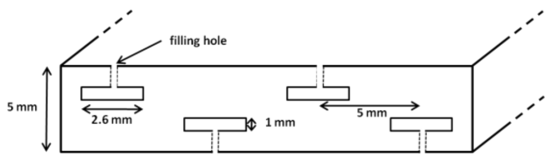

Fig. 3: Schematic cross section of the 42-layer module with four staggered stacked cavities

Manufacturing of green laminates

The functional efficiency of the whole antenna module depends on the compliance of the ceramic body with the designed geometry. Preliminary experiments with laminates without metallization structures were conducted. They were necessary to determine a suitable firing profile for the unusual bulky parts. Besides, the resulting sintering shrinkage values were needed for design and fabrication of printing screens and stencils.

Both the metallization free test samples and the final antenna device consist of 42 layers of commercial LTCC tape (CT707, Heraeus GmbH). After a relaxation step at 80 °C for 30 minutes, vias and cavities were generated by punching. Strip lines, planar metallization and resistive layers were applied on the tapes by screen printing. For via-filling and printing, three different Au-pastes with different solid content and two resistor pastes were used. For the surface metallization, a solderable Au/Pd-paste was chosen.

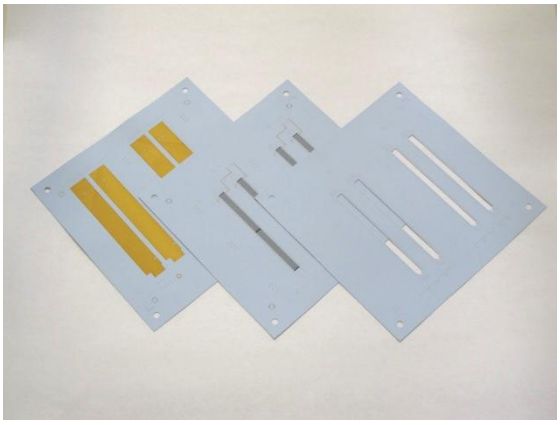

Fig. 4: Green tapes after punching, screen printing and cutting.

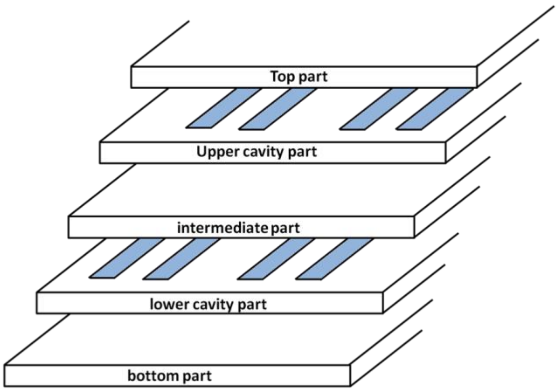

Fig. 5: Five subparts, laminated separately by thermocompression.

The green tapes were cut in 100 x 100 mm² sheets by a hot knife (Fig. 4) and stacked manually. Five subparts were laminated separately (Fig. 5), two parts with cavities (9 layers of LTCC tape), a top and a bottom part (7 layers each) and an intermediate part (10 layers). The lamination was carried out at 70 °C and 22 MPa in an uniaxial press using a customized pressing tool. The uniaxial pressure causes less deformation of the cavity edges than isostatic pressure would do. The subparts were joined in green state by low pressure lamination. Water based adhesive with solved cellulose was brushed on the laminates and a low pressure of 3 MPa was applied for 3 minutes on the preheated parts. The complete green body has a thickness of more than 7 mm and contains two arrays side by side (Fig. 6).

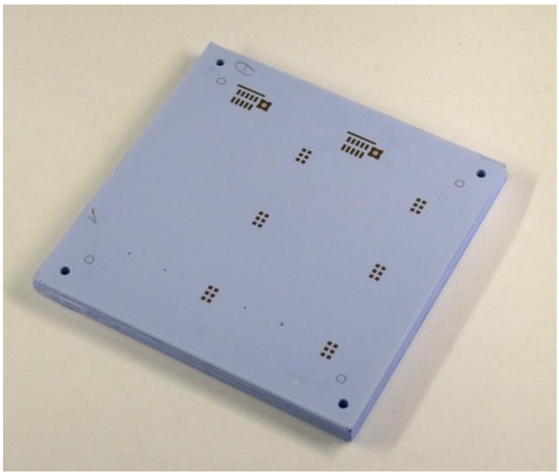

Fig. 6: Green Laminate with two arrays, 100 x 100 mm², 7 mm thick.

Its surface was scanned by an optical scanning microscope with a white light sensor (µScan, NanoFocus AG). A slight warping of the laminate and deflection of the material above the cavities was observed (Fig. 7). The deflection was below 20 µm in average, so the geometry and volume of the cavities were only moderately affected by the lamination process.

Sintering Process

The sintering was done in a LTCC sintering press (PHP 603 LTCC, ATV Technologie GmbH) at 865 °C peak temperature and 20 minutes dwell time. Due to the high thickness of the green laminates, binder burnout was done slowly with low heating rates and additional dwell times. Big parts with cavities are susceptible to delamination, especially between the glued layers. Applying an uniaxial pressure during sintering can prevent delamination. On the other hand, the pressure can affect the stability of the cavities, when the LTCC material softens at high temperatures. Severe deformation would be the result (Fig. 8). Therefore, a pressure of 0.5 MPa was only applied at a limited temperature range from 650 °C to 750 °C. In this way, delamination free parts with stable cavities could be produced. Fig. 9 shows a cross section of a sintered test sample. Apart from a slight side wall deformation, the cavities are undamaged.

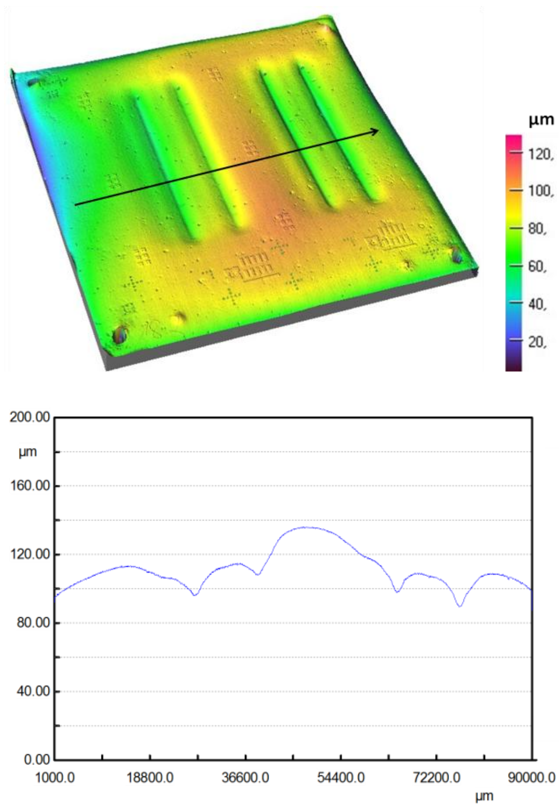

Fig. 7: Surface scan of a green laminate

In the temperature range within which the pressure was applied, constrained sintering took place and no lateral shrinkage occured. Consequently the final shrinkage was reduced significantly. The in-plane sintering shrinkage of the LTCC averaged 14 %, which is about 3-4 % lower than that of a freely sintered CT 707 ceramic sample. The shrinkage in thickness-direction was with 26 % accordingly higher.

Fig. 8: Cross section of sintered LTCC laminate with severe deformation of the cavities.

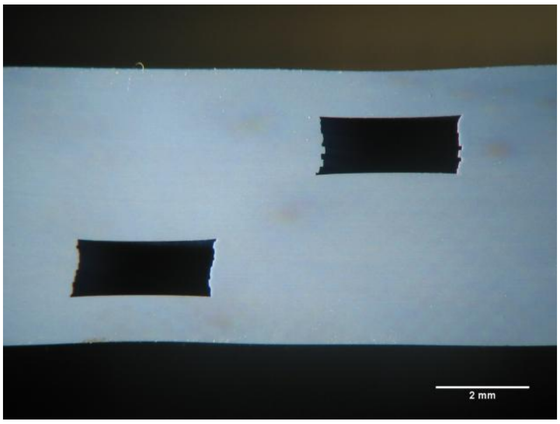

Fig. 9: Cross section of sintered LTCC laminate without metallization.

After sintering the surface was scanned again by optical scanning microscopy (Fig. 10). The deflection of the material above the cavities had clearly increased during sintering and is now around 60 µm. Also the cavities of the lower stacking level and some of the subsurface metallization caused a slight but clear impression on the surface. The sagging of LTCC into the cavity should not significantly affect the efficiency of the phase shifter though.

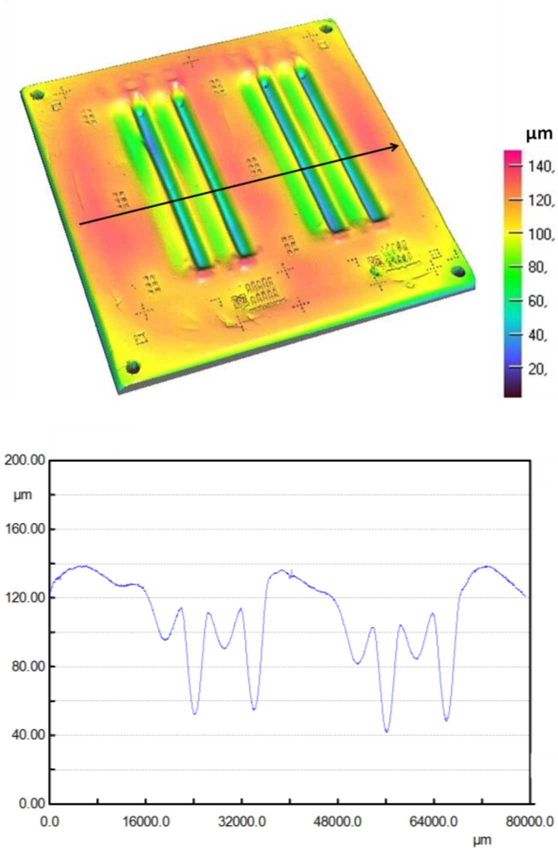

Fig. 10: Surface scan of a sintered laminate

Internal structures of the modules were analyzed by acoustic microscopy with a 100 MHz-transducer (D9000 C-SAM, Sonoscan Inc.). Fig. 11 shows two acoustic microscopy images from the connector-near end of two cavities. In both images, strip lines, metallization and vias are clearly visible. No defects like disconnections could be detected in the metallization structure. While the upper image shows an unharmed module, the lower image reveals a crack inside the ceramic. The crack´s origin is apparently at the corner of the cavity. These cracks were observed several times. Obviously the corners are a weak spot of the rectangular cavity design.

The two now 71 x 23 x 5 mm large modules were cut out. Finally, the four horn antennas were milled into the front end by micromachining.

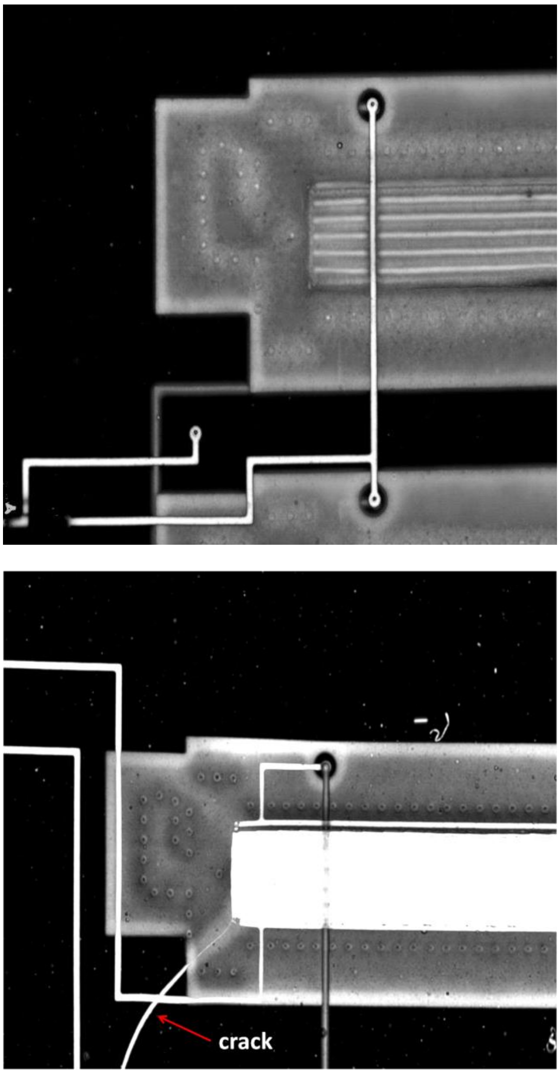

Fig. 11: Acoustic microscopy images of modules with metallization. top: unharmed cavity, below: crack with origin in the corner of the cavity

Summary and Outlook

A stackable antenna array with four liquid crystal phase shifters integrated in one LTCC module was presented. By a combined lamination and gluing process, thick green laminates with buried cavities could be manufactured. Complex thick film metallization and resistive layers were integrated. Only slight deformation of the green laminates surface above the cavities was observed. The lamination was followed by pressure assisted sintering. Sagging of the ceramic into the cavities was increased during sintering. The applied pressure prevents delamination between the ceramic layers. The process is sensitive to crack formation though. Cracks could be detected by non destructive testing with an acoustic microscope. The performance of the LC filled modules has yet to be evaluated. Computer tomography inspection is planned on the modules to rule out disconnections in the metallization structures and to check volume and geometry of the cavities.

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