LTCC Patch Array for RF-MEMS based Phased Array Antenna at 35GHz

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***Abstract*—In this paper, a LTCC patch antenna array for Ka-band RF-MEMS based electrically steerable antenna is demonstrated. The paper presents a novel hybrid integration concept for the RF-MEMS phase shifters intended to steer the main beam of the antenna in the H-plane of the aperture. According to the proposed configuration, the phase shifters realised in silicon technology are packaged using LTCC lids bonded on top of the silicon chips and are flip-chip mounted on the antenna realised on LTCC. The architecture allows for the realisation of highly integrated RF-MEMS based phased array for millimetre-wave front-ends and aims at reducing the complexity and costs of such modules. The design of the four by four aperture coupled patch antenna array is validated by satisfactory measurement results. A study of the repeatability of the LTCC process used to fabricate the antenna is carried out over a population of five samples and the behaviour of the matching of the antenna over temperature is investigated.**

I. Introduction

In the last decade, the fast and promising growth of millimetre-wave systems has produced the break-through of numerous challenging applications especially in the field of communication and sensors. Driven by the emergence of these novel millimetre-wave systems like automobile collision avoidance radars, military radars, or space- and air-borne communication systems, the development of phased array antennas has been the focus of many researchers since the late 80s. However, despite the huge effort put into the research, several issues still have to be solved and the need for low-cost, highly integrated efficient phased array antennas is not satisfied yet.

One of the limiting factors for a wide implementation of phased array antennas concerns their relatively low efficiency especially for antennas based on active T/R modules. Most of these antennas are heavy and power consuming and are therefore quite cumbersome to implement in on-board millimetre-wave systems. To overcome this situation, some alternative technologies like ferro-electric materials and RF-MEMS have been developed and have been used to realise low-loss phase shifters. Besides the advantage of having very low insertion loss, RF-MEMS phase shifters are less expensive than active T/R modules, which is, of course, of particular importance for large antenna arrays and consumer oriented applications.

Another critical aspect limiting the commercial use of phased array antennas and more generally of millimetre-wave antennas is their not-so-easy integration into front-ends. Due to their high operating frequency, millimetre-wave antennas are mainly realised on Teflon like low-loss organic substrates. These substrates have very low dielectric constant, which maximise the radiation efficiency of the antennas and offer excellent high frequency behaviour especially in terms of dielectric loss. However, they are quite incommodious to integrate in multi-chip modules, which are often realised on ceramics like LTCC or silicon. For these reasons, the idea of combining the low-loss and low-cost RF-MEMS phase shifter technology with an antenna fabricated on low-loss LTCC tape appears to be an attractive solution allowing for the realisation of highly efficient and highly integrable low-cost phased array antennas.

In this paper, a four by four patch antenna array for RF-MEMS based electrically steerable antenna is demonstrated. The integration concept of the RF-MEMS phase shifters on the LTCC antenna board is presented. The design of the antenna realised on low-loss LTCC material is described and is validated by good agreement between simulation and measurement. Finally, in order to characterise the fabricated antennas and to assess the reproducibility of the LTCC process, the measured return loss of five different antenna arrays is compared and the matching of the antenna over temperature is assessed.

II. Architecture of the Phased Antenna

The phased array antenna concept presented here is based on a millimetre-wave antenna realised on low-loss LTCC DuPont 943 material. The antenna is an aperture coupled patch antenna array fabricated on a multi-layer board, which could be the top layers of a highly integrated LTCC module containing the different components and electronic parts of a complete millimetre-wave front end. The patches are on the top LTCC layer. The feed network is realised in a buried layer, which is separated from the radiating patches by a layer of ground metallisation. The feeding lines and the patches are connected via aperture coupling through slots in the ground metallisation. The phase shifters are integrated between the antenna and the feed network to allow for one-dimensional beam steering in the H-plane. The packaged RF-MEMS chips are lip-chip mounted on the LTCC antenna board as part of the feed network. They are placed on the same layer as the radiating patches. Front and back views of the proposed concept are depicted in Fig. 1.

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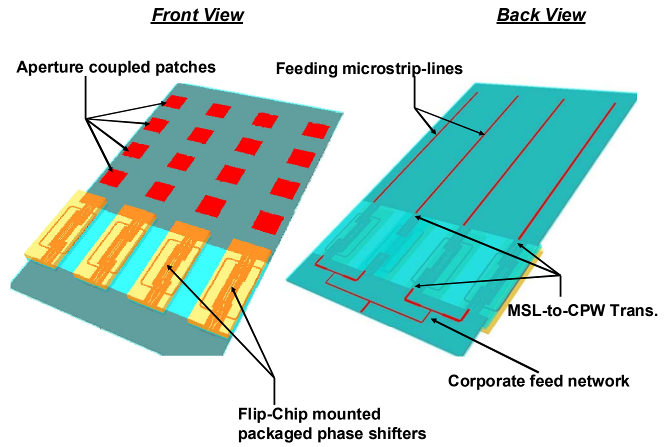

Fig. 1 Front view and back view of the phased array integration concept

The RF-MEMS phase shifters are realised in silicon technology and in a coplanar topology. Each one of the four phase shifters are packaged using a four-layer LTCC lid bonded on top of the chip using a sealing ring allowing for hermetic packaging of the MEMS circuits. The RF-coplanar signal lines of the phase shifter as well as the DC-control lines necessary to actuate the MEMS switches are connected to the top of the LTCC lid using LTCC vias passing through the four layers of the lid. The RF-coplanar lines and DC-control pads on the silicon chip are connected to the vias in the LTCC lid using solder balls. The metal chosen for the sealing ring and solder balls has to be carefully selected since the bonding temperature has to be low enough to be compatible with the MEMS circuits. Finally, due to the difference between the Thermal Coefficient of Extension (TCE) of silicon (silicon TCE=3ppm/°C) and that of the DuPont 943 material (DuPont 943 TCE=6ppm/°C), the size of the chip has to be kept as small as possible to minimise the stress in the sealing ring and solder balls. A cross-sectional side view of the packaged chip mounted on the LTCC antenna board is shown in Fig. 2.

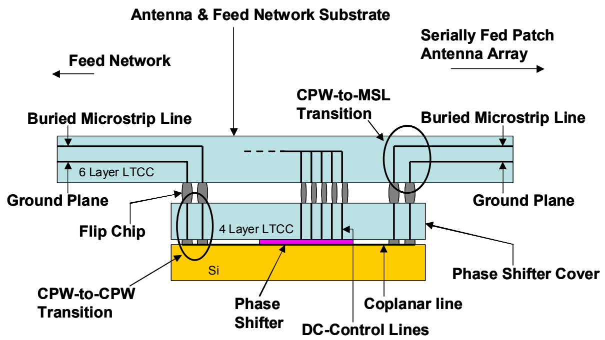

Fig. 2 Hybrid integration of the packaged phase shifter on the LTCC antenna board

III. DESIGN AND MEASUREMENT OF THE PATCH ARRAY

The antenna is a four by four patch antenna array designed for operation at 35 GHz and realised on a 6-layer low-loss LTCC Dupont 943 tape (ε_r=7.5, tanδ=0.002). The decision to manufacture the antenna on a LTCC DuPont 943 tape has been driven by the promising high frequency behaviour of this tape especially in terms of dielectric loss. On the other hand, the high dielectric constant of the LTCC affects the radiation efficiency of the antenna and limits its bandwidth. For this reason and in order to maximise the bandwidth of the antenna, an aperture coupled patch configuration has been chosen to design the antenna. The layout of the antenna array and its feed network is shown in Fig. 3

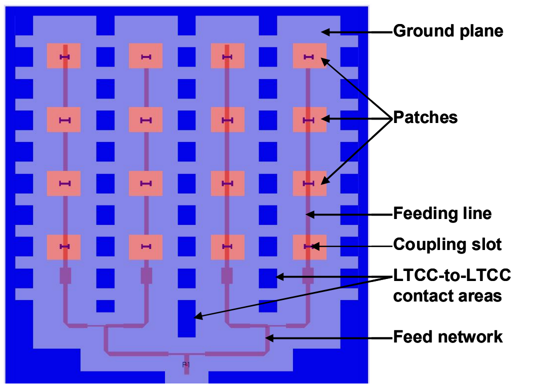

Fig. 3 Layout of the four by four aperture coupled patch antenna array

The antenna is formed by four serially fed patch antenna sub-arrays connected in parallel by a corporate feed network. The four patches connected in series are coupled to a feeding microstrip line through H-shaped slots realised in the common ground plane according to the aperture coupling principle. The patches are realised on the top one of the six LTCC layers. To facilitate the processing of the LTCC, the common ground plane containing the coupling slots is realised in the middle metal layer. The feeding lines have the same ground plane and are realised two layers below it as buried microstrip lines. This configuration has been chosen to ensure a strong enough coupling between the feeding lines and the patches and a reasonable width of the 50Ohm microstrip line compatible with the LTCC fabrication process. The dimensions of an aperture coupled patch cell are given in Fig. 4.

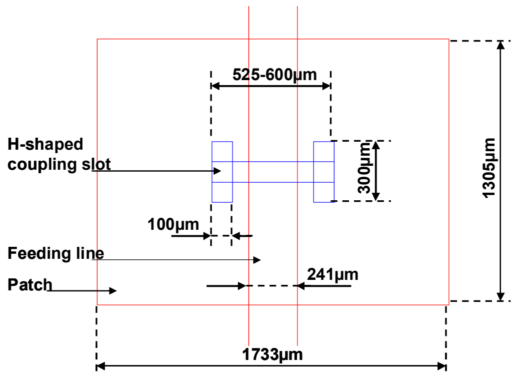

Fig. 4 Dimensions of a aperture coupled patch

The length of the microstrip line between two side-by-side coupling slots is equal to half of the guided wavelength in the buried microstrip line at the design frequency. It is necessary to feed the four patches of the row in phase and to achieve a broadside pattern in the E-plane of the aperture. In order to minimise the side lobe level, an aperture distribution is implemented along the row by selecting a suitable length for each one of the four coupling slots. This length is 525µm for the first and last patches of the row and 600µm for the two patches placed in the middle of the sub-array. For the same reason, the corporate feed network is realised with asymmetrical T-junction power dividers, which allow for the realisation of an aperture distribution in the H-plane. In order to prevent de-lamination of the LTCC tape above and below the ground metallisation the ground plane is patterned with metal-free areas forming LTCC-to-LTCC contact regions. The location of these metal-free zones is chosen reasonably far away from the patches and feeding lines to keep the field distribution and thus, the RF-properties of the antenna unchanged. Furthermore, they are small in design to prevent a possible back radiation of the antenna that would lower the antenna gain.

For measurement purposes, the antenna is realised with two different interfaces: a coplanar interface for "on-wafer" measurement of the return loss using measurement probes and a mini-SMP connector interface (produced by Rosenberger GmbH) to measure the radiation characteristic of the antenna in an anechoic chamber. Fig. 5 shows photographs of the realised antennas.

Fig. 5 Photographs of the realised antenna with coplanar interface (left) and with mini-SMP connector (right)

The H- and the E-plane far field radiation characteristics of the antenna measured at 35GHz are depicted in Fig. 6 and in Fig. 7, respectively.

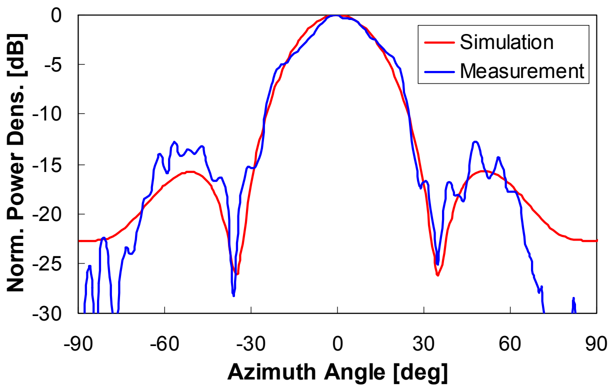

Fig. 6 H-plane radiation characteristic measured at 35GHz

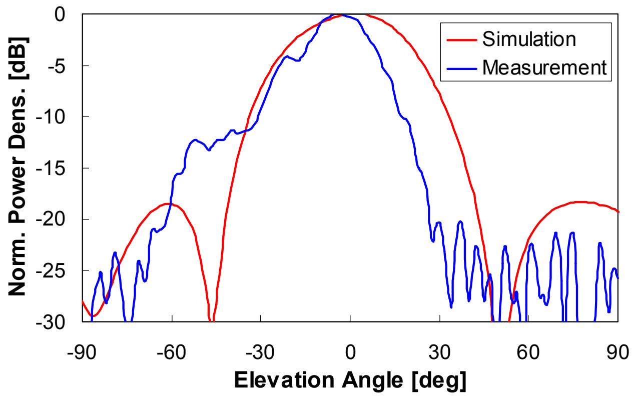

Fig. 7 E-plane radiation characteristic measured at 35GHz

Fig. 6 shows good agreement between measurement and simulation in the H-plane. The -3dB beam width is about 27° and the side lobe level is -13dB, which is slightly above the expected value. In the E-plane, a slight discrepancy between measurement and simulation is observed. It is believed to be due to the coaxial connector placed on the radiating side of the antenna. It disturbs the radiation pattern and creates the observed asymmetry in the E-plane. To prevent this phenomenon, a redesign of the antenna will put the coaxial interface on the back side of the antenna. The main beam of the antenna shows an off-axis angle of -3° and a -3dB band width of 22° in the E-plane.

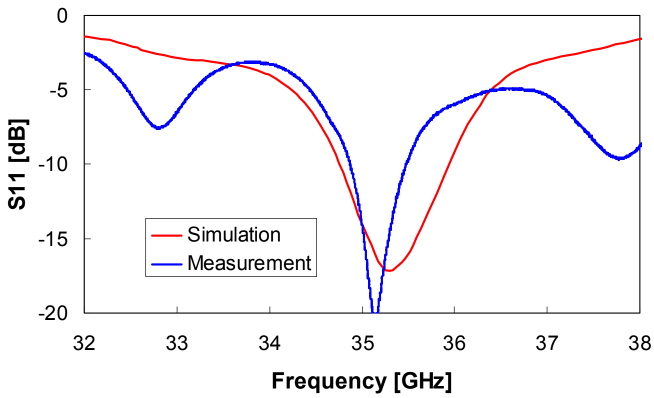

Fig. 8 Measured return loss of the patch antenna array

The return loss of the antenna array measured with coplanar measurement probes is shown in Fig. 8. It exhibits a good matching better than -12dB at the design frequency of 35GHz, which is met with a good accuracy. It is better than -10dB from 34.9GHz up to 35.5GHz, which corresponds to a relative bandwidth of 1.7%. The band width of the antenna is limited by the high dielectric constant of the LTCC material. It can be improved by implementing parasitic elements around the patches as in the dual stacked patch configuration or by designing slots in the patch itself. The antenna gain has been measured at about 12dB at the design frequency of 35GHz.

IV. Repeatability of the Process on LTCC DuPont 943

In order to assess the repeatability of the LTCC fabrication process and for the fabrication tolerances to cater for the next design step, five antennas realised with the same mask set on five different LTCC wafers have been measured. The return loss of the five antennas is shown in Fig. 9 and the relevant numbers are presented in Table 1.

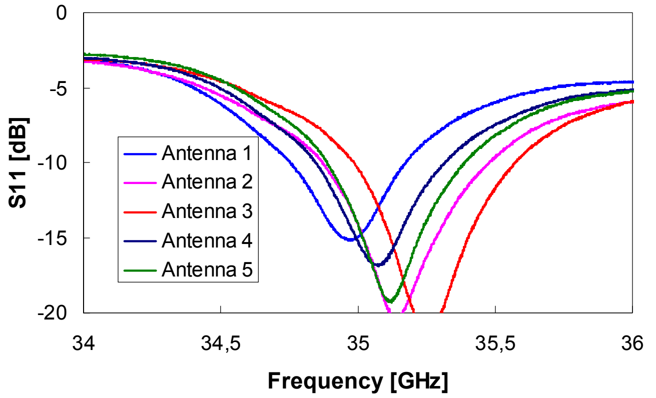

Fig. 9 Measured return loss of five similar antennas fabricated on different LTCC wafers

TABLE I

COMPARISON OF THE MATCHING PROPERTIES OF FIVE SAMPLES

Antenna	1	2	3	4	5
Matching Freq. [GHz]	35,0	35,2	35,3	35,1	35,1
Matching [dB]	-15,1	-20,3	-21,2	-17,2	-19,0
Rel. -10dB BW [%]	1,14	1,7	1,7	1,4	1,4

The matching frequencies of the five samples are between 35GHz and 35.3GHz with a standard deviation of 0.102. The measured relative band-widths of the antennas are between 1.14% and 1.7% with a standard deviation of 0.212. This dispersion of the matching frequencies and band-widths is attributed to the fabrication tolerances. A deviation in the radiating length of the patches affects the matching frequency. More importantly, variations in the dimensions and positions of the geometrically small coupling slots influence the strength of the coupling between the feeding lines and the patches and result in a drift of the matching frequency and band-width.

V. BEHAVIOUR OVER TEMPERATURE

Since the antenna is intended to be integrated in a complex fully integrated LTCC front-end module, it has to be capable of handling quite large temperature variations. In order to investigate the behaviour of the antenna in normal working conditions, its return loss has been measured over temperature. The dilatation of the structure observed when the temperature increases, results in larger patch dimensions and more importantly in increased lengths and widths of the coupling slots. This strengthens the coupling between the feeding lines and the patches and changes the matching properties of the antenna. Furthermore the temperature has an influence on the dielectric constant of the LTCC material, which changes the electrical lengths of the structures and affects the behaviour of the antenna. The matching properties of the antenna measured over a temperature range from room temperature up to 160°C are summarised in the plot shown in Fig. 10.

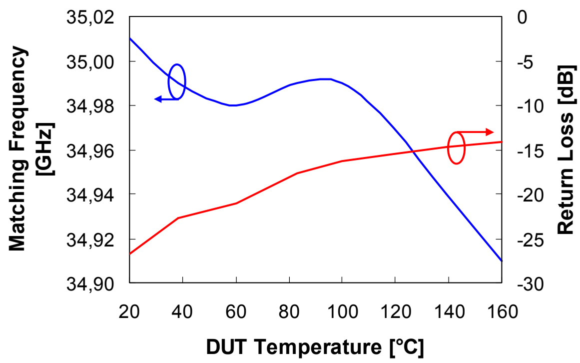

Fig. 10 Matching properties of the antenna over temperature

The matching frequency of the antenna is shifted from 35.01GHz at room temperature down to 34.91GHz at 160°C. On the other hand the increased temperature slightly damages the return loss of the antenna; it is measured at about –14dB at 160°C. These changes in the matching properties were expected, and need to be taken into account in the design of the antenna to guarantee satisfactory system performance over the entire temperature range in which it operates.

VI. CONCLUSION

In this paper, a four by four patch antenna array for RF-MEMS electrically steerable phased array antenna at 35 GHz is presented. The design of the aperture coupled patch antenna array is validated by good agreement between simulation and measurement. The hybrid integration and the packaging of the RF-MEMS phase shifters are described and the fabrication tolerances of the LTCC process as well as their consequences on the RF-properties of the antenna is addressed by measurement. The measured antenna exhibits a -3dB beam width of 27° in the H-plane and 22° in the E-plane. The measured side lobe level is about -13 dB and the band-width of the antenna is 1.7%. This antenna constitutes the first development step toward a complete LTCC integrated solution for RF-MEMS millimetre-wave phased array antenna.

ACKNOWLEDGEMENT

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