Design and Processing of 60 GHz Antennas on Low Temperature Co-fired Ceramic (LTCC) Substrates

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Abstract

Recent developments in the low temperature co-fired ceramic (LTCC) technology have enabled the integration of passive components including antennas in a cost-effective package up to the millimetre-wave frequencies. Suitable antenna types for the LTCC integration are, for example, microstrip dipoles, slot antennas, and various types of microstrip patch antennas [1,2]. In this paper, the design and manufacturing of an aperture-coupled microstrip line-fed microstrip antenna (ACMPA) and a slot-coupled coplanar waveguide-fed microstrip antenna (SCMPA) on LTCC substrate are presented. Also, the material characterisation of Ferro A6-S LTCC system with method based on ring resonators is shown. The return loss of -10 dB or better is achieved for the antennas within 3.4…6.6% impedance bandwidth. Our studies show that functional antennas can be fabricated with standard LTCC process and materials even for the 60 GHz frequency band.

Keywords: Millimetre-wave antennas, LTCC.

1. INTRODUCTION

The wide unlicensed frequency band around 60 GHz is suitable for short range communications with high data rates. So far, the high cost of radio technology for this band has prevented many commercial applications from emerging. The LTCC packaging technology and integrated circuits are widely used at the microwave frequencies in order to make cost-effective and high performance products. Recently, there has been much interest to develop also millimetre-wave applications for them [3,4]. Suitable applications at 35 and 60 GHz bands include short range communication links and collision-avoidance radars. Millimetre-wave antennas and arrays can be integrated along with passive components and CMOS MMICs on the same LTCC board, thus making it possible to have very complex radio systems in a cost-effective package. The results in this paper show that it is possible to make efficient 60 GHz antennas on LTCC boards.

2. LTCC TECHNOLOGY

Low temperature co-fired ceramic is a multilayer platform technology that can be used in fabricating components, modules and packages for the millimetre-wave frequencies. Main benefits of the LTCC are high packaging density, low conductor and dielectric losses, reliability and stability. Major challenges are related to the manufacturing tolerances at millimetre-wave region.

2.1 LTCC Process

In an LTCC process, via holes are first punched into the “green” glass/ceramic tapes. Then, vias are filled, and conductors are printed on each tape sheet separately. Then, different tape layers are aligned, laminated and sintered together with conductors. Finally, the substrates are diced.

Sintering temperature is below 900 ºC, and metals with high conductivity, such as silver, gold or copper, can be used as the conductor materials, which results in the low conductor loss. During the firing, the ceramic sheets shrink because of the burning of the binding material of the ceramic tape. The shrinking has to be taken into account in the LTCC process. Very accurate values of shrinking of glass/ceramic sheets and metallizations are quite difficult to predict because of the differences between the material lots.

2.2 LTCC Materials

Several commercial LTCC tape systems, such as DuPont 951, DuPont 943, Ferro A6-S and Heraeus CT 2000, are available for high-frequency applications. Traditional materials can be used in a free-sintering process up to the millimetre-wave frequencies. With special materials, such as Heralock, the zero-shrinkage processing is possible. The Ferro A6-S tape material with silver conductors was used in the fabrication of 60 GHz antennas. Fired thickness for Ferro A6-S is 99µm. The electrical properties of the silver conductor and the Ferro A6-S dielectric material were characterised with ring resonators.

2.3 Electrical Characterisation of Ferro A6-S LTCC

Ring resonators were designed in order to characterise the electrical properties of the conductor and dielectric. The analysis method is quite simple: the response of the resonating ring is measured, and the attenuation of the microstrip or stripline can be calculated for each order of the resonance i.e. frequency spots. Fig. 1 presents the measured response of one ring resonator. The response looks very good in the point of view of the electrical parameter calculation. The use of ring resonators in electrical characterisation of LTCC has been presented in [5]. Fig. 2 presents the calculated attenuation of the microstrip line.
The obtained microstrip line attenuation curve can be used in order to "calibrate" the loss factors of the simulation tools. For instance, the calibrated parameters for HFSS are: conductivity of silver conductor $\sigma_{Ag} = 7.4 \cdot 10^6$ S/m (includes roughness correction), dielectric loss tangent $\tan\delta = 0.0015$ and relative permittivity $\varepsilon_r = 5.99$. With these values the HFSS's loss modeling of the microstrip line is very accurate between 49 – 69 GHz when simulated and measured results are compared.

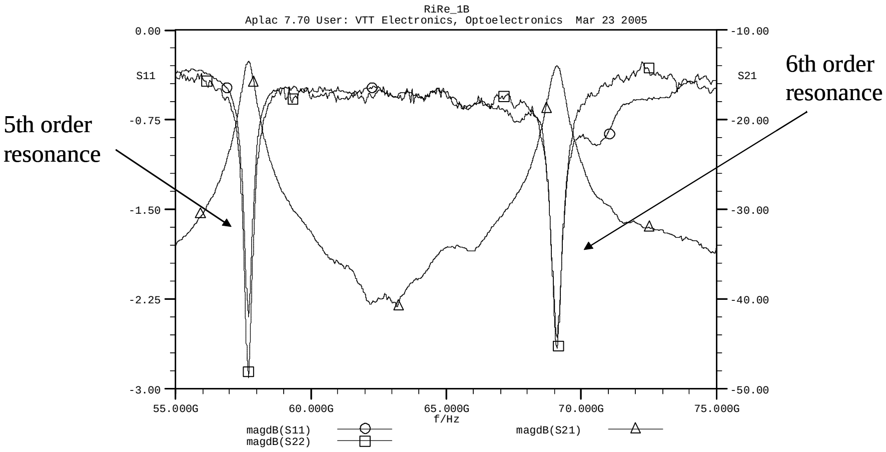
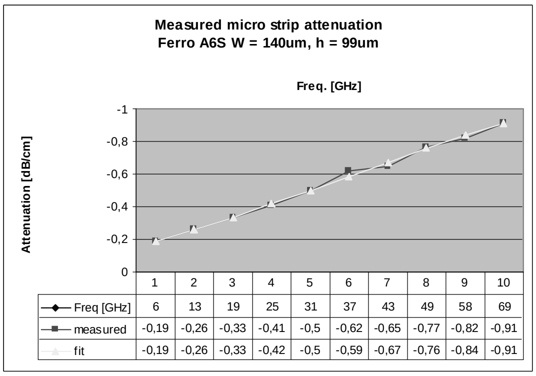


Fig. 1. Measured response of one ring resonator.



	1	2	3	4	5	6	7	8	9	10
◆ Freq [GHz]	6	13	19	25	31	37	43	49	58	69
■ measured	-0,19	-0,26	-0,33	-0,41	-0,5	-0,62	-0,65	-0,77	-0,82	-0,91
▲ fit	-0,19	-0,26	-0,33	-0,42	-0,5	-0,59	-0,67	-0,76	-0,84	-0,91

Fig. 2. The attenuation of the microstrip line defined by using a ring resonator.

3. ANTENNA DESIGN

Microstrip antennas have been used in LTCC applications also at millimetre-wave frequencies [6], [7]. The choice of the antenna topology depends on, for example, the antenna environment and integrability to other circuitry. Several feeding mechanisms are available for microstrip antennas. In addition to traditional probe or microstrip line feeds, different kinds of aperture-coupled feeds are nowadays widely used. Aperture- and slot-coupled antennas fed by microstrip line and coplanar waveguide (CPW) were designed and manufactured on LTCC.

3.1 Aperture-Coupled Microstrip Line-Fed Microstrip Antenna (ACMPA)

Aperture-coupled microstrip line-fed microstrip antenna (ACMPA) uses a microstrip line as the feed and the antenna element is excited by non-resonant aperture on a ground plane. ACMPA uses three metallization and two substrate layers. From the bottom to top there is first the microstrip feed, its substrate and ground plane common with the antenna element. Aperture is cut into the ground plane. Above the ground plane is the patch substrate, and the patch metallization is located on the top. ACMPA geometry is illustrated in Fig. 3a.
Substrates with thicknesses $h_{ms} = 100$ µm and $h_p = 300$ µm are used for the microstrip line and for the patch element, respectively. Microstrip line of width $w_{ms} = 150$ µm is used as feed in order to provide the characteristic impedance of 50Ω. Width and length of the patch element are $w_p = 790$ µm and $l_p = 750$ µm. Three variants with different H-shaped aperture lengths were fabricated: $l_{ap} = 560$ µm (ACMPA1), $l_{ap} = 504$ µm (ACMPA2) and $l_{ap} = 616$ µm (ACMPA3). Width of the aperture was kept constant, $w_{ap} = 80$ µm. The open-ended stub below the aperture provides impedance matching of the antenna, and optimal design is achieved with the stub having a length of $l_s = 315$ µm. Metallization thickness for silver conductors is $t = 10$ µm.

3.2 Slot-Coupled Coplanar Waveguide-fed Microstrip Antenna (SCMPA)

Two metallization layers, separated by one substrate layer in between, are needed for the SCMPA. The CPW and the patch use the same substrate. The structure is very simple and provides easy integration with MMICs. Design parameters for SCMPA are as follows: width of the CPW center strip $w_1 = 200$ µm, widths of the CPW slots $s = 50$ µm, coupling slot width $w_{sl} = 130$ µm, substrate thickness $h_p = 300$ µm, gap width $w_g = 55$ µm, matching stub length $l_{st} = 80$ µm and patch length and width $l_p = 740$ µm, $w_p = 790$ µm. Three variants with coupling slot lengths $l_{sl} = 215$ µm (SCMPA1), $l_{sl} = 194$ µm (SCMPA2) and $l_{sl} = 237$ µm (SCMPA3) were fabricated. The SCMPA geometry is presented in Fig. 3b.

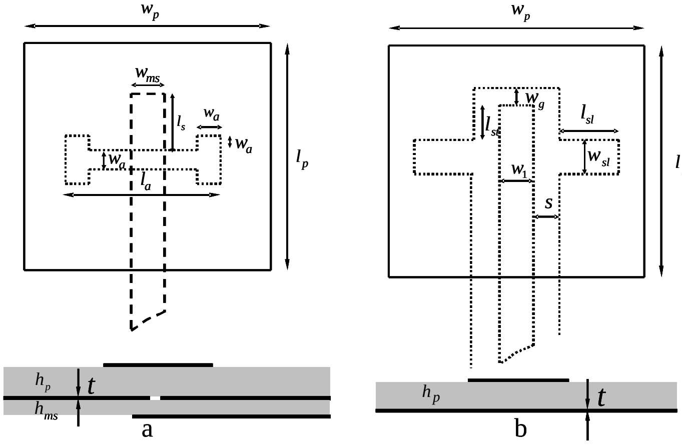


Fig. 3. Antenna geometries: a) ACMPA and b) SCMPA.

3.3 Slot-Coupled Grounded Coplanar Waveguide-Fed Microstrip Antenna (SCGMPA)

In order to measure radiation patterns, the antennas had to be connected to a test fixture. Anritsu Wiltron 3680V universal test fixture provides either CPW or MS connection and reliable measurements up to 65 GHz and it was used in our work. To connect the antenna to the test fixture, direct the radiation upwards from the fixture and minimise back radiation of the antenna, some modifications were done to the SCMPA. Substrate with thickness $h_{cpw} = 500$ µm and an additional ground plane were added below the CPW. In addition, conducting walls 900µm apart from each other were placed inside the lower substrate to prevent additional modes from arising. Walls were fabricated using vias between ground planes with diameters of 180µm and mutual distances of 450µm. In simulations, vias were replaced with solid walls in order to reduce complexity and simulation time. HFSS simulation model of the SCGMPA is shown in Fig. 4. The feed transforms from air-filled GCPW (grounded CPW) into dielectric filled GCPW. CPW parameters were sought with simulations to keep the characteristic impedance at 50Ω. Air-filled GCPW and dielectric filled GCPW had dimensions $w_1^a = 200$ µm and $s_1^a = 50$ µm, $w_1^d = 200$ µm and $s_1^d = 160$ µm, respectively. Other design parameters were: $l_{st} = 70$ µm, $l_{sl} = 200$ µm, $w_g = 160$ µm, $l_p = 750$ µm and $w_p = 750$ µm. Feed lines were ~15 mm long in order to place the patch apart from the test fixture.

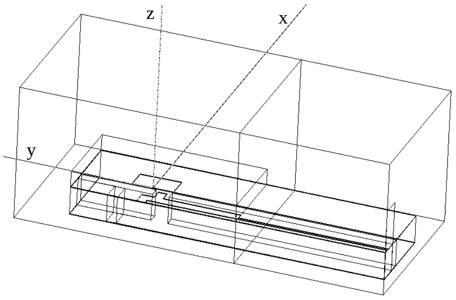


Fig. 4. HFSS simulation model of the SCGMPA.

4. TEST MEASUREMENTS

4.1 Scattering Parameters

The S-parameter measurements for ACMPA and SCMPA antennas were carried out with Cascade on-wafer probe station at frequency range 50 - 75 GHz. GSG-probes with 150µm pitch between signal and ground probes enabled direct connection to CPW feeds in SCMPAs. In order to use the same probes for testing ACMPAs, small metal plates connected with vias into the ground plane were added in manufacturing. Antennas were positioned on top of a 1 cm thick Rohacell foam sheet ($\varepsilon_r < 1.15$) with Cuming Microwave C-RAM GDSS absorber slab on the bottom. Since the far field limit is at distance ~0.32 mm at 75 GHz, the Rohacell and absorber sheets were adequate to simulate far-field conditition and prevent multiple reflections.

The SCGMPA was tested with the test fixture. Measurements were conducted with a HP 8510C vector network analyzer (VNA). Calibration was carried out with HP 85109B K19 coaxial calibration kit for coaxial cable with diameter 1.85 mm. Test fixture was covered with Cuming Microwave C-RAM FLX-10/PSA 0.0062" absorber. Absorber sheets located approximately at distance 2 cm from the antenna element and far-field conditions were fulfilled. Measurement arrangements are shown in Fig. 5a with on-wafer probe station, and in Fig. 5b with the test fixture.

4.2 Radiation Pattern

Radiation characteristics of SCGMPA was tested in an anechoic chamber. A small and accurate antenna positioner was controlled using custom LabView software. A suitable horn antenna was used as the transmitting antenna and signal was detected by an Agilent Spectrum Analyzer. The E-plane pattern was distorted by multiple reflections from the test fixture but full H-plane pattern was stored. Data was collected with 1° steps at 59.5 GHz.

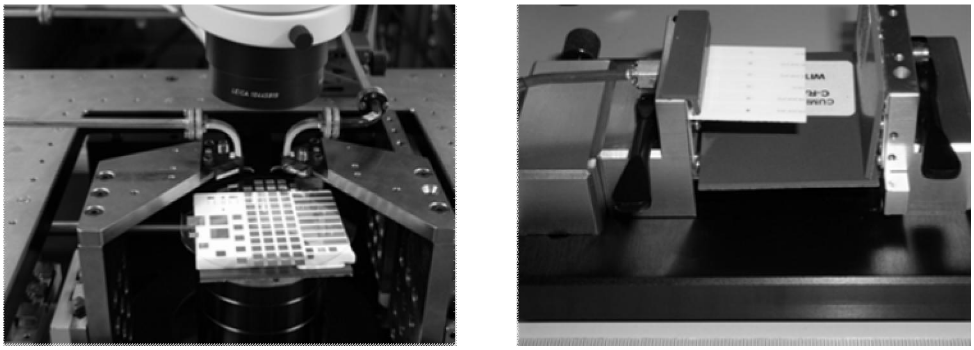


Fig. 5. Scattering parameter measurements with probe station (left) and test fixture (right).

5. RESULTS

5.1 Scattering parameters

Normalised input impedance (normalised to 50Ω) and return loss for SCMPA and ACMPA antennas are presented in Fig. 6. Simulations were conducted with Ansoft HFSS 8.0. After checking the dimensions of the SCMPAs using a Wild Heerbrugg M3Z microscope, the antennas were re-simulated with the realised parameters. Deviations between the results are caused by errors in realised dimensions of the antennas. Errors arise from shrinking of the LTCC tapes and conductors during the sintering process. However, it is seen that a return loss of -10 dB or better is achieved over frequency range 59.4…61.5 GHz and 58.5…61.5 GHz for SCMPA1 and SCMPA3, which results in impedance bandwidths 3.5% and 5%. Corresponding values for ACMPA1 and ACMPA3 are 57.4…59.4 GHz ($BW_{imp} = 3.4$ %) and 56.2…60 GHz ($BW_{imp} = 6.6$ %). Differences in center frequencies are caused by deviation in patch lengths due to manufacturing.

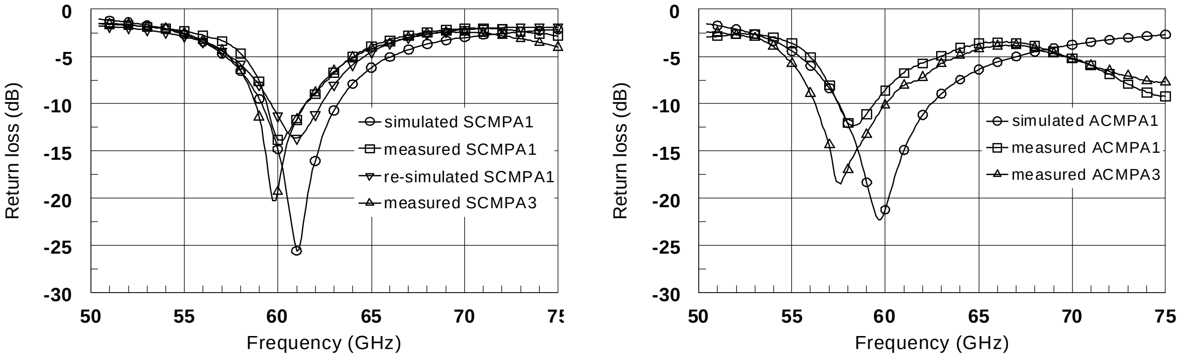


Fig. 6. Return loss of SCMPA and ACMPA antennas.

5.2 H-plane gain

Simulated and measured H-plane normalised gain patterns are compared with each other in Fig. 7. The angle θ' denotes the rotation angle of the antenna positioner. When $\theta' = 0$, the major lobe is directed to the transmitting horn. It is seen that simulated and measured gains in the H-plane are quite similar. There is a small deviation between the results at angles -120º…-60º and 60º…120º. Deviation is caused by the multiple reflections from the metal parts of the test fixture. Simulated maximum gain, half-power beam width, and back-lobe level of SCGMPA were 3.5 dB, 85.4º, and –17.2 dB, respectively.

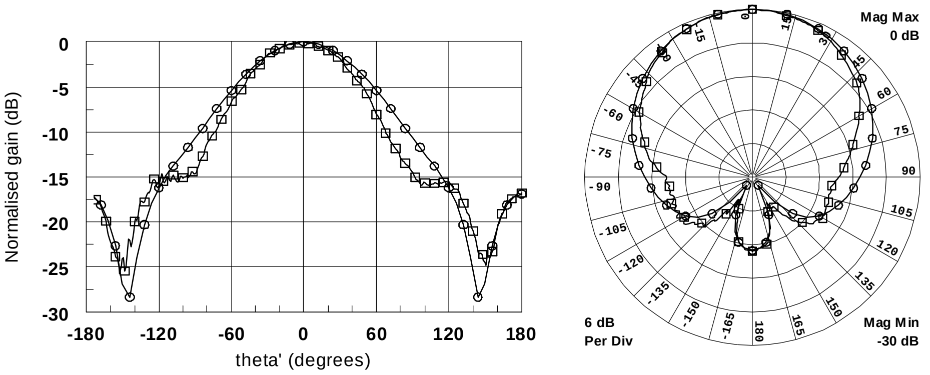


Fig. 7. Normalised gain of the SCGMPA in H-plane (○: simulated, □: measured).

6. CONCLUSIONS

Microstrip antennas for the 60 GHz frequency band were designed, manufactured and tested. Several feeding mechanisms enable tuning of the input impedance without additional matching stubs or circuits. Aperture-coupled microstrip-line fed microstrip antennas (ACMPA) and slot-coupled coplanar waveguide-fed microstrip antennas (SCMPA) were tested with on-wafer probe station. In addition, slot-coupled grounded coplanar waveguide-fed microstrip antennas (SCGMPA) were designed and fabricated in order to measure radiation pattern with the test fixture. Our studies show that functional antennas can be fabricated with a standard LTCC process and materials even for the 60 GHz frequency band. In the near future, an array will be designed and fabricated on LTCC. Beam steering will be demonstrated with an array integrated with active phase shifters.

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