RF to millimeter wave integration and module technologies

T. Vähä-Heikkilä
VTT Technical Research Centre of Finland, Millimetre wave Laboratory of Finland – MilliLab,
Communication Systems
Tietotie 3, Espoo, P.O. BOX 1000, 02044 VTT, Finland

ABSTRACT

Radio Frequency (RF) consumer applications have boosted silicon integrated circuits (IC) and corresponding technologies. More and more functions are integrated to ICs and their performance is also increasing. However, RF front-end modules with filters and switches as well as antennas still need other way of integration. This paper focuses to RF front-end module and antenna developments as well as to the integration of millimeter wave radios. VTT Technical Research Centre of Finland has developed both Low Temperature Co-fired Ceramics (LTCC) and Integrated Passive Devices (IPD) integration platforms for RF and millimeter wave integrated modules. In addition to in-house technologies, VTT is using module and component technologies from other commercial sources.

Keywords: RF, millimeter wave, LTCC, IPD

1. INTRODUCTION

Integration of multiple chips and functions to the same radio module is a key issue when the size of a radio front-end is tried to minimize. Passive components are used basically in all modules and systems especially in radio frequency applications. One trend is to integrate as many passives as possible to semiconductor integrated circuit chip and other trend is to use as much external discrete passive components in printed circuit board (PCB) or other technology modules [1]. Practical realizations are something between. IC technologies allow high integration density but on the other hand, surface area is rather expensive and RF performance of large area passives is rather low due to low resistivity substrates. Especially inductors have low performance and they are expensive to realize in IC technologies because of their large size. On the other hand, discrete passive components have high performance but they are typically large in size and requires assembly to modules. Integrated passive devices (IPD) technology is an alternative way for realizing high quality factor (Q) passives in low loss substrates. Combining most of passive components to IPD and then integrating IPD based module to sub-system allows to have high performance, high integration density and lower assembly cost. Especially RF front-end modules and components requiring high-Q inductors are beneficial to integrate to IPD such as baluns, couplers, filters, LC-resonators and matching circuits. LTCC is also a very good technology for hermetic packaging resulting in good RF performance, lightweight modules and rather high integration densities.

This paper presents both LTCC and an integrated passive device (IPD) technologies for RF components and multi-chip module integration applications. The main focus the paper is passive components and circuits realized using inductors and capacitors. The LTCC and IPD technologies can also be used as an integration platform for multi-chip modules technology with hybrid integrated active circuits. The benefit of LTCC is that it can be used for module level hermetic packaging.

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*tauno.vaha-heikkila@vtt.fi; phone +358 40 758 7941

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2. LTCC TECHNOLOGY AT VTT

Low temperature co-fired ceramic technology is stable and lightweight technology also being suitable for harsh environments. It combines many thin layers of ceramic and conductors. It has often used as a 3D module platform, with rather low permittivity ($\varepsilon_r = 4–9$) dielectric compositions. It also allows design and integration of passive microwave components, such as transmission lines, filters, antennas, inductors, capacitors, phase shifters and dividers. The realization of integrated capacitors requires higher The low sintering temperature (<900 °C) allows the use of highly conductive metals, such as Ag or Au as conductors. Other important parameters to consider include thermal expansion of coefficient (CTE) match with typical semiconductor materials, high strength and high thermal conductivity. Typically the material properties remain constant over a wide frequency range. Instead, the millimeter wave performance of the LTCC modules is mainly affected by processing issues, such as line width variations due to printing steps or shrinkage during firing.

Following figure shows typical LTCC module fabrication process. The first step is ceramic sheet blanking. It is followed by via punching (2.) and via metallization (3.). The next steps are conductor printing and cavity punching (4). These are followed by layer alignment and lamination (5.). The last step in actual LTCC fabrication is sintering (6.) Post-processing steps include dicing (7.) and component or module separation (8.). Surface Mount Devices (SMD) and other chips are then assembled to modules (9.). The last step is to seal cavities or package LTCC modules (10.). Some of the sealing methods provide hermetic sealing.

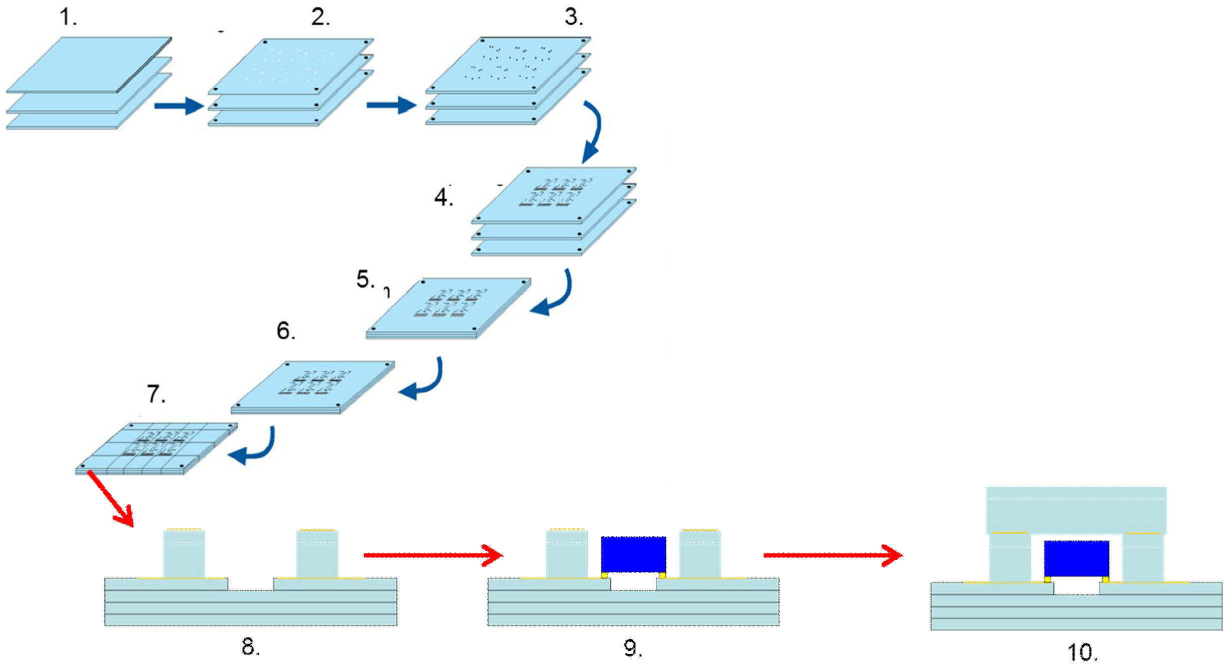

Figure 1. LTCC module fabrication steps from sheet cutting to hermetic sealing. The first step is ceramic sheet blanking. It is followed by via punching (2.) and via metallization (3.). The next steps are conductor printing and cavity punching (4). These are followed by layer alignment and lamination (5.). The last step in actual LTCC fabrication is sintering (6.) Post-processing steps include dicing (7.) and component or module separation (8.). Surface Mount Devices (SMD) and other chips are then assembled to modules (9.). The last step is to seal cavities or package LTCC modules (10.).

VTT has several commercial LTCC material systems available. VTT's millimeter wave applications are mainly based on Ferro A6-M system. Its relative permittivity is 5.74 at 60-70 GHz, and loss tangent 0.0023. The system utilizes screen-printed gold (Au) conductors, with the conductivity of 2.5 x 10^7 S/m. Typical processing parameters have been compared in Table 1 between VTT and typical commercial manufacturers. VTT's focus has been to develop accurate process suitable for microwave and millimeter waves.

TABLE I

COMPARISON OF PROCESSING PARAMETERS BETWEEN COMMERCIAL FOUNDRIES AND VTT.

Parameter	Typical values with commercial manufacturer	VTT's typical values
Min line width [µm]	150	50
Tolerances of linewidths [µm]	±20	±5
Layer-to-layer positioning accuracy [µm]	60	15

At millimeter waves, the assembly methods have to be considered carefully. Flip-chip interconnections eliminate the parasitic inductances caused by bonding wires. If the flip-chip process is not feasible in some cases, ribbon bonding can be used instead of conventional wire-bonding. VTT's flip-chipping process is based on the use of Au stud bumps. The diameter of the bumps is about 60 µm and the height about 20 µm. The attachment of a component is then made with thermo-compression method. The bonding force and temperature has to be optimized for each component type. The fabricated LTCC module is attached onto a printed wiring board with reflow process. The size of the BGA balls has to be selected by making a compromise between the high-frequency properties and reliability [2].

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The use of LTCC technology is the most beneficial when integration level is high in modules. Typically, passive components, MMIC circuits and antennas can be integrated to the same module as well as package them when needed. Following figure shows a 3-dimensional layout drawing of a 60 GHz transmitter module designed at VTT. It shows that LTCC modules can have integrated antenna arrays, flip chipped or wire/ribbon bonded active millimeter wave circuits, surface mount passive devices (SMD) and place for a connector if needed. The radiating patch antennas are on the other side of the module.

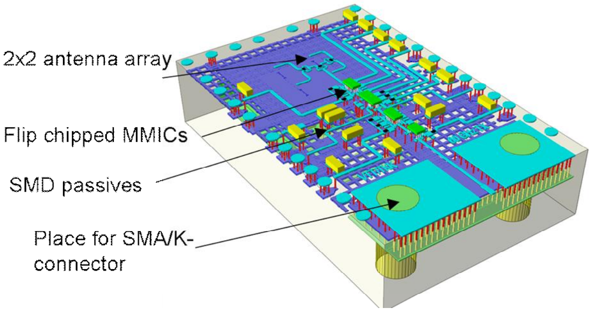


Figure 2. 3D-layout drawing of a 60 GHz transmitter module on LTCC showing integration capabilities of the LTCC technology. The multi-chip module has integrated antennas, flip-chipped MMICs and SMD passives and place for a connecter with through module interconnection holes.

3. INTEGRATED PASSIVE DEVICE INTEGRATION PLATFORM

In addition to ceramics based LTCC modules, VTT has also been developing an integrated passive device (IPD) component and module integration platform. It uses clean room processes similar as used in IC manufacturing. Following figure shows schematical view of an IPD module. There is a flip chipped RF IC, integrated LC filters, biasing and matching circuits.

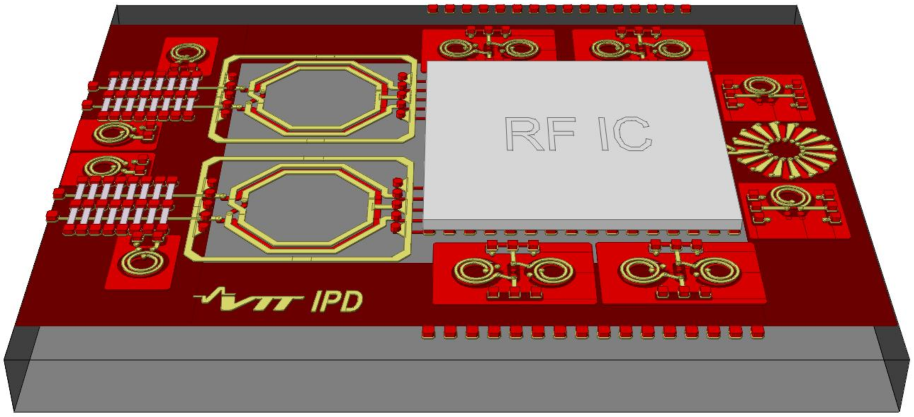


Figure 3. IPD technology used for RF front-end module realization with high-Q passive components such as inductors, capacitors, LC-resonators, baluns, couplers, matching circuits, and filters.

IPD technology at VTT can be manufactured to any substrate which is suitable for thin film processing in clean rooms. Fused silica, quartz or high resistivity silicon are typically used for RF applications due to their good RF properties. The IPD layers can also post processed to active device wafers such CMOS, SiGe or GaAs in order to have high Q passives and re-distribution layers (RDL).

VTT has several different IPD processes which are optimized for different purposes. Schematical sideview of VTT's three metal layer IPD technology is shown in Fig. 2 and properties in Table II. It is a multi-purpose technology being suitable for many RF applications and frequencies from VHF to millimeter waves. It has thin film resistors, metal-insulator-metal (MIM) capacitors between metal 1 and metal 2, a 10 µm thick copper metal layer (metal 3) for high quality factor transmission lines and passive components. The thick metal layer is separated from the thinner metal layers by 10 µm polyimide layer (P1) and lines in metal 3 (M3) are separated from each other with the second polyimide (P2). As a last step, 50 µm flip chip bumps are deposited to allow component assembly to modules. A SiO2 is used as a dielectric material in VTT's standard IPD process but other materials are also available if higher capacitance densities are needed. For example, Ta_2O_5, HfO or ZrO_2 have permittivities of 25, 16 and 20. The resistance of the thin film resistor layer can be chosen according to application. For example, resistance of the standard process thin film resistors (8 Ω/□) is good for matched RF terminations and resistor for resistive Wilkinson power dividers. Applications such as RF MEMS biasing circuits need resistance values preferably above 500 Ω/□.

The IPD technology is closer to 2D integration platform while LTCC is a 3D integration platform. On the other hand, IPD supports accurate line widths and component tolerances compared to other RF integration platform technologies.

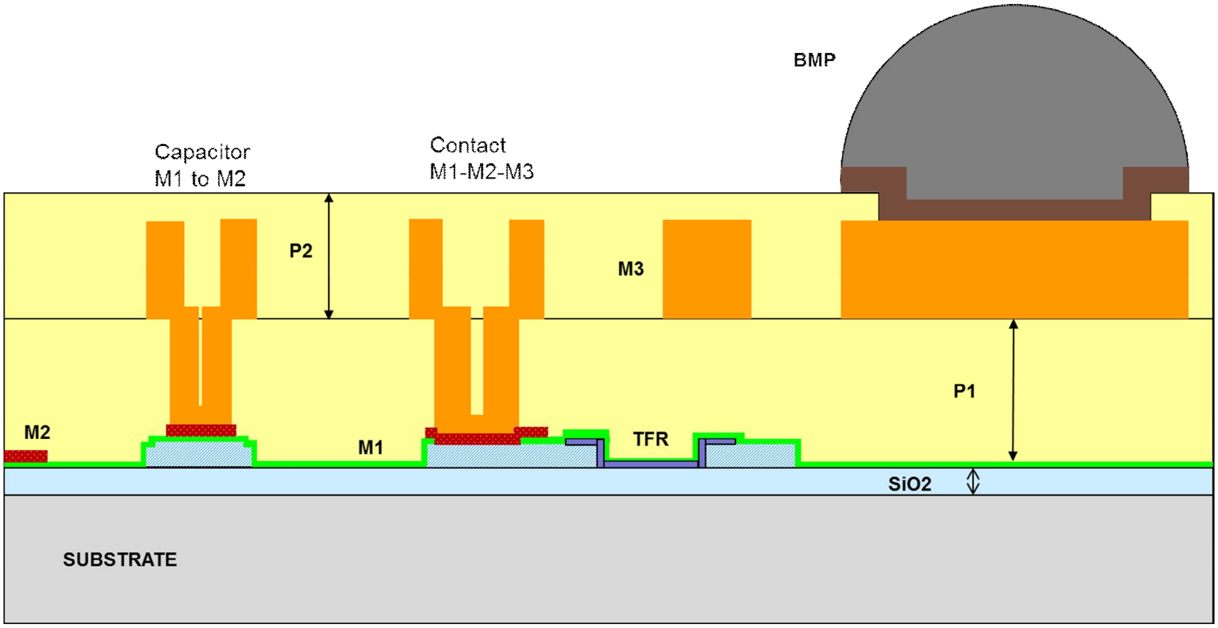


Figure 4. Cross-sectional view of VTT's three metal layer IPD process. Metal-insulator-metal (MIM) capacitor is formed between metal 1 (M1) and metal 2 (M2). Metal 3 (M3) is used for high-Q passives and transmission lines. Bump can be used for reflow soldering and flip chip assembly.

TABLE II

VTT IPD PROCESS LAYERS IN 3 METAL LAYER TECHNOLOGY

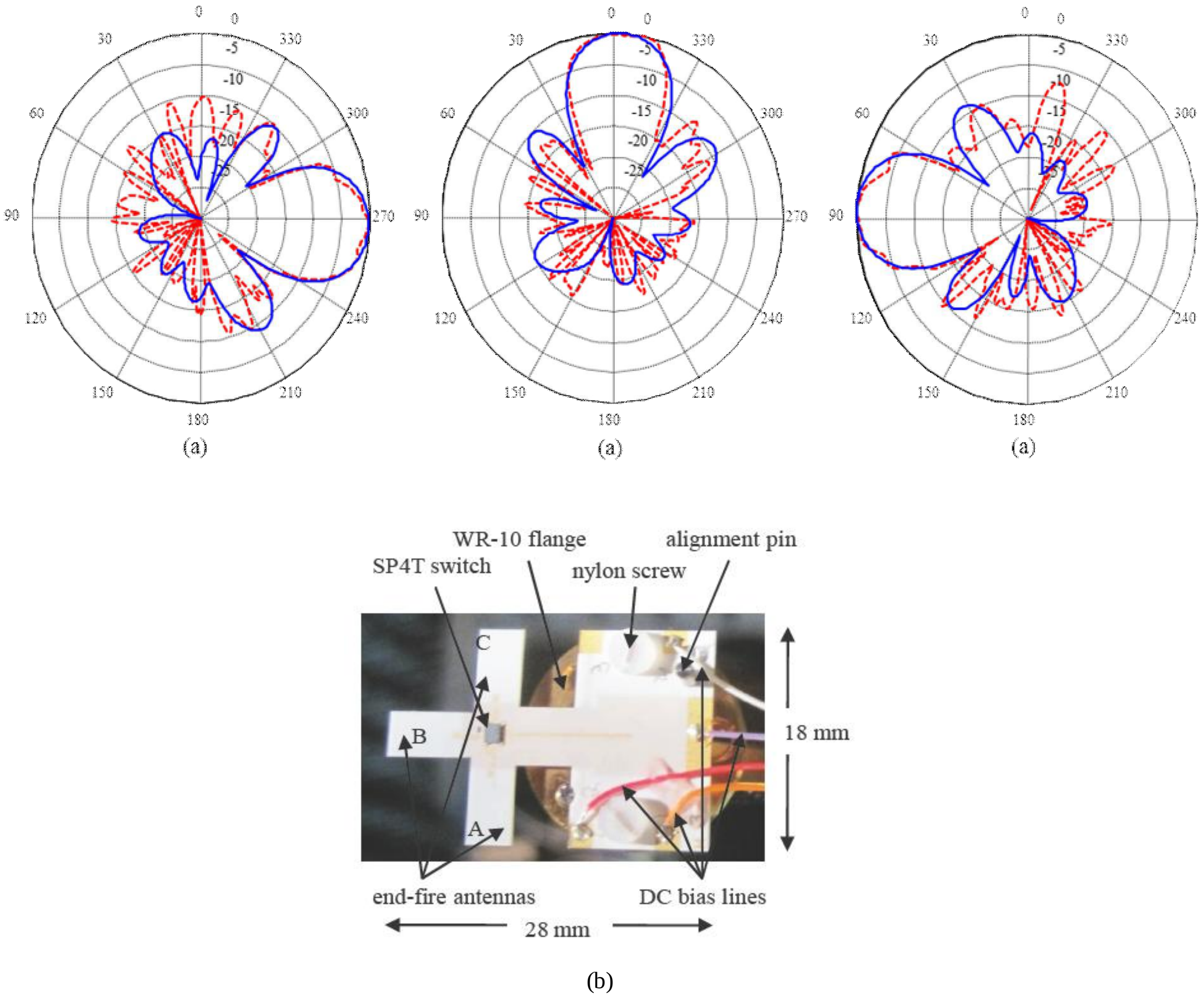
Layer	Definition	Thickness/Property
TFR	Thin film resistor	8 Ω/□
M1	1st metal layer	1 µm
DIEL	MIM-capacitor	0.2 µm, 0.15 nF/mm2
M2	2nd metal layer	0.5 µm
P1	1st polymer	10 µm
M3	3rd metal layer	10 µm
P2	2nd polymer	12.5 µm
BMB	Flip chip bump	50 µm

4. RF TO MILLIMETER WAVE COMPONENTS AND MODULES

In this chapter, few examples of realized antenna, front-end module and filtering components are presented.

Beam switching millimeter wave antenna module

Antenna beam steering is typically realized with phase shifter. However, there are no available commercially off-the-shell (COTS) phase shifters at millimeter waves. Another option is to use switchable antenna elements or sub-arrays and control them with single-pole-N-throw (SPNT) switches. VTT has worked with both of the concepts. The next figure shows an example of switched beam E-band antenna module [3. It can switch the antenna beam with 90 degree steps. The end fire antenna elements are realized on LTCC. The electrical switching is realized with a Gallium Arsenide (GaAs) switch which is flip chipped to the LTCC.



(a) (a) (a)

(b)

Figure 5. a) Measured (continuous line) and simulated (dotted line) radiation patterns for electrically switchable beam-switching antenna with three different switch settings. b) Photograp of a fabricated switched beam antenna on LTCC having integrated waveguide to LTCC transition and flip-chipped single-pole-4-throw switch [3].

Integrated passive device filters

The IPD integration platform is very suitable for passive component realization and front-end module integration. The next figure shows measured results for an integrated millimeter wave filter [4]. It has loss about 1.0 … 1.2 dB at 60 GHz.

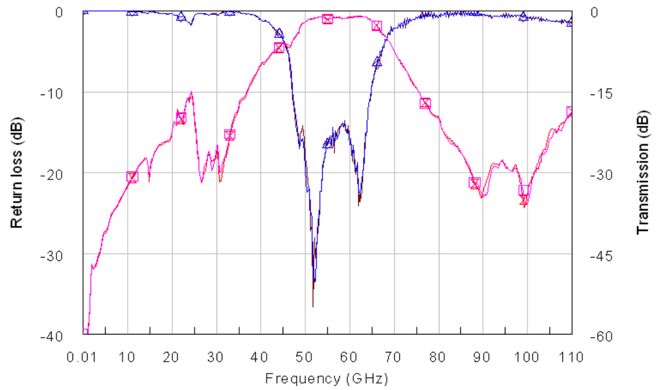
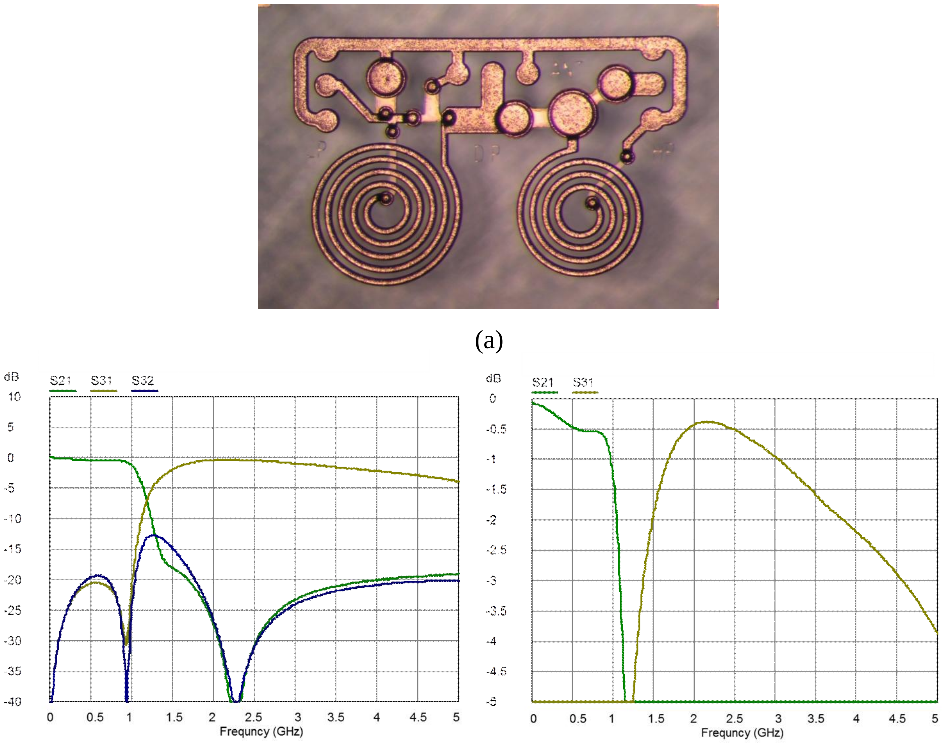


Figure 6. Measured results for a 60 GHz planar Co-Planar Waveguide band-pass filter. Filter has two side-coupled resonators. [4]

The next figure shows the photograph of the diplexer having the size of 1.1 mm x 1.7 mm as well as measured results. The diplexer on high resistivity silicon show measured loss less than 0.5 dB in the mobile phone bands both below 1 GHz and above 1.7 GHz.



(a)

(b) (c)

Figure 7. a) Photograph of a diplexer designed for cellular phone applications. Size of the diplexer is 1.1 mm x 1.7 mm . b) and c) Measured S-parameters for the diplexer with loss less than 0.5 dB in cellular bands [4].

5. CONCLUSIONS

An overview of RF passive and integration platforms was given focusing to LTCC and IPD integration platforms. Both are suitable from RF to millimeter wave applications. The IPD is suitable for high accuracy RF and millimeter wave applications with tight flip chip capabilities. The LTCC integration platform is a real 3D integration technology suitable for RF front-end module realizations and millimeter wave antenna arrays.

REFERENCES

[1] T. Vähä-Heikkilä, “LTCC - 3D Integration Platform from Handset to Millimeter Wave Modules,” Workshop on 3D Microwave and Millimeter-Wave Packaging,” IEEE International Microwave Symposium, Anaheim, USA, May 2010, (2010).

[2] T. Kangasvieri, J. Halme, J. Vähäkangas, M. Lahti, “Low-Loss and broadband BGA Package Transition for LTCC-SiP applications”, Microwave and Optical Technology Letters, pp. 1036–1040, (2008).

[3] A. Lamminen, J. Säily, "77 GHz beam-switching high gain antenna on LTCC" Proc. of ICECOM 2010, (2010).

[4] T. Vähä-Heikkilä, J. Saijets, J. Holmberg, P. Rantakari, H. Ronkainen and R. Tuovinen, ” Integrated Passive Device Process for High Quality Factor Passive Components and Modules,” Proceedings of European Microwave Conference 2013, Nurnberg, Germany, 2013, pp. 100-103 (2013).