Buried Microwave Designs using LTCC Multilayer Technology for High Density Integrated Space Hybrids

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INTRODUCTION

For a microwave series production on high volume levels the achieved process reliability and the degree of automation are preconditions to achieve highest First Time Yield (FTY). This has been proven at TESAT in production of roughly 65.000 pieces of terrestrial telecommunication TRX modules for one of the largest network providers worldwide.
The idea is now to re-use the existing manufacturing methodology applied for terrestrial high volume production for future space applications at low volume but highest quality requirements. On the field of applied materials the LTCC-multilayer substrate with buried microwave structures has been a key component for success.

This paper focusses on the achieved progress in development and manufacturing of advanced RF-Systems in Package (RF-SiP) for space. Such high density integrated designs (HDI) provide a new level of integration density for space hybrids combining the hermetic package, a PCB environment and a mechanical housing. Characteristic for such hybrids is reduced size, weight and cost at increased quality.

TESAT has defined 10 layers as an internal standard for LTCC substrates. The microwave conductor and interconnect layer is the 2nd layer above ground. A strip-line system is used with ground at two layers below the RF conductor (substrate backside) and two layers above. For filters and impedance matching additional layers can be used. GaAs- and GaN-devices are directly attached to the heat-sink by use of a so-called pocket- and window-technology. See Fig. 1. The pocket lips provide RF- and DC-bondpads for wire-bonded interconnects between semiconductors and required blocking capacitors. A pocket is surrounded by a fence of grounded vias through the whole substrate. This base construction provides a high shielding and large decoupling between building blocks as of schematic (e.g. TX-RX) even in case of an open hybrid module. In practice, a TX-RX isolation of >110dB has been achieved on less than 20mm physical distance between transmitter output and receiver input.

This paper presents some of the recent product developments. They contain buried impedance matching, 3dB-couplers, EMI-filters, coupled inductors, Wilkinson-dividers, edge couplers, attenuators, resistively loaded striplines, strip-line to coax transitions and strip-line to waveguide transitions.

L-BAND 40W GAN SSPA BUILDING BLOCK

A 40W GaN solid state power amplifier (SSPA) has been developed based on a 12mm GaN50 power bar from Fraunhofer Institute for Applied Solid State Physics (IAF). A 10x LTCC multilayer based buried microwave design contains input and output impedance matching (buried inductors, capacitors and resistors).

For Gallium-Nitride semiconductors power densities of 3-6W/mm gate width are characteristic. Silicon carbide as chip base material provides a good on-chip thermal conductivity (approx. 350W/m*K) but standard heat-sink materials like

MoCu or CuMoCu (CMC) can't longer be applied. Diamond composites are one choice to reduce thermal resistance and channel temperature significantly. See Fig. 2. They enable an increased life-time for space applications.

For the described GaN-SSPA building block the hermetic package applies a 2-step solder hierarchy on an aluminum-diamond heat-sink with a thermal conductivity of λ=500W/m*K. Gold-Germanium solder (Au88Ge12) is used for package brazing. The GaN power bar is assembled by a fully automated eutectic die attach using gold-tin solder (Au80Sn20) in a 2nd step.
Similar packaging technology can be used for monolthic microwave integrated circuits (MMIC) at higher frequencies.

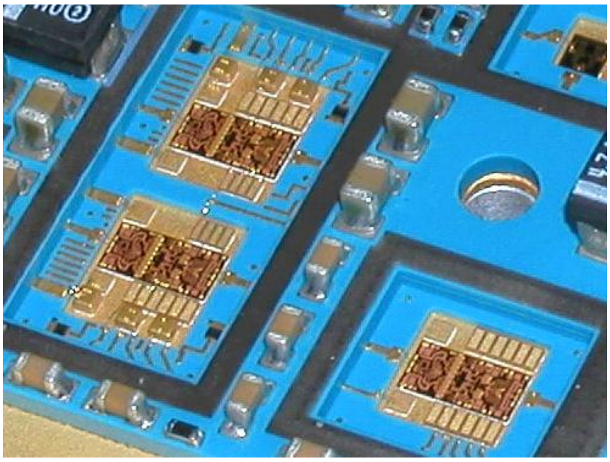


Fig. 1: LTCC pocket & window technique

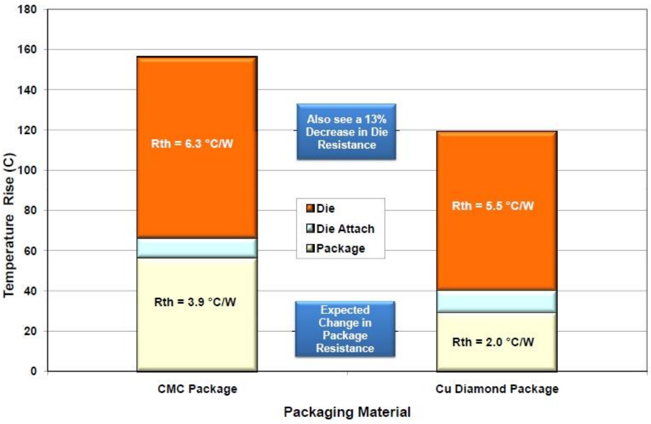


Fig. 2: Temperature rise versus power density
(source CREE Inc.)

RF simulations have been performed on Keysight's ADS/Momentum 2009 platform (see Fig. 3 to Fig. 8) and for substrate layout the microwave hybrid design system (HyDe) has been used.

Fig. 3 depicts the ADS/Momentum 3D simulation model. After successful RF design this is taken over into HyDe for LTCC layout. Layout can also be started in HyDe in order to meet the fundamental design rules initially and then be exported to ADS/Momentum for simulation. This design and layout process is usually an iterative one.

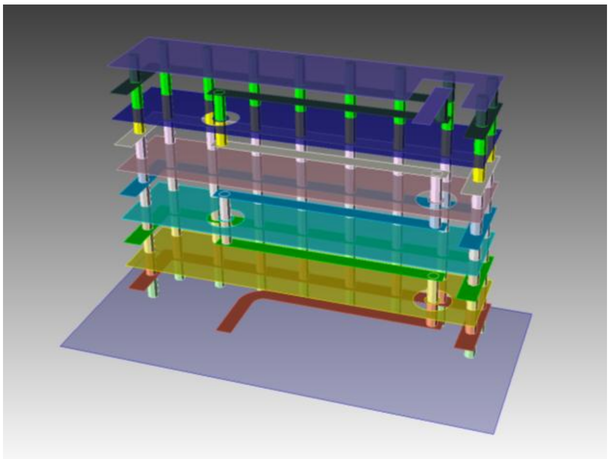


Fig. 3: Impedance transforming gate bias feed

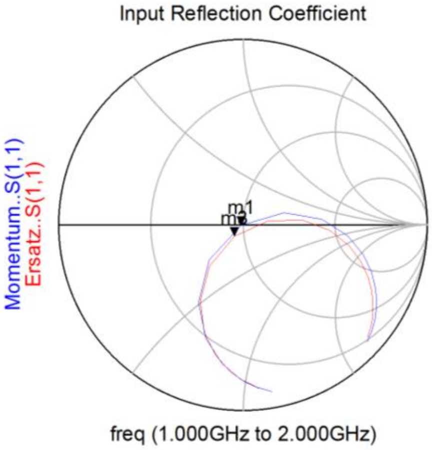
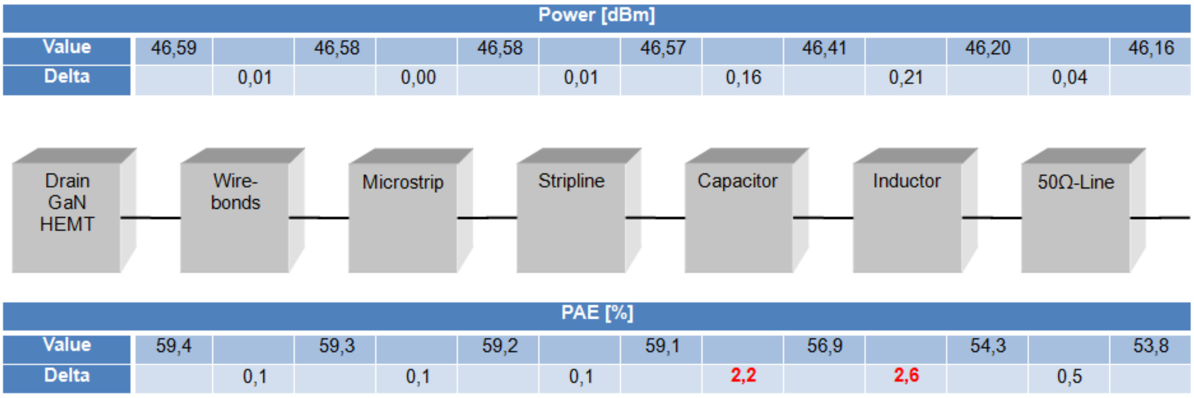


Fig. 4: Output matching network (Zref = ZLopt*)

Focal point of view has been on load pull simulations (see Fig. 6) in order to match the GaN-HEMT for optimum output power and on a step by step analysis of effective power losses between drain terminal and 50Ohm load (see Fig. 4). Each circuit element has been evaluated carefully (see Fig. 5). Design and layout challenge has been the shunt inductance to ground at the amplifier's output due to the limited gold paste conductivity. The amount of high frequency current through this coil is significant. Despite its design optimization, this single element causes 0.21dB effective power loss and a 2.6% PAE drop.

DC bias feed lines at amplifier in- and output are of quarter wavelength type and are also used to optimize impedance matching. Due to their length, they are distributed over six conductor layers.

Similar solutions are available up to C-band. For frequencies at X-band and higher GaN-MMICs with on-chip matching will be the preferred choice and the LTCC package complexity is reduced to DC biasing and 50Ohm RF ports. Nevertheless the constant wire length wire-bonding technique (see the converter designs below) supports RF performance.

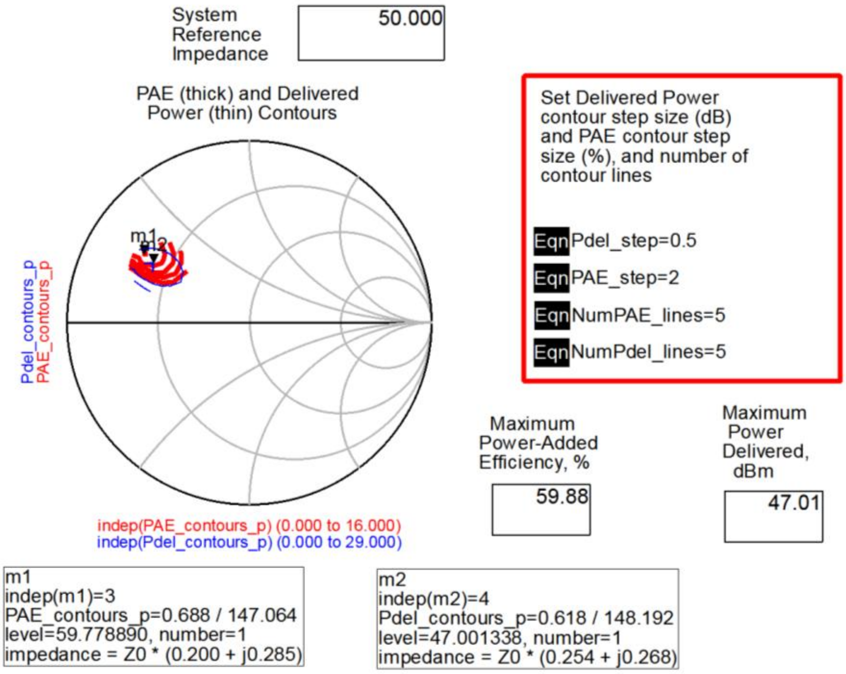


Power [dBm]													
Value	46,59		46,58		46,58		46,57		46,41		46,20		46,16
Delta		0,01		0,00		0,01		0,16		0,21		0,04	

PAE [%]													
Value	59,4		59,3		59,2		59,1		56,9		54,3		53,8
Delta		0,1		0,1		0,1		2,2		2,6		0,5	

Fig. 5: Output network analysis on effective power losses and PAE

Fig. 6 depicts load-pull calculations, contours of constant PAE and constant delivered output power. Benchmarks are 59% power added efficiency (PAE) at 47dBm output power.



Eqn Pdel_step=0.5
Eqn PAE_step=2
Eqn NumPAE_lines=5
Eqn NumPdel_lines=5

m1
indep(m1)=3
PAE_contours_p=0.688 / 147.064
level=59.778890, number=1
impedance = Z0 * (0.200 + j0.285)

m2
indep(m2)=4
Pdel_contours_p=0.618 / 148.192
level=47.001338, number=1
impedance = Z0 * (0.254 + j0.268)

Fig. 6: Load-pull calculation for 12mm GaN HEMT

Characteristic elements of this design are 22pF (input) and 90pF (output, see left part of Fig. 8) multilayer microwave capacitors, a buried high current inductor (see right part of Fig. 8) and a 0.7Ohm stability resistor in series to the gate terminal of the GaN power bar. This size and type of capacitor can only be realized in multilayer substrate technology. These impedance matching capacitors act as DC blocking capacitor as well.

The 0.7Ohm resistor, as close as possible to the HEMT's gate has very low series inductance and is of highest importance for amplifier stability but should not consume too much gain on the other hand. LTCC technology is predestined for such solutions.

Fig. 9 depicts the complete assembly of a LTCC-multilayer package. The hermetic cavity contains vertical layer DC blocking capacitors (100V working voltage for GaN) as well as a MEMS pressure sensor die.

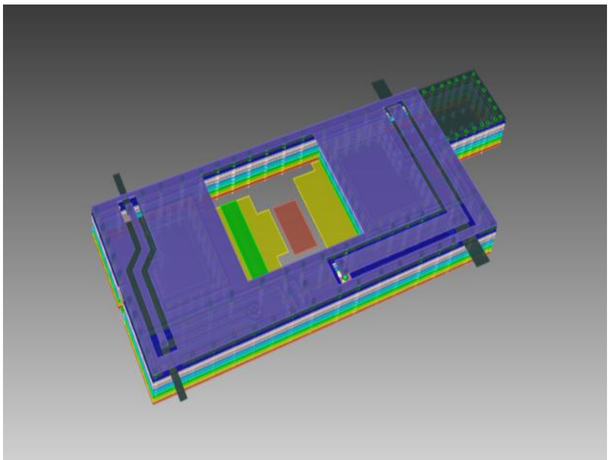


Fig. 7: Complete LTCC 3D model

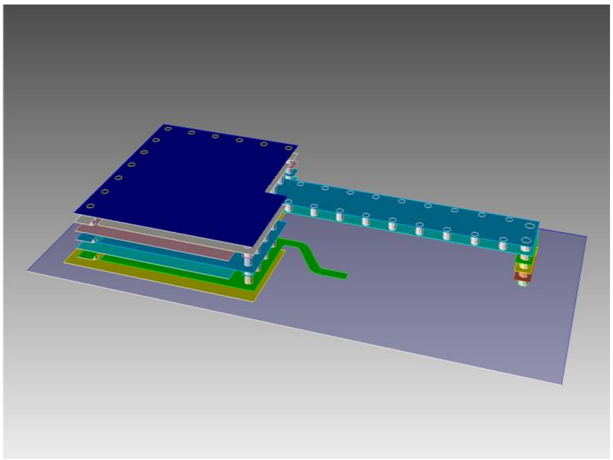


Fig. 8: Output impedance matching
(series C and shunt L)

These three elements are the only remaining components on the multilayer which are not integrated within the LTCC substrate. Besides the two RF ports the LTCC package contains hermetic lead-through terminals for gate and drain as well as for the required pressure sensor connectivity.

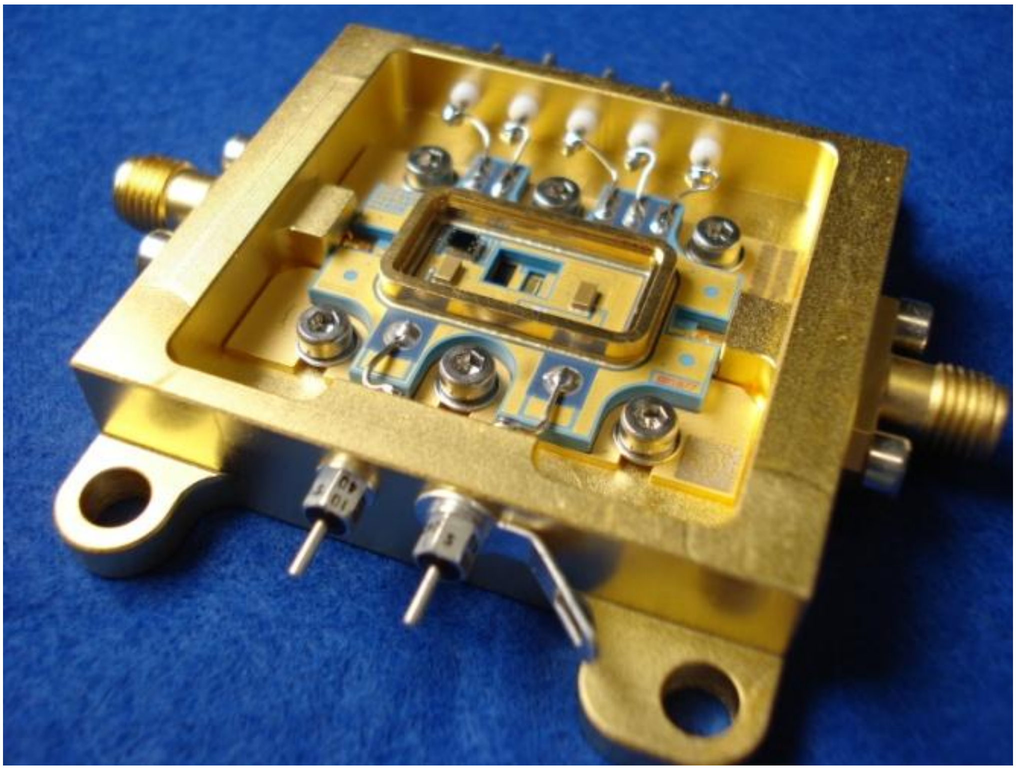


Fig. 9: 40W GaN SSPA Building Block

Pressure Decay Leakage Test Method

RF hermetic cavity pressure monitoring is a new technique to replace tracer gas leakage testing (TESAT patent pending). Using a conventional tracer gas system would suffer from gas deposition/desorption at undesired locations outside the hermetic cavity. This is especially the case for Multi Chip Modules (MCM) and RF Systems in Package (RF-SiP) having complex mechanics and electronics outside the hermetic chamber.
The new leakage test method eliminates the disadvantages of tracer gas methods and allows reliable measurements with respect to the new MIL-STD883J, class S, K and V (level space). This new requirement is by two decades tougher than for military applications. See Fig. 9, Fig. 11, Fig. 15 and Fig. 22 for integration of the MEMS pressure sensor die.

KA-BAND LOW NOISE DOWN-CONVERTER

A 27-31GHz frequency down-converter (see Fig. 10 and Fig. 11) has been realized using an integrated stripline to rectangular waveguide transition at the input port of the low noise amplifier within the LTCC substrate (see Fig. 11 and Fig. 12). The stripline to waveguide transition is a really characteristic example of what LTCC based buried microwave technology can carry out. Other buried elements are couplers and an integrated IF filter. DC circuitry is attached to a NiPdAu plated wire-bondable printed cicuit board (PCB). The PCB allows to implement DC-circuitry which doesn’t make sense in chip & wire. Main purpose of the PCB is to provide an interface between LTCC and a DC-connector. Actually there is no space qualified solution available for a DC-connector mounted on top of the hermetic LTCC hybrid package which can withstand 800 temperature cycles from -55°C...+125°C.

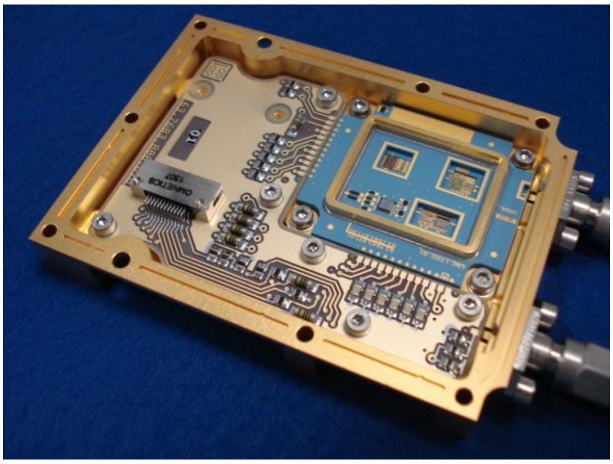


Fig. 10: 27-31GHz low noise down-converter (1)

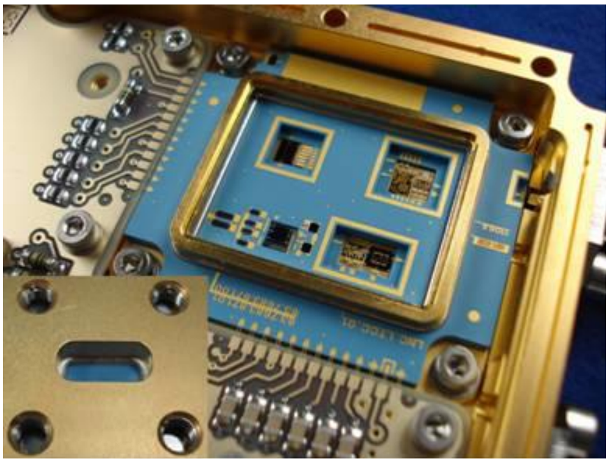


Fig. 11: 27-31GHz low noise down-converter (2)

Insertion loss of applied stripline to waveguide transition is 0.65dB. Measured residual noise figure is better than 3dB, see Fig. 13. Payback of the quite high input loss value is a robust, reliable and cost effective manufacturability. Within the LTCC substrate this RF transition is for free.

Substrate space above can be used for DC-circuitry or as location of the MEMS pressure sensor die. Fig. 15 shows the integrated MEMS pressure sensor for leakage test. Its connectivity is provided through 4 hermetic LTCC terminals, fed over wire-bonds to the PCB and an Omnetics DC-connector for cable connection to the automatic leakage test station.

Another design highlight is a wire-bondable K-connector. It is used here as a 9GHz local oscillator input (see Fig. 14). The same design is applied within described frequency up-converter (see Fig. 22) up to 30GHz. A K-connector with air dielectric is not wire-bondable by nature. The TESAT approach is to apply a defined adhesive under-fill using a non-conductive glue with specified dielectric properties. This automatically dispensed adhesive depot stabilizes the inner conductor of the K-connector against rotation and vibration. Thus the connector pin is wire-bondable. This under-fill provides electrically a small capacitance to ground. This capacitance, the inductance of the bond-wire in series and the bond-pad on the LTCC side (capacitance to ground) build a C-L-C low pass filter. This filter has a corner frequency of roughly 40GHz using 500µm wire-length and allows dedicated large gaps at reasonable long wires. The feature is under control of the wire-bonder. The machine applies a constant wire length (CWL) after pattern recognition of both “pads” to be interconnected. Those interconnects provide an excellent wideband return loss.

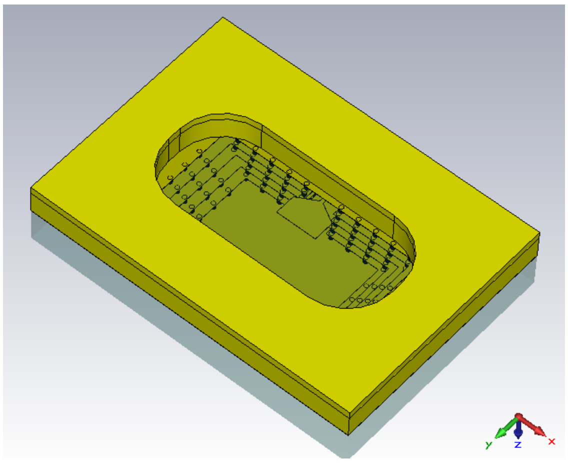


Fig. 12: Strip-line to waveguide model as generated in CST "Microwave Studio"

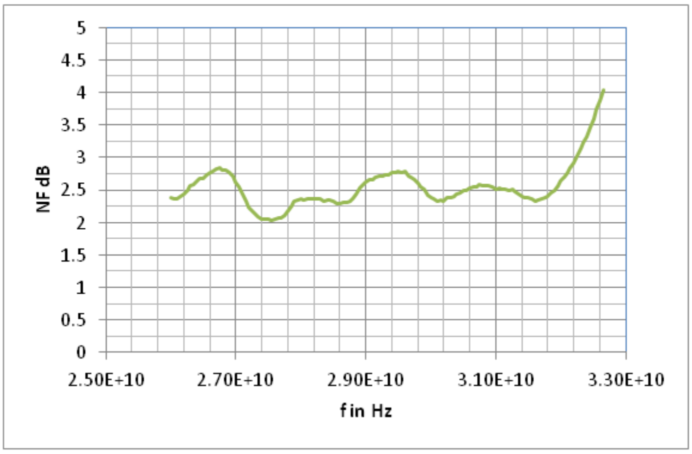


Fig. 13: Noise figure measurement of the low noise down-converter

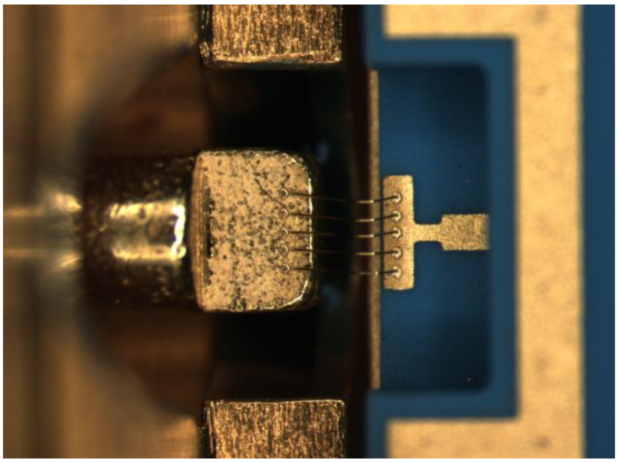


Fig. 14: K-connector with adhesive under-fill

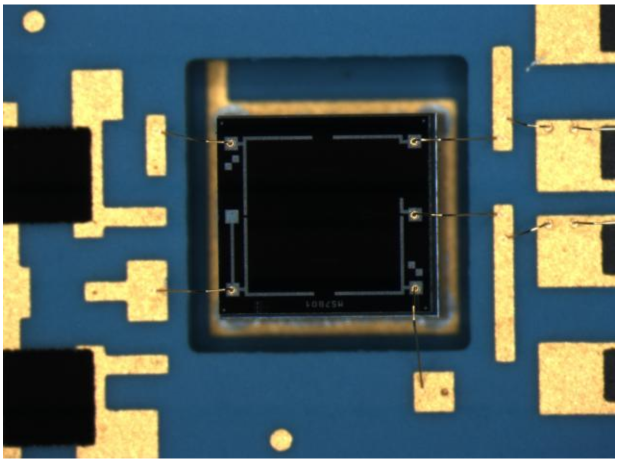


Fig. 15: MEMS pressure sensor die in LTCC pocket

25-27.5GHZ UP-CONVERTER FOR A HIGH DATARATE WIDEBAND MODULATOR

This development (see Fig. 22) re-uses the LTCC substrate pocket and window technology as of the frequency down-converter. Thus the GaAs-MMICs are directly mounted onto a Molybdenum heat-sink. As for all other RF-SiPs at TESAT, the LTCC hybrid applies a MEMS pressure sensor die for hermetic cavity pressure monitoring.

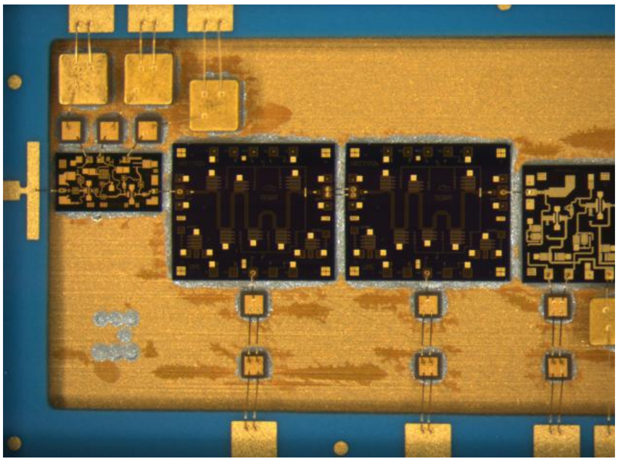


Fig. 16: Ka-band UpCon - LO chain input section

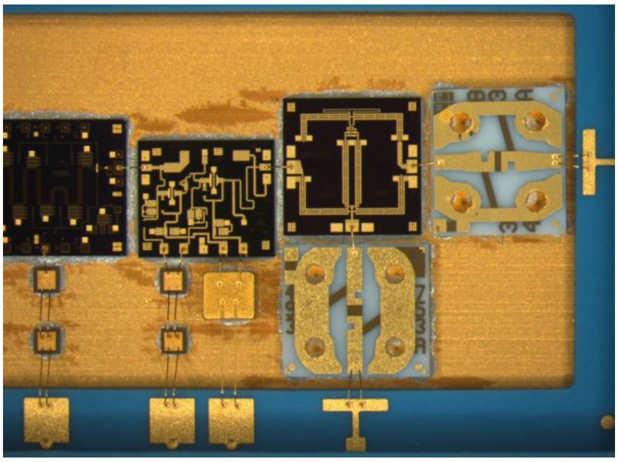


Fig. 17: Ka-band UpCon - mixer section

Fig. 16 and Fig. 17 depict the LO & mixer chain. The intermediate frequency (IF) input signal of the frequency converter (centre connector of Fig. 22) is an X-band high data rate modulator signal. The LO signal is doubled in frequency, amplified and fed into a GaAs mixer. All MMICs are TESAT foundry designs except the frequency doubler (UMS design). Small thin-film attenuators are applied in order to improve circuit matching and to decrease wideband ripple. DC blocking is performed using 100pF border caps (standard RF blocking capacitor) as well as 10nF vertical layer caps (standard DC blocking capacitor).

LTCC pockets can be closed by adhesive attached thin gold plated Kovar shims, so-called pocket lids. The lids have a small ventilation hole in order to assure an efficient vacuum bake before sealing. The application of such lids depends on specific design and related requirements. They may be used for extreme shielding above values as mentioned within the introduction chapter.

Fig. 18 and Fig. 19 describe two more examples for buried microwave structures within the LTCC-multilayer substrate. Fig. 18 shows a buried band-pass filter between LO/mixer pocket and RF amplifier pocket which suppresses LO and IF signals. Fig. 19 depicts a RF output signal coupler which uses several substrate layers. The coupled line feeds an output signal probe towards the detector MMIC pocket (see the very right pocket of Fig. 22). The other coupled port is terminated by a thin-film absorber on aluminium-nitride located outside the hermetic chamber.

Sometimes thin-film terminations make more sense than LTCC terminations due to their higher resistor accuracy and performance. This depends on specification requirements of the RF system. Nevertheless this hybrid contains roughly 20 buried resistors where higher tolerances can be accepted. Those can for instance be ESD grounding resistors, gate series resistors or voltage dividers using the same paste for both resistors. Resistive loading of long DC lines is possible as well.

The pictures below show the 25-27.5GHz RF output path (see Fig. 20) and the RF output power level detector (see Fig. 21). Source for the detector is a buried microwave coupler depicted in Fig. 19. The detector MMIC is a re-used component out of a level-controlled TESAT channel amplifier design.

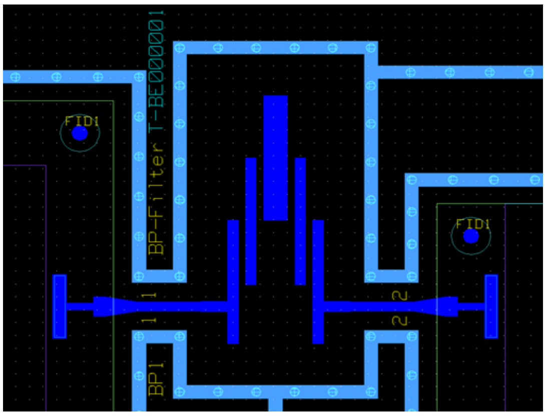


Fig. 18: Buried 27-31GHz band-pass filter

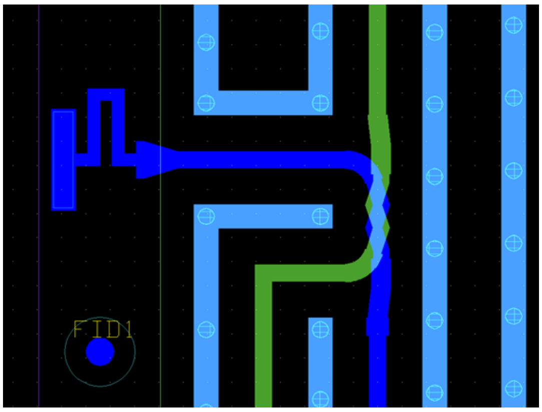


Fig. 19: RF output coupler to level detector pocket

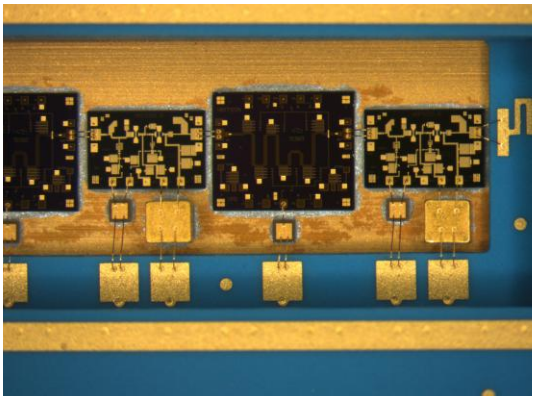


Fig. 20: Ka-band UpCon – RF output section (1)

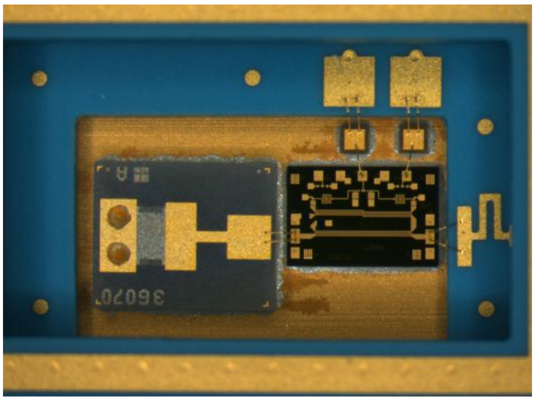


Fig. 21: Ka-band UpCon – RF signal level detector

OTHER TECHNOLOGY ASPECTS

Heat-sink, Kovar frame as well as Kovar lid are thin gold plated. Standard plating thickness for the frame is 0.5…1µm gold and for the lid 200-300nm gold. The Kovar frames originally have been partially gold plated. The partial plating process has either been performed by adding or removing gold. Both processes require mask resists. However, the frame suffered under mask resist residues which has often limited the performance of the package brazing process (solder wetting).
The lid is now also gold plated in order to laser-engrave data-matrix code, clear text and company logo. This process removes the thin gold only and the Nickel plating remains as protection against corrosion. Such laser engraving provides good contrast, especially for data-matrix code readers.

Sealing is performed by laser-welding through the thin Au plating. A remarkable gold content within the Kovar melt cannot be detected using EDX analyses. This has been proven by micro-sections.

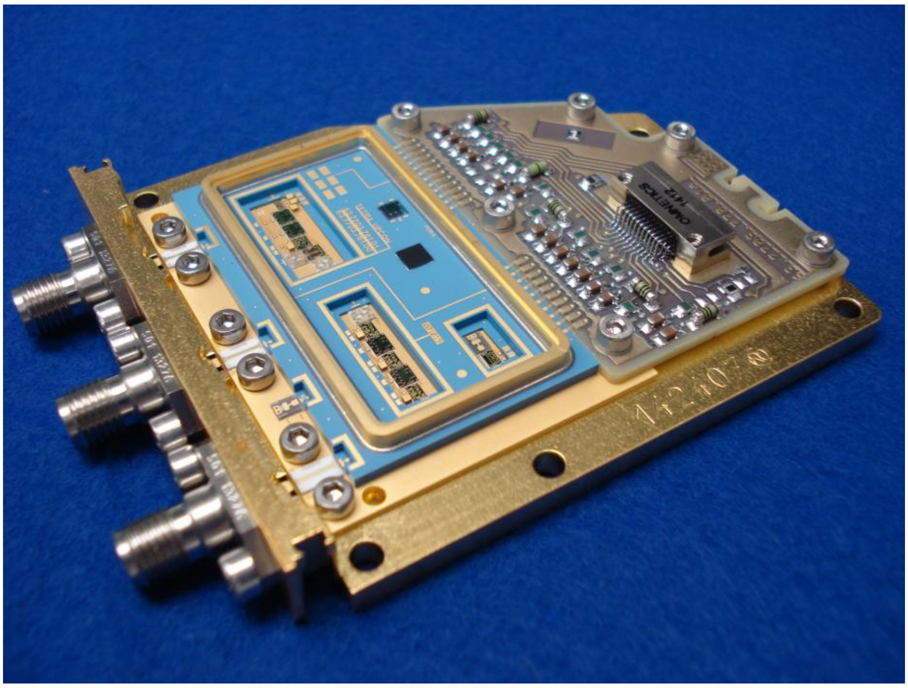


Fig. 22: Ka-band frequency up-converter (27-31GHz) for a wideband telemetry transmitter

CONCLUSION

This publication describes a couple of applications using buried microwave technology in high density integrated RF-SiPs. The drivers for high density integration of future space hybrids are reduced size, weight and cost. TESAT is going to re-use the available high process reliability, the related automation and the applied methodology - as developed and installed for series production of more than 65.000 LTCC-multilayer hybrids for terrestrial telecommunication - for space applications at low quantities but highest quality requirements.

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