RF Modules (Tx–Rx) with Multifunctional MMICs

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Abstract — Next generation RF sensor modules for multi-function active electronically steered antenna (AESA) systems will need a combination of different operating modes, such as radar, electronic warfare (EW) functionalities and communications/datalinks within the same antenna frontend. They typically operate in C-Band, X-Band and Ku-Band and imply a bandwidth requirement of more than 10 GHz. For the realisation of modern active electronically steered antennas, the transmit/receive (T/R) modules have to match strict geometry demands. A major challenge for these future multifunction RF sensor modules is dictated by the half-wavelength antenna grid spacing, that limits the physical channel width to < 12 mm or even less, depending on the highest frequency of operation with accordant beam pointing requirements. A promising solution to overcome these geometry demands is the reduction of the total monolithic microwave integrated circuit (MMIC) chip area, achieved by integrating individual RF functionalities, which are commonly achieved through individual integrated circuits (ICs), into new multifunctional (MFC) MMICs. Various concepts, some of them already implemented, towards next generation RF sensor modules will be discussed and explained in this work.

Keywords—Multifunctional (MFC) MMIC; GaN; Si/SiGe BiCMOS; T/R Module (TRM); Multilayer ceramic (MLC, LTCC, HTCC); MMIC packaging; Tile array;

I. INTRODUCTION

T/R modules (TRM) are key building blocks for modern phased arrays with active electronically steered antennas (AESA). Often hundreds or even thousands of TRMs are used in different platforms, like airborne fighter nose radars, satellite based synthetic aperture radar (SAR) antennas or ground surveillance and security radars [1]. As a typical example, Fig.1 shows the SMTR®, a standardized modular X-Band T/R module developed at Hensoldt during the last decade, which is employed in many applications since then.

Fig. 1. SMTR® Module

In the SMTR, all receive-, transmit- and low-power-functions are realized with single GaAs- and Si-MMICs. A three-port-circulator routes the signal from the module's transmit path to the antenna (Tx mode), from the antenna to the module's receive path (Rx mode) and additionally isolates both directions. This T/R module uses the chip&wire technology on an LTCC based multilayer package with a soldered baseplate and frame. A final laser welding process of a lid onto the frame ensures a hermetic isolation of the single channel TRM.

Looking at military phased array radar systems, detailed cost figures of the main segments are indicating that the *phased array* antenna accounts for nearly 50% of the cost, whereas remaining segments like the segment-units *processor*, the *receiver/exciter* and *mechanical/thermal* issues filling up the other 50%. Observing the cost distribution for the phased array antenna itself, the *T/R modules* cover more than 45% cost, whereas s*tructure, sssembly/test* and *RF boards/cabling* determine the residual cost [2].

Two main options allowing a decrease of TR module cost in future are identified here:

(1) The reduction of the total active chip/MMIC area, representing the main cost driver of TR modules, and (2) the use of packaged MMICs in low-cost commercially available quad flat no lead (QFN) packages for assembly on RF printed circuit boards (PCBs).

It is quite evident that the applicability of these options depend on the target application (airborne/space vs. ground/naval). Within the last years, the development of disruptive semiconductor technologies like GaN and Si/SiGe BiCMOS has reached a high level of performance that enables the replacement of GaAs based components in future RF modules. The key characteristics of GaN based components and MMICs, compared to GaAs, are an increased power density, higher supply voltages (up to 50V) and an impressive robustness. This allows not only the design of small size high output power amplifiers, it also enables the realisation of compact high power handling RF switches, thus making the bulky circulator obsolete.

Furthermore, with SiGe/BiCMOS technologies, much higher levels of integration are possible. Combining RF control functions (e.g. phase-shifting, amplitude control and low power RF switching) with the control logic for the complete T/R-module, the chip and hence the module size can greatly be reduced.

A block diagram (artist´s view) in Fig. 2 shows an arrangement for a new generation of RF modules.

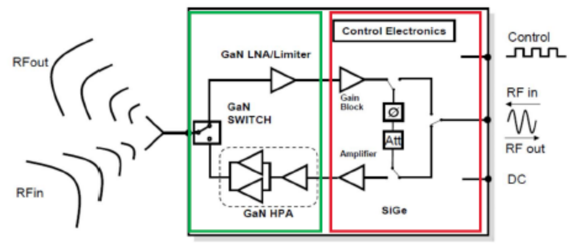

Fig. 2. 2-chip arrangement (RF module)

Following the world-wide challenges in technology trends of SWAP-C (i.e. lower size, weight, power and cost), this arrangement minimizes the number of MMICs to one GaN-Frontend-MMIC (green frame) and one SiGe-MMIC (red frame).

Within the GaN-part, all TRM frontend functionalities (HPA, LNA, Switch) are integrated into one single MMIC. Within the SiGe-part, the RF control components (i.e. phaseshifter and variable attenuators, T/R switch) and all digital functions such as e.g. a two wire control interface are integrated into another single SiGe/BiCMOS MMIC.

Focusing on the lower size demand, one approach (as shown above) is to integrate more electrical functions into one MMIC, such that the amount of components will be reduced. These compact MFC MMICs can then be mounted on substrates resp. packages with high routing densities, as e.g. the case in LTCC-based approaches, which in turn allows to design very compact T/R modules. Further, these MFC MMICs can be put into packages and assembled by surface mount techniques (SMTs) on low cost PCBs in high volume assembly lines. These approaches can be done both in the so called brick-style architecture (module orientation perpendicular to the antenna plane), an SMD based slat array or plank configuration or a modern AESA tile array approach with the module orientation parallel to the antenna surface [2].

II. MFC MMIC BASED RF MODULES

This chapter describes various approaches for next generation RF modules based on multifunctional MMICs.

A. Compact dual polarization X-Band T/R module

This type of module will allow a simultaneous operation in Tx and Rx with 2 polarisation modes, e.g. H- (horizontal) and V- (vertical) polarisation. An excellent linear and circular performance can be achieved by nearly identical RF performances of both TRM channels. Furthermore, single, dual and even quad-polarisation operational modes are enabled by such an arrangement.

The combination of a custom designed GaN based single-chip frontend MMIC with a size of less than 13mm² [3] in combination with a compact Si/SiGe BiCMOS based core chip [4], allows the design and realization of a compact dual polarisation T/R module even within the geometry demands of a half-wavelength grid at X-Band frequencies. Fig.3 shows the schematic overview of the dual polarisation module.

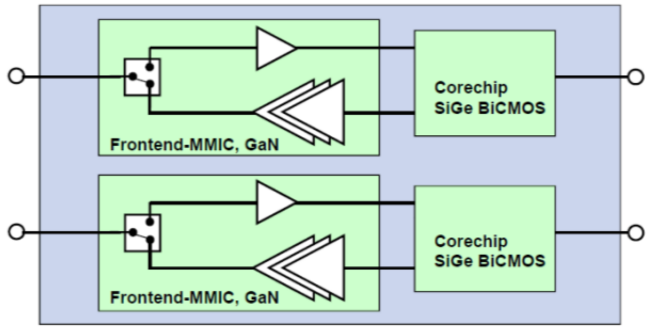

Fig. 3. Schematic overview of a dual polarisation module

This type of module can be realized with the mentioned MFC MMICs assembled on a multilayer LTCC enabling highest density of RF, control and supply routing.

Due to GaN's superior physical properties and the large thermal conductivity of the SiC-substrate, power densities five times higher than in GaAs technologies can be achieved by GaN-devices. However, this increased power density and dissipation demands for optimized chip assembly techniques.

Hensoldt therefore developed the following two-step approach for assembling MFC GaN MMICs:

(1) The MFC MMICs are mounted on a coefficient of thermal expansion (CTE) matched CuW heatsink with an optimized, pressure-less, automatic silver based sintering process. Based on detailed X-ray inspections, a high quality of the MMIC/heatsink-interface was confirmed.

(2) This so-called drop-in is soldered with AuSn into a cavity of the LTCC, which in turn is mounted directly on a metal baseplate that spreads the dissipated heat of the drop-in. As a final step, all required RF- and DC-interconnects of the MMIC are realized using wire bonds.

B. TRM multipack baseline for wideband applications

Wideband T/R modules for multifunctional AESA systems shall operate in different modes and dedicated frequency bands, e.g. radar in C- and X-band, data-link in Ku-band and jamming resp. sensing (EW) in a frequency range covering almost DC to 20GHz. So, a main challenge is the very high bandwidth of more than 10 GHz to be covered, whereas the highest frequency determines the AESA maximum allowed grid spacing. This immediately shows that the geometry of a classic circulator working at the lowest frequency within the required band cannot be harmonized with the wideband grid requirement. Hence, the replacement of circulators by compact GaN based RF switches becomes inevitable.

A wideband multipack partitioning design approach is shown in Fig. 4.

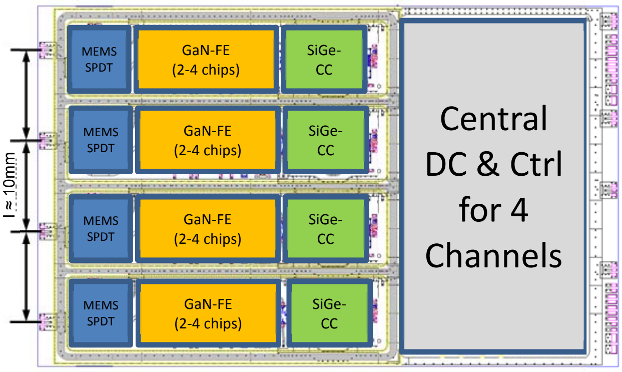

Fig. 4. Wideband multipack partitioning design approach

The main challenge to realise the wideband T/R channels suitable to the antenna grid (here about 10 mm) is overcome by a quadpack approach. With a standard arrangement of single modules with separate frames, the remaining space for placing chips and wire bonds would be sufficient. Therefore, an arrangement of four channels into one common module has been identified as a sensible trade-off between size constraint and the inherent multipack drawbacks with regard to flexibility in antenna size (four is the smallest unit) and production yield (if one channel fails four are rejected). Omitting frames was not an option for the RF part as channel crosstalk and coupling have to be kept as low as possible. As for the DC and control part, the channel separation is not an issue as combining digital functions for multiple channels into common control devices minimizes the required the area of these functions.

III. Tile Array Architecture

Low weight 2D antenna arrays with shallow installation depths are of steady growing interest e.g. for systems to be installed on unmanned aerial vehicles UAVs. Such requirement can be met with tile modules, where the module resp. the mounting layer(s) are orientated in parallel to the antenna surface. In such approach, all components of a TR channel have to be arranged and interconnected within an area of the squared antenna grid.

The corresponding half-wavelength (i.e. the antenna grid for a full array) geometry vs. frequency is shown in Fig. 5.

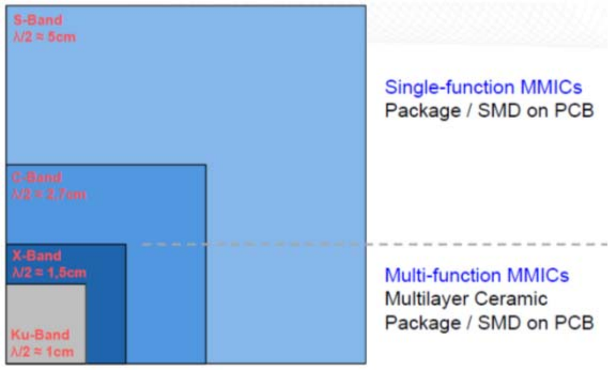

Fig. 5. Corresponding half-wavelength vs. frequency; geometry needs for 2D AESA

For S- and C-Band applications, the resulting grid geometry may allow design and manufacturing processes of tile arrays with packaged single function components on PCBs using one mounting layer. An accordant approach in X-band or above requires the use of several (stacked) mounting layers, bare dies, highly integrated MFCs or even a combination of it.

In 2005, R. Rieger et al. presented an X-band T/R module to be used in a tile array configuration [5]. This cubic module was built of three specific multilayer HTCC-substrates including cavities and offering four mounting layers. All single function GaAs MMICs (HPA, driver-amplifier, LNA, RF control) and the circulator were pre-assembled and tested on single-layer level. All multilayer substrates were soldered onto each other, resulting in a single-channel TRM. On top of the final multilayer, a patch antenna could be realised. Like illustrated in Fig. 6, these cubic modules can be arranged on a flat signal distribution baseplate or even on a shaped board structure to build a conformal array.

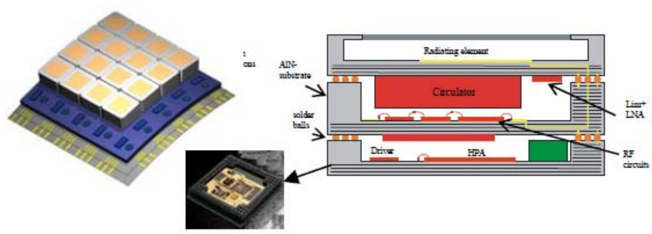

Fig.6. Cubic T/R modules with HTCC package for tile arrays

In [6], Leonardo UK demonstrated for an airborne X-Band application a similar module approach with an LTCC package containing bare dies on (at least) two mounting layers. On the backside of the hermetically sealed LTCC package, there is a ball grid arrays (BGA)-interface via which these TRMs can be mounted onto a multilayer PCB which contains the manifolds (DC, RF and control), provides the cooling channels and on the opposite side exhibits the patch antennas.

A 2-chip TRM approach with our previously shown MFC MMICs will allow similar compact tile arrays. With the scheme shown in Fig.7, the bare die MMICs can be assembled in one mounting layer of the multilayer substrate (LTCC or HTCC).

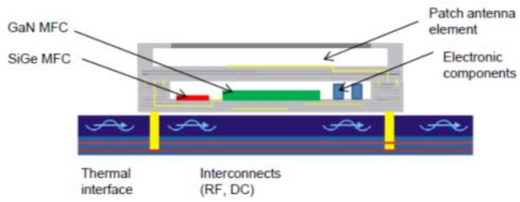

Fig.7. Flat tile array with MFC MMICs

The arrangement onto a distribution manifold, e.g. a PCB with an integrated cooling layer (thick cupper) and integrated connectors for RF and DC can be assembled with single TRM devices or with multipack TRMs into a higher level “tile” forming an x by y-array (e.g. 2x2, 4x4, 8x4, …) with the advantage that these arrays will be scalable. Hence, application- and geometry-specific tile AESA arrays can be realised.

Plastic QFN packaged devices for commercial, high volume SMD assemblies form a key factor for lower cost products, mainly in fields of RF applications. MACOM demonstrated an impressive example with its multifunction phased array radar (MPAR) working in S-Band [7]. In this approach, 64 T/R-modules with a land grid array (LGA)-interface are integrated together with PCBs and housed into an 8x8 antenna panel which forms a line-replaceable unit of a bigger antenna.

With regard to higher frequencies, today various vendors are visible on the market, e.g. ANOKIWAVE and RFcore, who are offering specific SMD-components for AESA applications in X- and even in Ku-Band. Besides GaAs- or GaN-based front-end MMICs, 4-channel SiGe core chips are available in QFN-packages, here.

Furthermore, upcoming activities inside Hensoldt will cover GaN- and SiGe- MFC packaging activities.

The integration of accordant SMD devices (RF MFC plus standard circuitry as resistors, capacitances etc.) will be done onto a so called integrated T/R active zone (3-D stack) as part of the multilayer PCB tile (see Fig. 8.).

Fig.8. Tile array concept with packaged MFC MMICs

IV. Conclusions

Based on highly integrated, multifunctional MMICs, a new generation of compact transmit-receive modules was presented in this paper. All TRM frontend functionalities (HPA, LNA, Switch) are realized in one GaN/SiC MFC MMIC, the RF control components and digital functions are integrated in another Si/SiGe BiCMOS MFC MMIC.

MFC based RF modules are key building blocks for future multifunction AESA systems and will allow to increase additional system functionality due to a high level of miniaturisation. The design approach for a dual polarization X-Band T/R module and a wideband TRM multipack was described. These high-end modules are based on chip&wire technology and for typical airborne/space applications the housing and package will be hermetically sealed.

QFN packaged MFC MMICs will enable an arrangement and interconnection within the frequency dependent grid area of tile array architectures, up to higher frequency bands, such as X- and Ku-Band. In combination with standard RF substrate materials, this approach provides a cost-effective solution for RF sub-systems.

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