EXPERIENCE AND PROPECTIVE OF MMIC'S FOR SPACE PROGRAMES

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THE EVOLUTION OF SPACE INDUSTRY:

Until now the satellite market have been driven by geo-stationary telecom payloads. For such an application, a typical number of produced satellites was 3 to 4. Consequently, for a given program, the production of identical equipment was limited to few tens.

The emerging market of multimedia services by satellite is drastically changing this status. In order to minimise the communication delays between users and gateways, those services will largely be based on Low Earth Orbit (LEO) satellite constellations. To provide a global earth coverage, these constellations actually need a large number of satellites. For example, SKYBRIDGE is based on a 64 and TELEDESIC on a 288 satellites constellation. Table 1 gives the main figures for the some announced programs.

System	*Iridium*	*Globalstar*	*ICO*	*Teledesic*	*SkyBridge*
Companies	**Motorola** Lockheed M, ...	**Loral** Alcatel, Alenia, Mitsubishi Hyundaï	**ICO** (Inmarsat) Hughes, TRW ...	**B.Gates,** C.Mc, Caw, Boeing, Hughes,MMS Motorola...	**Alcatel** Aerospatiale Loral, Sharp Mitsubishi Toshiba, SPAR
Services	Mobile Com	Mobile Com	Mobile Com	Multimedia	Multimedia
Orbit	LEO (780 Km)	LEO (1400 Km)	ICO (10300 Km)	LEO (1400 Km)	LEO (1450 Km)
Frequencies	Ka / L	C / L,S	C / L,S	Ka	Ku / Ka
Inter-Sat.Link	Ka	No	No	Ka	No
Number of Satellites	66	48	12	288 (Prev:840)	64
Start Date	1997/98	1998	2000	2003	2001

A trivial problem is associated with the launch : in order to keep with an affordable cost, the satellites will have to be launched by groups. Then, their mass and size have to be minimised. These constraints are, of course, directly impacting the RF equipment that constitutes the payload of the satellite. RF equipment for multimedia services by satellite have to be small, light and designed for an high volume production at low cost.

ALCATEL SPACE has done a first step in accordance with this evolution through its participation in GLOBALSTAR. For this program about 900 models of C-Band to S-Band down-converters (Fig. 1) have been produced which corresponds to the use of more than 5000 MMICs.

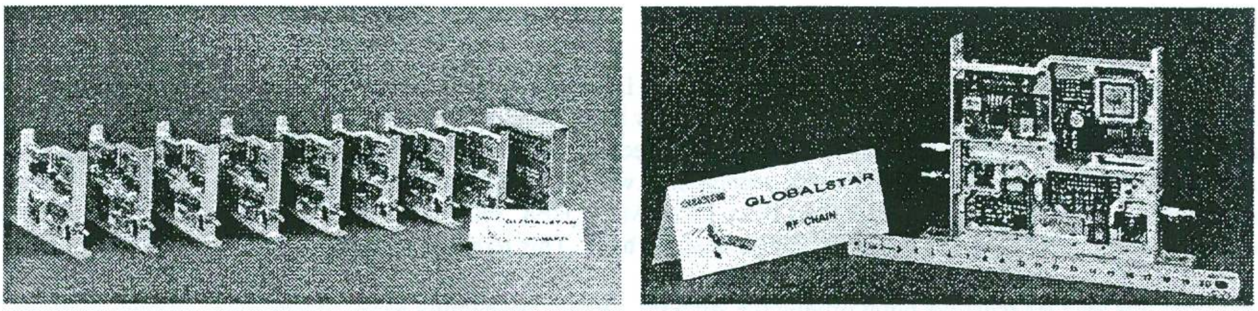

Figure 1 : Globalstar C/S Converter.

A second step must be done to be able to comply with the SKYBRIDGE challenge depicted above. And beyond SKYBRIDGE, a second generation of multimedia dedicated programs is already imagined, including certainly the last emerging component which are blossoming by now.

PACKAGING IS A KEY ISSUE

In the past twenty years a considerable amount of work has been done on microwave circuit integration, mainly using GaAs material. MMICs were finally introduced to the space-borne equipment in the early 90s. They are now clearly unavoidable and many systems are presently in operation with GaAs chips on board [1]. Now, with the maturity of MMIC, everyone agrees that packaging is the key issue. Micro-packages favoured the penetration of MMIC space systems (Fig. 2). They brought hermeticity, modularity, testability that were necessary for assessing their ability to respect space constraints.

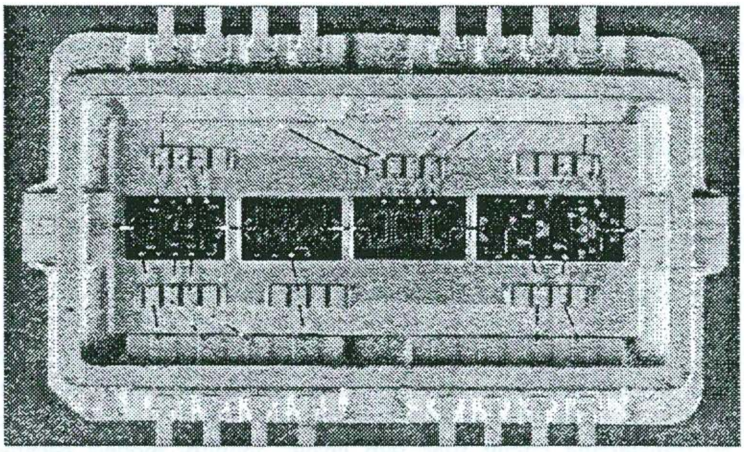

Figure 2 : MMICs in micro-package

Current efforts are now with MCM-C technology. Our choice is based on a high temperature co-fired multilayer ceramic substrate with hermetic areas. All components, including GaAs MMICs and Si ASICs, are employed in bare die form. Connections between RF cavities are made with ceramic feed troughs [2]. A MCM Channel Amplifier (CAMP) has been developed at Ku-Band and is presented on Fig. 3. With this new packaging technology a factor of about 2 in mass reduction is obtained compared with the previous micro-package solution [3].

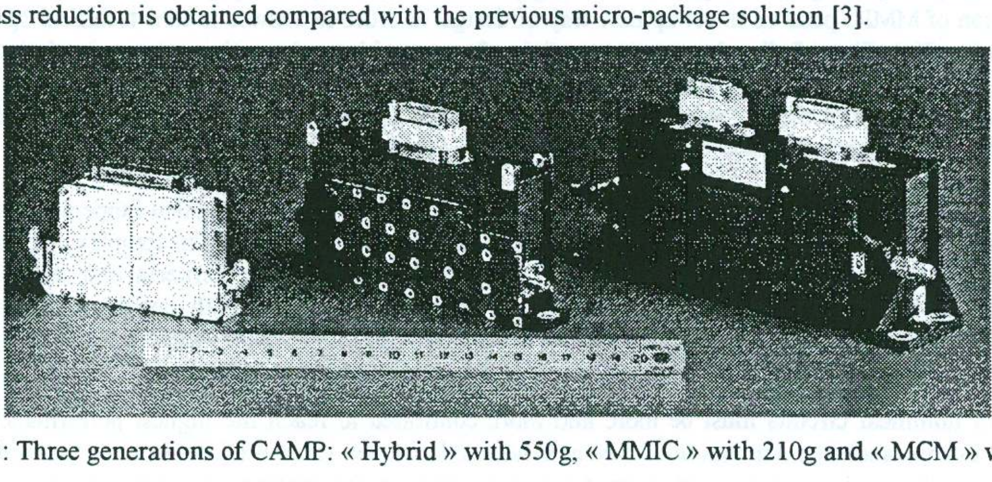

Figure 3: Three generations of CAMP: « Hybrid » with 550g, « MMIC » with 210g and « MCM » with 95g.

EXPERIENCE IN MMIC DESIGN

A very aggressive policy has been set up in the early 90s to introduce MMIC in space equipment. The first step was to choose preferred suppliers able to produce high quality low level or power MMICs up to Ku band even if the required quantities were not so important. MMIC processes have been formally space qualified [4] following the methodology proposed by French Administration [5]. The second step was to develop MMICs as "building blocks", families of generic simple circuits were designed (Gain Bloc, LNA, MPA, HPA, Phase Shifter, Flatness Correctors, multipliers, mixers, oscillators, etc...) [6-12] mainly in C band and Ku band. This represented more than 100 different MMICs.

Cycle time was another sensitive point driving the strategy. In fact, developing MMIC takes time : design, fabrication and test. A one year cycle time is required for a given project with several MMIC while same time frame is necessary for developing equipment. This is an other reason why component families were developed and became available "on the shelves". Figure 4 shows an example of single balanced mixer family developed in LEMMIC. Same topology is used but each one is optimised in the appropriate bandwidth.

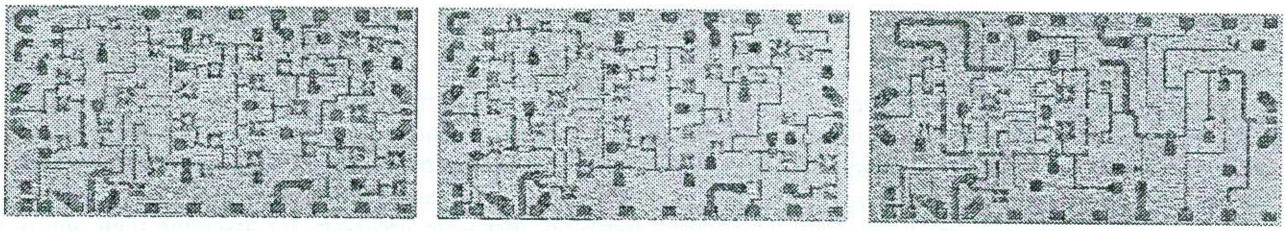

Figure 4: Example of mixers family developed by LEMMIC in C, X and Ku band.

These functions families have been used by assembling to design equipment for classical telecom payloads[3]:

- RECEIVERS transposing input frequencies down to output frequencies (6/4 GHz, 14/ 12 GHz)
- CHANNEL AMPLIFIERS (CAMP) adjusting the gain (with Automatic Level Control)
- LINEARIZERS to correct the non linear effects of power amplifications
- SOLID STATE POWER AMPLIFIERS (SSPA)
- TTC (Telemetry, Tracking and Command) receivers and transmitters

All these MMICs correspond to the first generation. They have been developed using commercial software: on one hand a microwave simulator (linear simulations : gain, return losses, NF and first order in non linear behaviour: conversion losses and P1dB) and on the other hand a drawing software to make the layout. But this way had some limitations: error risks by transferring circuit files into layout, foundry models became not accurate enough to simulate, limitations in active device size, coupling effect between elements, inadequate to predict second order non linear effects (Inter-modulation, spurious etc...), stability etc...

NEW CONCEPTS IN THE DESIGN AND EVOLUTION:

Even if "design yield" was good and gave us a strong position to make space equipment with MMIC, moving to the new generation of MMIC push us to set up new way of design in order to answer to new technical specifications and new frequencies (Ka). First of all only one commercial software making schematic capture, simulation, optimisation, layout up to reticule generation were used completely avoiding errors and mistakes. A strong effort in modelling [13] associated with the state of the art pulsed characterisation from University of Limoges in France, gave us accurate active models independently of foundries.

Circuit stability even if it is essential is often occulted. Method based on K factor is often inoperative because of multi - loop ways especially in very large power amplifiers , or with common bias circuitry in complex circuits. Taking one's inspiration from theory of the closed loop systems from Bode and Nyquist's criteria and following Plastzker's recommendations [14], a rigorous method determining the number of poles with positive real part (Normalised Determinant Function) has been set up with commercial software and allows us to evaluate potential instability of any kind of circuit [15] and to correct it by placing element in the efficient position with the right value.

The design of nonlinear circuits must be more and more controlled to reach the highest performances with a good design yield. For instance, the simulation of mixers is now well known. Commercial harmonic balance simulators are able to compute the mixing process with a good accuracy. But, on the contrary, 2 years ago, there was no general methodology, dedicated to mixer design, which can be directly used with commercial softwares for all types of mixers. The main reason is probably that mixers involve simultaneously a great number of frequencies. The mixing phenomenon produces not only the useful IF intermediate frequency (f_{LO}-f_{RF}) but also numerous spurious frequencies as $nf_{LO}\pm mf_{RF}$ products. The mixer conversion loss, at the nonlinear device ports, depends on the RF and IF loads, but also on the loads at these unwanted mixing frequencies.

The idea of the Statistical Load Pull [16] is then to make the spurious frequency loads vary at random in a practical impedance range, following a uniform statistical law (Fig. 5). This approach leads to a quite general view of the mixing performances which can be obtained with the studied nonlinear device. The Statistical Load can be directly implemented on a commercial circuit simulator and applied to other nonlinear phenomenon involving a great number of frequencies like the inter-modulation or the frequency multiplication.

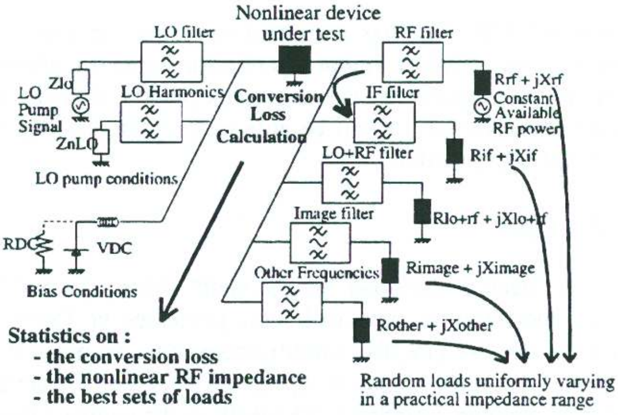

Figure 5: Principle of the statistical load pull.

MMICs exclusively designed with commercial software have successfully been developed and are included in our equipment. Nevertheless many points are not so clear: the first is the accuracy of passive library based on characterisation (measurement precision of small elements, de-embedding) then modelling (capability of a model to simulate the reality) and the second is interaction between passive elements. The use of electromagnetic simulators (2.5D or 3D) is very favourable at this two levels and several example (Spiral inductors, capacitors, Lange couplers and even part of matching circuits for instance output power combiner for power amplifier or inter-stage matching network have demonstrated that they are now indispensable in MMIC design [17].

One of the main limitation in MMIC designs is to have the right transistor size for a given application. Classic scaling rules , on the entire device, are not enough accurate and can not provide reliable extrapolated model. Geometric parameters (finger number, gate width, electrodes layout, ...) are limited by available transistor samples. Designers have then to choose between extensive measurements and modeling and a reduce model choice. Systematic modeling is time consuming and not cost effective. A reduce model choice brings technical limitations and does not allow DC power consumption, chip size and electrical response optimizations. This is the reason why the versatile model has been developed [18]. The transistor model is divided in a passive part, a [S] matrix corresponding to the metallic electrodes response, connected with "n" identical equivalent schemes modeling the "n" finger semiconductor electrical behavior. A standard model equivalent circuit is used to model the intrinsic active finger electrical response. The whole metallic network is simulated with an EM software, Momentum from HP-EEsof. This EM simulation gives an [S] matrix. This matrix takes into account both extrinsic access resistances, capacitances and inductances and also connection lines. In order to connect the EM resulting [S] matrix with the active finger models, the EM input layout contains internal ports in each gate, drain and source electrodes of the transistor (Fig.6). Metallic layout and active finger are separately known. Thus, the transitor layout can be separately optimized without any geometrical limitation. To predict a new transistor response, we only need to simulate new metallic electrodes and to connect the [S] matrix with "m" finger identical intrinsic model already known. This is a significant progress for MMIC designers as, from now on, they can use transistors they really need. Their choice is no more limited in devices already saved in database. Indeed it is now possible to choose finger number, total gate development but also electrodes geometry to optimize the MMIC performances without active device model ability problem. There is no limitation of this versatile model and we are validating this method replacing linear finger model by a non linear simple or distributed model.

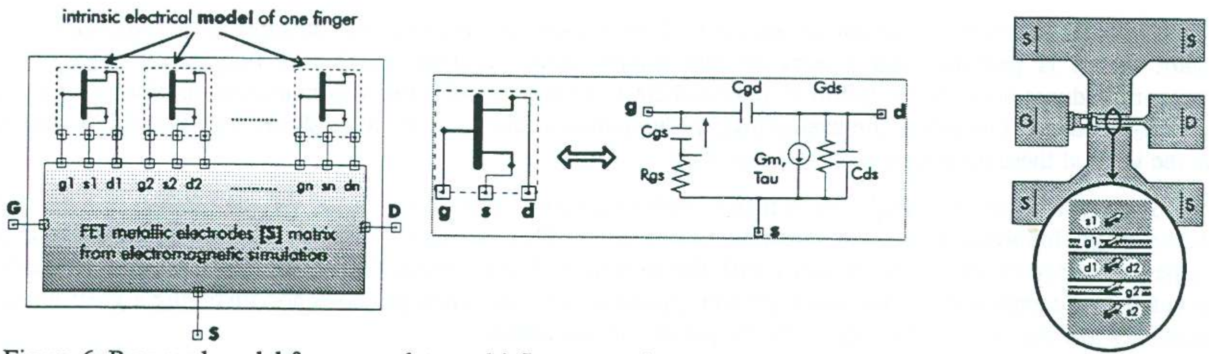

Figure 6: Proposed model for a complete multi-finger transistor

Electromagnetic analysis of passive MMIC part has permitted to design circuits with a better efficiency and with higher performances than in the past, nevertheless limitations of segmentation methods are now more and more clear. In fact, this new approach including electromagnetic simulations of passive element and active part of a circuit is the first step to the future microwave simulator which will be able to integrate circuit, device physics, electromagnetic, thermal simulations to perform "Global Simulation".

INCREASING CHIP FUNCTIONALITY

All this concept or tools allowed to reach a very good "design yield". More that 95% of the circuits developed has a full functionality or needs minor modification even with new processes or foundries. Multifunction concept has consequently been introduced with success [19,20]. Multifunction can be defined as a circuit including several "building blocks" gain amplifiers, attenuators, mixers optimised together reducing GaAs surface, interfaces or simplifying systems. One of the best example designed in LEMMIC is the compact double balanced 14 /12 GHz mixer associated with RF, IF and LO amplifiers and LO attenuator (Fig. 7). The single chip receiver which includes 5 different functions was successfully developed at the first pass with Philips Microwave Limeil and will be used in the next generation of telecommunication satellite and in particular in SKYBRIDGE.

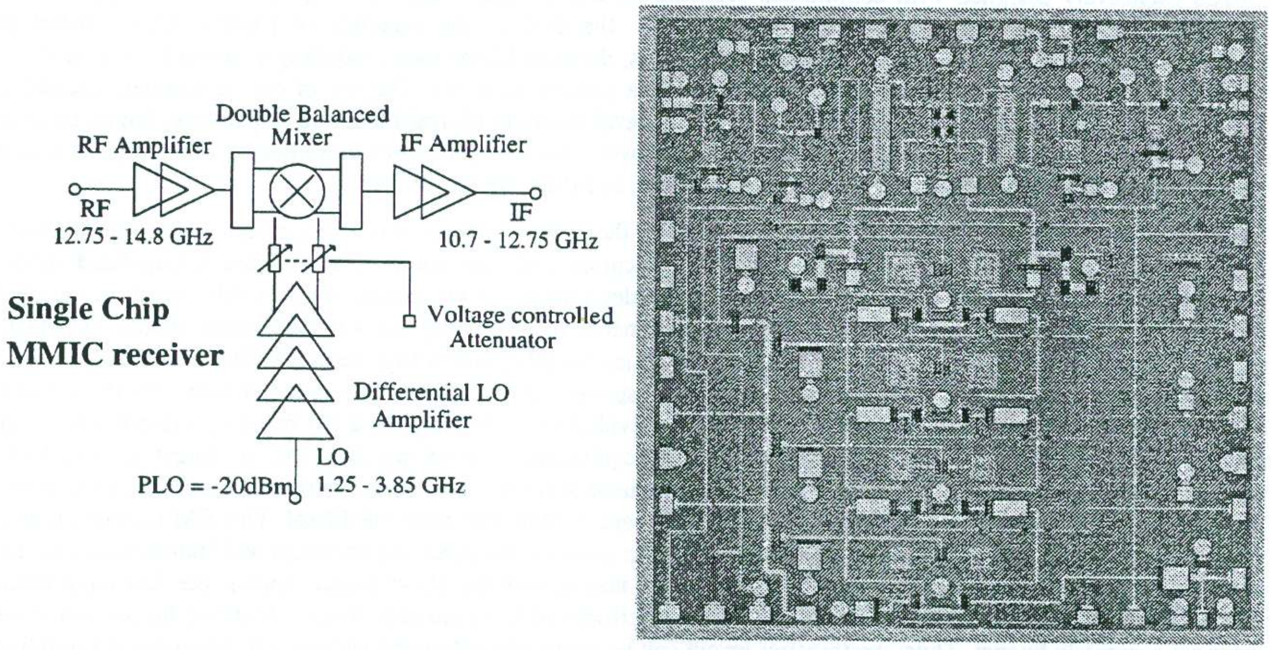

Figure 7 : Ku band micro-strip multifunction schematic and layout (size: 4 x 4.1mm^2)

The miniaturisation is still on-going with the study of the same multifunction with a coplanar design. The fabrication run is currently in process with Philips Microwave Limeil foundry. Results are expected in July 98. These experiments will allow us to compare micro-strip and coplanar designs for selecting the most fitted with our applications.

In order to push integration at module level by reducing the number of I/O interfaces and to simplify commands routing, another axis concerns the MMICs combining analogue and digital functions (Fig. 8). Digital attenuators and phase shifters in Ku and Ka-Band are under manufacturing. These new generation MMICs need a process with a complementary logic, i.e. with both On and Off transistors.

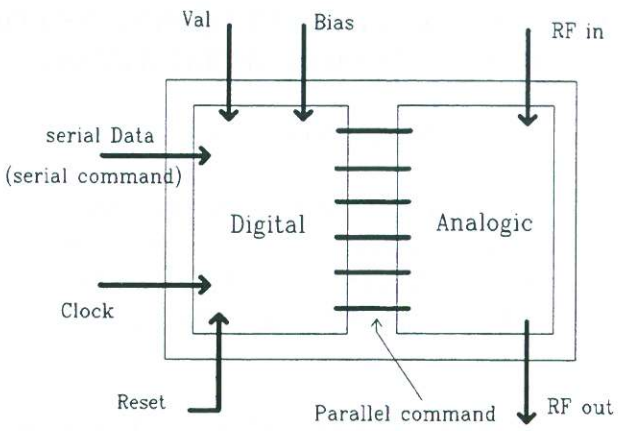

Figure 8 : Schematic of Mixed RF / Digital control function.

PROSPECTIVE AND CONCLUSION

The use of MMICs has been an important change in the traditional satellite payload equipment. They have permitted a mass and cost reduction by a factor 2.5 from the previously employed discrete FETs hybrid family. Nowadays, the emerging market of multimedia services are based on satellite constellations which work in high frequencies and which need to use very large numbers of microwave modules. So, to be competitive, the satellite mass and size have to be minimised. The microwave modules will be extremely compact, demanding a lot efforts for higher integration, for higher performance, for lower cost. It requires circuits more and more specific and compact. This request lead us to find more and more efficient and advanced techniques to master the design and to move to the new generations of MMIC (multifunction MMICs, mixed analog / digital MMICs, mixed process MMICs, ..) and the new promising technologies (SiGe HBT, GaN devices, InP devices,...) associated with the packaging development (Multi Chip Module , 3 D module,....) will be the new values for satellite constellation multimedia services.

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