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Application of GaAs MMICs in space: an ESA perspective

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Abstract

This paper presents the evolution of the application of MMICs in on-board space equipment's. Advantages and disadvantages are highlighted and the major trade-off factors are described. Several examples of recent on-board equipment's based on MMICs are given with the major achievements.

Introduction

In the last few years the number of on-board microwave equipment's based on MMICs (Monolithic Microwave Integrated Circuits) has increased tremendously. This has been the result of several factors that will be described in the next paragraphs. However MMICs have not completely replaced other older technologies as some of these still offer better overall advantages.

The boundary conditions

The traditional boundary conditions for on-board equipment's have always been:

- power consumption
- mass
- reliability.

Power is limited in all spacecraft's and even though satellite platforms have evolved, (today the largest of them can offer a payload power capability of up to 8 to 10 kW), on-board equipment's are designed to minimize power consumption. Mass is limited by the launcher capabilities, (the biggest satellite payload is now around 4000 Kg) and developers concentrate on the reduction of equipment's mass by the use of appropriate technologies, materials and technical solutions. Reliability is also essential for space applications: satellite operators and users count on reliable units to provide and utilize services for a guaranteed number of years.

New boundary conditions have appeared in the recent years due to the rapid evolution of satellites toward commercial applications:

- cost
- fast production cycles of equipment's.

Nowadays, the production of space equipment's for commercial programs is primarily driven by these last conditions. Equipment manufacturers must be able to deliver cost effective, on-board space hardware in a period as short as 6 to 9 months after receipt of order.

Furthermore, as a result of the commercial environment, satellite payloads have become increasingly complex: in fact, the larger the number of channels an operator can make available from a single satellite, the greater will be his revenues. The consequence is that equipment's shall be made even less power hungry, more miniaturized, and suitable for large quantity production. Published data of launcher costs [1] indicates figures close to 5000 $ for each W of power consumption, and approximately 30000 $ for each Kg of mass. These data give a priority factor when power consumption and mass have to be traded off. If, for instance, by using MMICs I can save 500 g in a unit but the unit is less power efficient and consumes 4 W more, from a pure cost point of view it would be better to select alternative technologies! This is clearly a very simplified situation: in practice, other factors come, into the overall trade-off (e.g. easier accommodation, lower production cost, faster availability).

MMIC advantages and disadvantages

The use of MMICs can, in many cases, satisfy the boundary conditions for space equipment's, highlighted above. By using MMICs, microwave equipment's can be made smaller and lighter.

For example in fig.1, (courtesy of Alcatel Espace, F), we can see the mass and volume reduction of a Ku-band channel amplifier over the years. The biggest unit (550 g, 614 cm^3, discrete bare chips, printed circuit board (PCB) for power supply and interfaces) was developed in 1988. The medium size unit is the version available today (220 g, 286 cm^3, micro-packaged MMICs, PCBs for ancillary functions) . The smallest unit is the new generation version, soon available (95 g, 165 cm^3, multi-chip modules with MMICs and Si ASICs for ancillary functions). In fig.2, (courtesy of Bosch Telecom, D), we can see the reduction obtained at building block level for a Ku-band gain block. In fig.3, (courtesy of Alenia Aerospazio, I), a compact assembly of three Ku-band channel amplifiers is shown. The microwave section is composed of eight MMICs brazed on open carriers and integrated into a single package, hermetically sealed. A mass lower than 50 grams is achieved with a high integration factor and impressive reduction in the tuning effort with respect to a more traditional approach using discrete FET devices [2]. In fig.4, (courtesy of Dassault Electronique, F), the evolution of a delay line shifter (for ECM applications) is shown. A ten times reduction in volume has been achieved by moving from a standard MIC implementation, to a module based on many ICs (MMICs and ASICs). A further ten times volume reduction is obtained today by integrating most of the functions on a single MMIC.

From all the above examples, it is clear that the use of MMICs shall be combined with the use of other advanced technologies to minimize the overall equipment mass and size. In fact, beside the microwave section, any space microwave equipment's normally includes an EPC (electronic power conditioner), a TT&C interface (Telemetry, command and control) , and various other ancillary DC circuits (e.g. compensating circuits for minimizing variation of parameters over temperature). The overall unit mass and size are minimized only when these functions are also implemented with advanced technologies and techniques. For example, technologies such as Si based, ASICs (Application Specific Integrated Circuits), advanced (e.g. multi-layer) thin-film Alumina substrates, and advanced design techniques (e.g. high frequency DC/DC converters) would be considered.

An example of an advanced equipment implementation is shown in fig. 5 (courtesy of Alenia Aerospazio, I). It is a S-band BFN developed for the former ESA DRS satellite which utilizes MMICs integrated with MIC circuits and co-fired multi-layer circuits integrating control circuits based on Si ASICs.

The reduction in power consumption is of major importance in applications such as down-link transmitters. In this case the use of MMICs is normally not the best choice for two reasons:

- GaAs is a relatively poor thermal conducting material (46 W/m°C compared to 118 W/m°C for Silicon)
- electrical losses of transmission lines on GaAs are higher than on ceramic substrates, such as Alumina.

Minimizing the channel temperature of active devices is fundamental to maximizing the equipment life time and its performance (e.g. output power , gain and power added efficiency). In this respect the poor thermal conductivity of GaAs is a drawback considering that GaAs MMICs substrates cannot today be thinned to less than 100 μm while maintaining a reasonable production yield. On the contrary, GaAs discrete devices can be fabricated with a thickness of 50 to 40 μm, greatly improving the device thermal conditions.

Transmission lines on ceramic substrates provide less losses than on GaAs. There is therefore a distinct advantage to utilize discrete devices assembled in MIC structures using, for example, alumina substrates for the matching networks and power combiners. In fact even few tenths of dB could dramatically degrade the performance of a satellite payload. In figure 6 the effect of output losses on the power efficiency of an amplifier is shown. Let us take, for example, the ASAR antenna of the ESA ENVISAT-1 program, where 320 transmit/receive modules containing 10 W amplifiers are used. This amplifier, manufactured by Alcatel Telettra, I, is based on discrete GaAs devices integrated into a hermetically sealed packaged using MIC technology (see fig.7). In this case the amplifier efficiency is of the order of 35 %. If, instead, MMICs were used, an additional loss of 0.2 dB at the output would require an increase of the overall antenna peak power consumption by approximately 300 W to maintain the same level of transmitted power.

Similarly, the additional losses of transmission lines on GaAs also reduce the use of MMICs in the input front-end of low noise amplifiers. In these equipment's discrete devices and MIC integration techniques provide the best performance. In this case few tenths of dB are extremely important to maximize the signal to noise ratio (S/N) of the up-link budget. Figure 8 shows the resulting degradation of the S/N for additional losses at the input of the low noise amplifier (assuming an antenna noise temperature of 150 °K). For example, a 0.25 dB additional loss in a LNA with a noise figure of 2 dB at room temperature would degrade the S/N by about 0.4 dB, a significant degradation in the overall satellite system budget. To recover this additional loss and obtain the same noise figure it would be necessary to cool the amplifier to -23 °C !

If MMICs are not the best choices for on-board low noise amplifiers and power amplifiers, they are largely utilized in all the other satellite microwave equipment's (gain blocks, variable attenuators, variable phase shifters, down and up converters, local oscillators, linearisers, etc.). As previously suggested, the main reasons for this wide spread use are the mass and size reduction, the improved reliability, (due to the reduction of assembly steps), and the overall reduction in production time and cost.

There are many reasons for these last advantages:

- The relative cost (\$ per mm^2) of discrete devices is normally higher when compared to MMICs specifically designed and produced by an equipment manufacturer using an external foundry.
- The procurement of several discrete components (active device, capacitors, resistors) from various suppliers is more costly and time consuming than buying the single MMIC, integrating all these components, from a single supplier.
- The number and duration of assembly, integration processes and inspection steps are much larger for units based on discrete devices.
- When the design of a MMIC is fully consolidated, the tuning of an equipment is significantly reduced due to the reproducible performance of MMICs (this is an even more important asset when systems based on active arrays have to be implemented).

The above cost and time advantages clearly offset the additional design cost and time of MMICs for certain conditions. A detailed trade-off (assuming two foundry runs with a 3" medium cost process) performed for a 2 stage Ku-band gain block has shown that there is and overall cost advantage for MMIC based equipment's only if you produce 250 or more blocks. Figure 9 shows the cost comparison for different quantities. The cost cross-over can be reduced if, for example, the designers are experienced and require only a foundry run to achieve the specified performance. Additional saving for large quantities can be obtained by reducing the MMIC size, and by using processes on 4" wafers.

Typically, the requirement for a higher quantity productions, (to justify the use of MMICs from a cost consideration) can often be solved by satellite equipment manufacturers designing a set of "standard" MMICs for different satellite frequency bands. Using this approach, the same MMIC (for example a gain block) can be used in different types of equipment's. This "building block" approach has the additional advantages of reducing the development time of new equipment's and simplifying the procurement flow.

In addition to the advantages indicated above, MMICs also have other positive characteristics. For example, they can easily provide electrical functions that would be almost impossible to obtain with discrete technologies, at least without major manufacturing and tuning efforts: this is, for example, the case of structures which require highly balanced and symmetrical circuit topologies (e.g. SSB mixers, vector modulators). One example of this type of circuits is shown in fig. 10: it is a 9 by 9, S-band beam forming network implemented using MMICs (designed at ESTEC and manufactured by the PML foundry, F), integrated by means of a multi-layer substrate (based on Dassault Electronique technology). The same performance would not be achievable using discrete devices and conventional MIC technologies [3].

Additionally, MMICs enable cost effective and high performing equipment's for mm-wave applications due to the fact that the discontinuities and interconnection parasitic reactances are minimized. This area of mm-wave satellite applications is rapidly expanding, especially for inter-satellite link communications, remote sensing and scientific missions. In ESA, for example, the future PLANCK mission will use hundreds of MMICs for implementing continuous comparison radiometers in the frequency range between 30 to 100 GHz. Limb sounders, such as those required in the future ESA programs MASTER and SOPRANO, will also need several MMICs for radiometers at mm and sub-mm wave frequencies. Moreover the ESA Cloud Radar mission, at 94 GHz, will require the implementation of several functions using mm-wave MMICs.

To minimize noise figure and maximize the gain per stage ratio (which reduces the overall power consumption; an important advantage, considering that many of these equipment's shall be cryogenically cooled), all this type of applications envisage the use of InP MMIC technologies. ESA is investigating InP technologies from two European sources: IMEC in Belgium and Daimler Benz Research in Germany. In fig.11 the typical performance levels obtained by IMEC with their 0.25 μm InP MMIC technology are shown. In fig, 12 the performance is shown of a 80 GHz amplifier based on the Daimler Benz Research 0.25 μm InP MMIC technology.

GaAs MMICs also have the advantage of being much less sensitive to radiation effects than Si based devices, at least at the level of radiation expected in common satellite applications. This simplifies the electrical and, especially, mechanical design of equipment's, by avoiding the need for thick radiation shields.

The use of digital technologies for implementing satellite equipment's has increased significantly in recent years. An increasing number of traditionally analogue functions will be replaced by digital functions [4], most of them, in the future, based on MCMs. System functionality, flexibility and performance will increase due to the tremendous advances in VLSI technology that have taken place over the past few years.

Therefore, in telecommunication applications, the trend is to transform the analogue signals to digital formats and vice-versa, as close as possible to the on-board transponder front-end and transmitter, respectively. Following the conversion to digital format, various options exist for treating the signal (e.g. beam-forming, routing and de-modulation/modulation in case of regenerative transponders). One of the most recent example of digital functions for on-board satellite applications is the Skyplex concept [5], based on an ESTEC patent. Skyplex enables operators to have distributed up-link of digital television signals, making it economically viable for small broadcasters to use digital satellite television transmission. The Skyplex payload is manufactured under the responsibility of Alenia Aerospazio - Space Division and a picture of one of its building blocks, (the digital multiplexer), is shown in fig.13.

These functions are primarily based on high complexity, (order of 100Ks gates) ASICs, using CMOS technologies. However, for some of the functions, (e.g. ADC, DAC with high data rate, typically above 1 GS/s, multiplexers, demultiplexers, etc.), the use of GaAs or SiGe digital MMICs is foreseen. Additionally, other digital functions such as numerically controlled oscillators, digital direct synthetizers, and optical-microwave interfaces will also utilize fast digital MMIC devices.

Design approach

The design approach for MMICs to be used in on-board space applications is, in many aspects, not very different from the design for other applications. Notably however, there are some basic differences, mainly related to a design strategy aimed at maximizing reliability and reduce manufacturing risks. In particular, any schedule impact must be avoided considering that the time from order to delivery is constantly reducing.

In terms of reliability, typical commercial satellites of today are required to operate reliably for 15 years. This means that no compromise, beside introducing proper redundancy schemes at equipment level, can be made in order to guarantee this long-life cycle for the individual MMICs.

Degradation of MMIC performance can be, generally speaking, related to:

- operating temperature of the active devices (channel temperature)
- current density in transmissions lines and DC lines
- level of signal power compression and ratio between average and peak power
- assembly, integration, testing procedures and processes
- packaging procedure and processes.

A good review of the reliability issues for MMICs in space applications is reported in reference [6].

Over the operating temperature range, the device biasing point and class of operation has to be selected to minimize the channel temperature under the worse signal level conditions (e.g. no-signal in class A operation). This is typically a critical design challenge for power amplifiers, where the design aims at maximizing power added efficiency while maintaining good linearity and avoid excessive gate currents and excessive compression levels (see following remarks).

Concerning current densities, (normally to be maintained below 2 10^5 A/cm^2), this is an issue that normally affects the gate metal, as they have the smallest dimensions in the active devices, and, to a lesser extent the DC biasing lines and choke inductors which normally carry the highest DC currents. For the gate metal the designer must pay particular attention to limit the average total gate current by reducing the degree of compression, especially in presence of signal with high peak to average voltage ratio,. It is important therefore to correctly set the impedance of the DC biasing network in order to limit this current.

Regarding the compression level, high values of RF overdrive can cause the generation of hot-electrons near the drain end of the channel. If these electrons possess sufficient energy, they can tunnel in the SiN passivation, becoming trapped there, thus degrading the device performance. The phenomena is aggravated when the RF signal has an high peak to average power ratio (such as the multi-carrier signals typical of satellite telecommunication applications). Also in this case the designer must ensure that in all operating conditions, including over the temperature range, the degree of compression at each stage is maintained within safe limits [7].

In relation with assembly, integration and testing procedures and processes, the designer, when feasible, has to design circuits to make them more robust against ESD (electrostatic discharge) events. This may be accomplished, for example, using high pass matching networks (with inductors going from the signal line to ground) against low pass networks.

For packaging, the designer must ensure that the selected package is treated in a manner so as to avoid the release of hydrogen which can significantly degrades the MMIC performance. In addition and when possible, the designer shall select processes that are more resistant to this contaminant (e.g. with Al based gates). Particular care shall also be given to the optimization of the packaging and sealing processes to minimize moisture content in the hermetically sealed package.

In terms of specifications, the design of MMIC for on-board space applications is often different in terms of bandwidth of operation (typically smaller than, for example, for military systems but wider than for terrestrial communications), type of RF signals, environmental constraints, etc. Operating temperature ranges are, for example, different and generally wider than in other applications (e.g. airborne equipment's can be maintained, in many cases, over a more limited temperature range by cooling and/or heating). To avoid extremely sophisticate compensating schemes, the designer should predict performance over temperature and, when possible, use on-chip compensation techniques.

Additionally adequate performance margins shall be built-in during the design to reduce the risk of delays and additional costs during the equipment production cycle. These performance margins should also include a stringent review of the MMIC stability behavior, to exclude possible oscillations or spurious generation which could jeopardize the manufacturing schedule of a unit, or even the payload/instrument performance if not detected well in advance. In particular, special attention shall be concentrated on excluding possible common-mode oscillations that could arise in circuits containing balanced structures (e.g. power amplifiers), which are not detectable by using the standard input-output stability analysis and verification methods [8].

Moreover the selection of the foundry and of the foundry process shall be done to guarantee availability during the multi-year development time of programs that are typical for non-commercial projects. In terms of space qualification, it is a good starting point for a designer to design MMICs with processes that are proven for large volume production (e.g. for consumer, terrestrial markets). These processes are so well controlled that they will inherently provide highly reliable products also for space, when applying the specific design and application strategy mentioned above.

At the European Space Agency the most important recommendations for the design of MMICs for on-board space applications are included, together with documentation and test requirements, in a specific document [9] which is applicable to all ESA R&D contracts including MMIC designs.

Qualification

There is no one standard approach toward MMIC qualification at world-wide level (see [10] for ESA requirements). However, we can at least distinguish between two general philosophies: one is the so called "Capability Approval" approach and the second is the "Project qualification" approach. In the first case a process at a foundry is defined within a "capability domain" and specific evaluation tests are carried out at process level to demonstrate its quality characteristics, and the capability is maintained over the years with regular maintenance testing. If a MMIC is designed and manufactured according to the "capability domain", then only a limited number of testing is required to procure this specific MMIC. This approach is convenient if a large number of different devices have to be procured from the same supplier, using the same process. This has been the case for the ESA project ENVISAT-1 for which most of the MMICs for the SAR T/R modules have been produced by GEC-MMT using their process F20, under ESA Capability Approval, [11].

In all the other cases, the approach is more oriented to specific MMIC devices, for a specific project. After the process has been submitted to evaluation tests, qualification tests, (wafer acceptance test, lot acceptance tests), are performed on the specific MMIC to be procured. This last approach gives more flexibility to procure devices using different suppliers and different processes and this is the trend most used today in MMICs procurement.

In the space equipment industry, there is a growing tendency to reduce the number of inspection steps and periodic verification, thus relying more on the device manufacturer to monitor the process. An additional trend is to reduce the number of specifications used for procuring devices for space, and to simplify them. Moreover, recent studies and experience have enabled a more exact determination of the reliability limiting factors of devices in space [7]. This results in increased confidence and better definition of the safe operation area of devices and in the acceptance of additional technologies that can be used on-board spacecraft's (e.g. use of plastic packages [12]).

In general, the rules and specifications introduced 20 - 25 years ago are not fully applicable to today's commercial satellite procurement and new approaches are developing within the space equipment manufacturer community toward simplification and consequent lower procurement cost, accompanied by a better scientific knowledge of reliability phenomena.

Processes

The largest number of GaAs MMICs used in space applications have been based on conventional, ion-implanted, 0.5 μ MESFET processes. More recently, especially in view of the exploding new market for on-board Ka-band equipment's for multi-media satellite applications, the number of

MMICs using GaAs 0.25 or 0.15 μm P-HEMT processes has been constantly growing. In addition, the interest is growing for some applications to utilize normally-on/normally-off technologies to reduce power consumption in low signal applications, and/or to implement mixed analogue/digital MMICs.

For applications above 30 GHz, the use of InP based, P-HEMT MMIC technologies has already been considered, especially in applications such as wide-band radiometers where the noise figure minimization is fundamental for the instrument performance. (Even cryogenically cooling of devices is envisaged to reduce further the noise-figure). However the maturity of these processes is still limited, mainly because there is no clear market demand for these, still quite expensive, processes.

Concerning HBT processes, their application to space units could be advantageous, for example, for high efficiency, pulsed power amplifiers at frequencies below Ku-band. However, limitations in process maturity and general concerns on the process reliability have, until now, practically excluded these devices from on-board space applications, at least in Europe.

The situation is different for power HFET devices (non to be confused with HEMT devices). HFETs are practically an improvement of MESFET devices, where higher break-down voltage, higher power added efficiency, higher gain in class AB and B operation, higher reliability has been accomplished using a low doped AlGaAs layer on the top of a standard GaAs channel. However, the applicability range for these devices is also limited to frequencies below Ku-band. The major source for this technology, (available for discrete devices and MMICs), is Texas Instruments (USA), but other suppliers are working on similar concepts which are potentially very interesting for applications in on-board solid state transmitters. Equipment's which utilize HFETs are already flying in several satellites.

One disadvantage of MMICs available today concerns the lack of processes, at least at industrial level, which allows different types of device technologies to be integrated together. This factor limits the number of multi-function devices that can be realized: for example it is not possible to integrate PIN diodes with P-HEMTs, which would be desirable for LNAs in radar applications.

Most of the processes described above are available in Europe, (for a summary of GaAs MMIC processes available in Europe the reader can find a good reference at: http://www.estec.esa.nl//xrmwww/mmic/mmicpr.htm). However, space equipment manufacturers have to accept the process availability, performance and trends which are driven by the large volume, consumer market. This means, for example, that most of the processes for application below 2 - 3 GHz have been developed with the target of reducing the bias voltages (from 5 -6 V, typical of the '80s to today's requirement of less than 3 V [13]) to satisfy the huge market of wireless, portable equipment's. On the contrary, for space application where primary voltages are above 30-50 V, the lower the secondary power the smaller the conversion efficiency of a DC/DC converter (fig.14): in these applications devices which operates at high voltage and low currents would be desirable.

Ground applications

The design and applications of MMICs for satellite ground terminals does not differ from other commercial applications of MMICs. In particular, the DBS receiver market is one of the biggest consumer applications of GaAs MMICs (the other being the mobile phone market). The introduction of MMICs in this area is justified only when the overall cost is minimized, and where the performance is acceptable. Even in the DBS receiver market, until recently the standard chip set for a Ku-band outdoor unit would be constituted by discrete P-HEMT chips and one MMIC down-converter.

The coming market for Ka-band multi-media services will constitute a new opportunity for GaAs manufacturers with respect to high volume production of various MMICs. In particular the implementation of low cost, 30 GHz power amplifiers with 1 to 2 W output power capability will pose a great challenge both at design and process level.

Conclusions

MMICs are used in most of today's on-board space equipment's. Their application is not, however, generalized to all functions due to performance and reliability restrictions, and should be accompanied by other miniaturized technologies to maximize the overall advantages. MMIC design for space applications must be oriented toward reliability, production cost reduction, and schedule risk minimization. In the future, the use of MMICs in on-board space equipment's will further expand to higher frequencies, multi-function circuits, manufacturing using different devices (HBTs, P-HEMTs) and other semiconductor compounds (e.g. InP), and also to a few digital applications. Ground terminals already constitute a large volume, consumer application of MMIC technologies and will further expand to meet the requirements of the new, multi-media Ka-band satellite applications.

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Note

This paper is an extended version of a paper presented by the same author at WOCSDICE 1997, [14].

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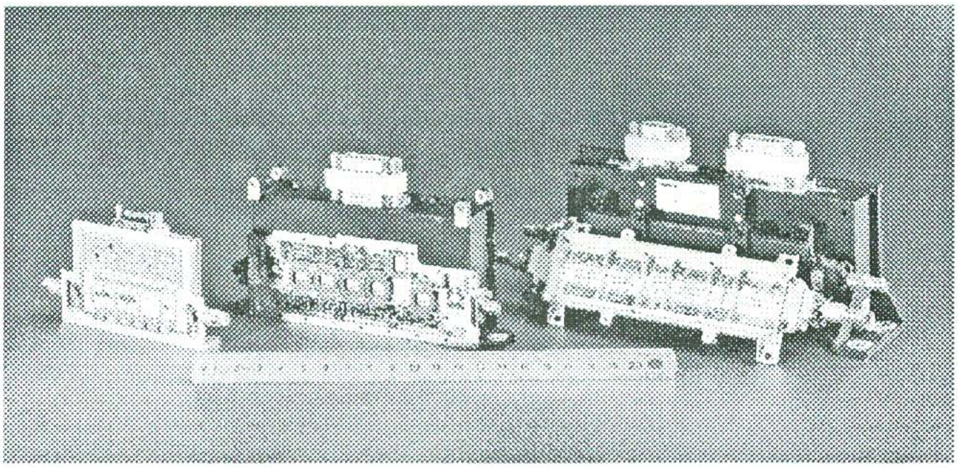

Figure 1: Alcatel Espace (F) Ku-band channel amplifiers

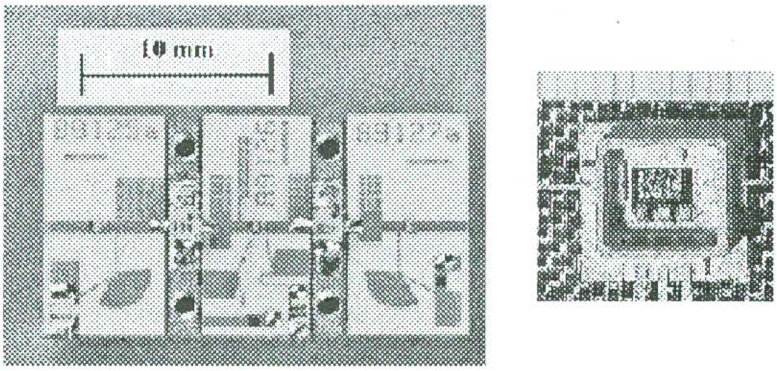

Figure 2: Bosch Telecom (D) Ku-band gain blocks

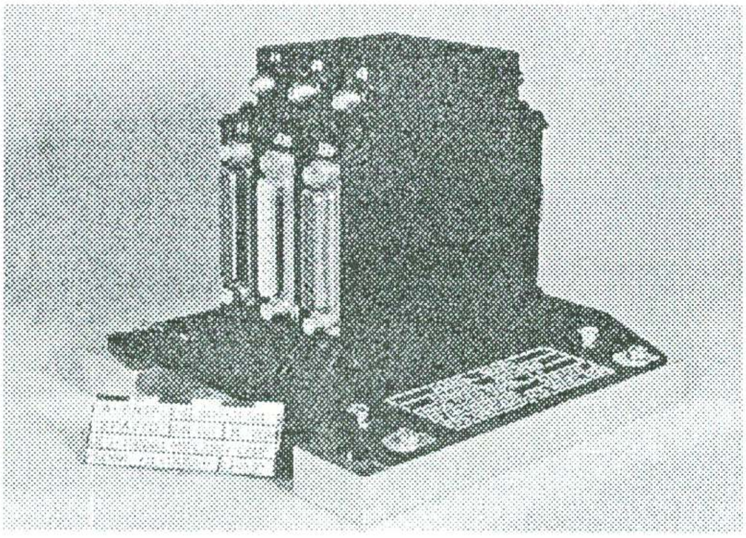

Figure 3: Alenia Aerospazio Ku-band channel amplifiers (combination of three units)

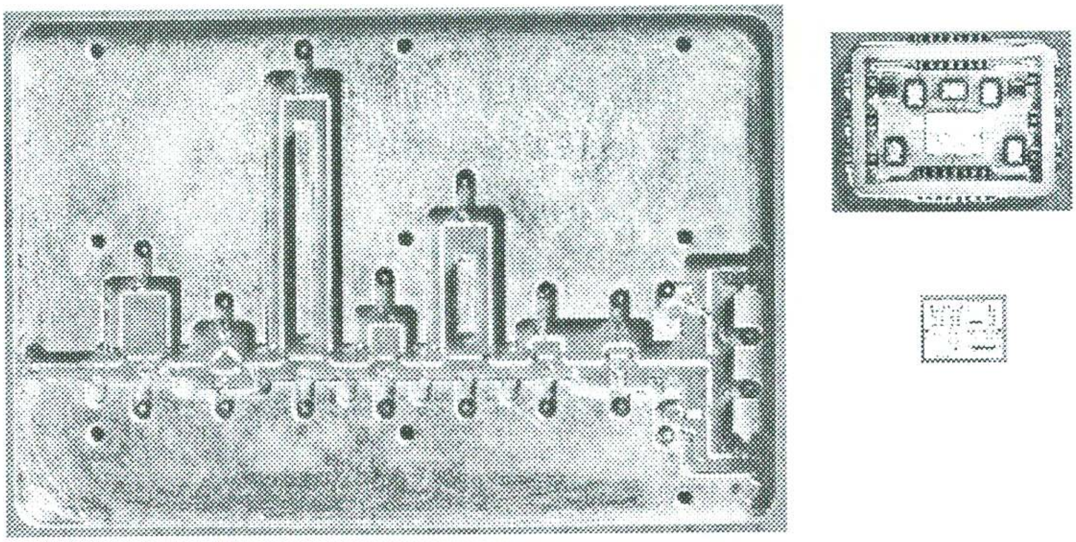

Figure 4: Dassault Electronique delay line shifter

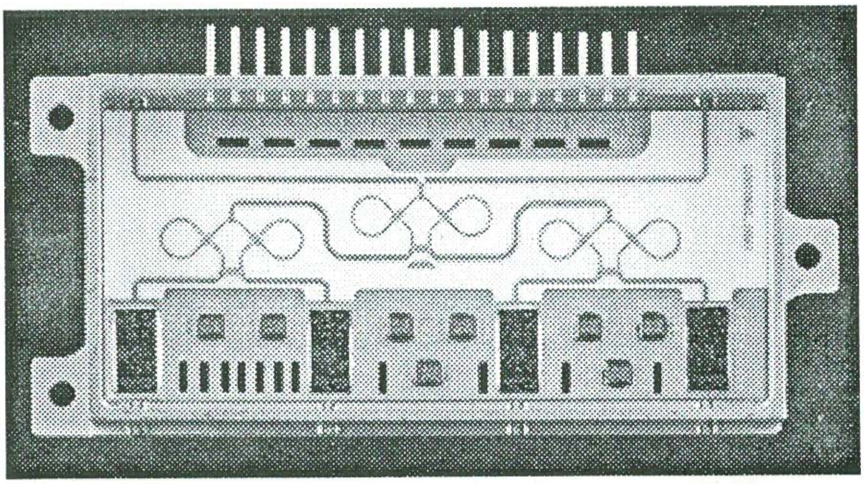

Figure 5: Alenia Aerospazio S-band phase shifter

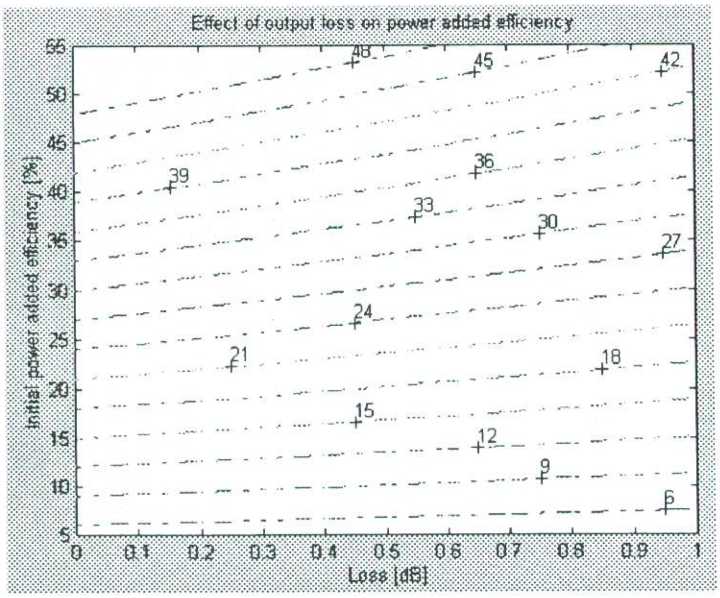

Figure 6: output loss effect on power added efficiency

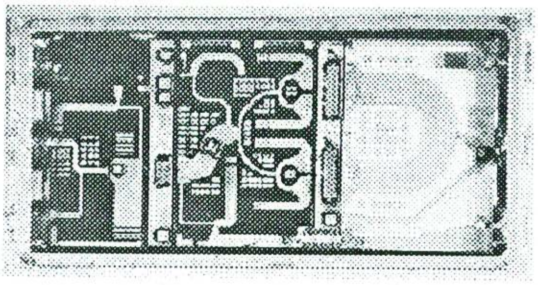

Figure 7: Alcatel Telettra 10 W C-band SSPA

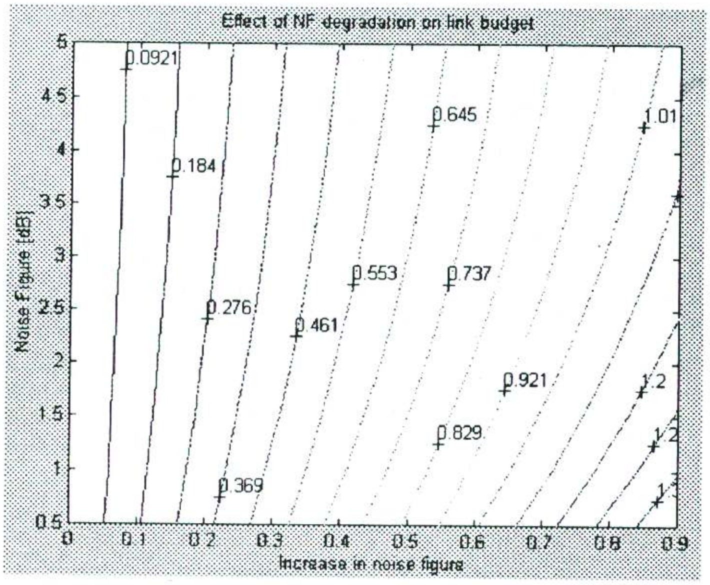

Figure 8: effect of input loss on S/N

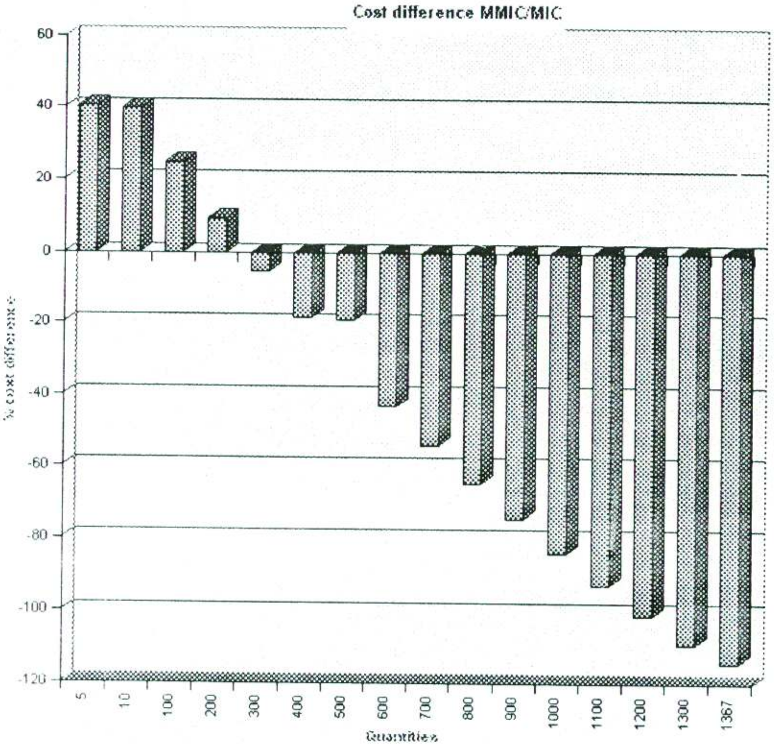

Figure 9: MIC versus MMIC, Ku-band gain block

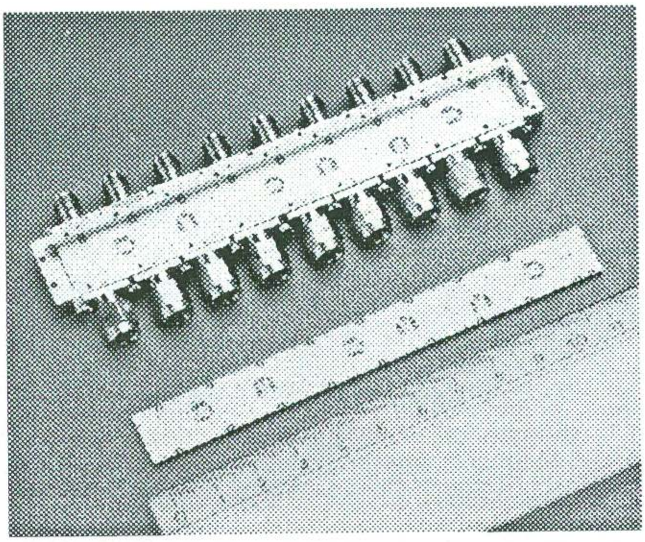

Figure 10: 9 x 9 beam forming network

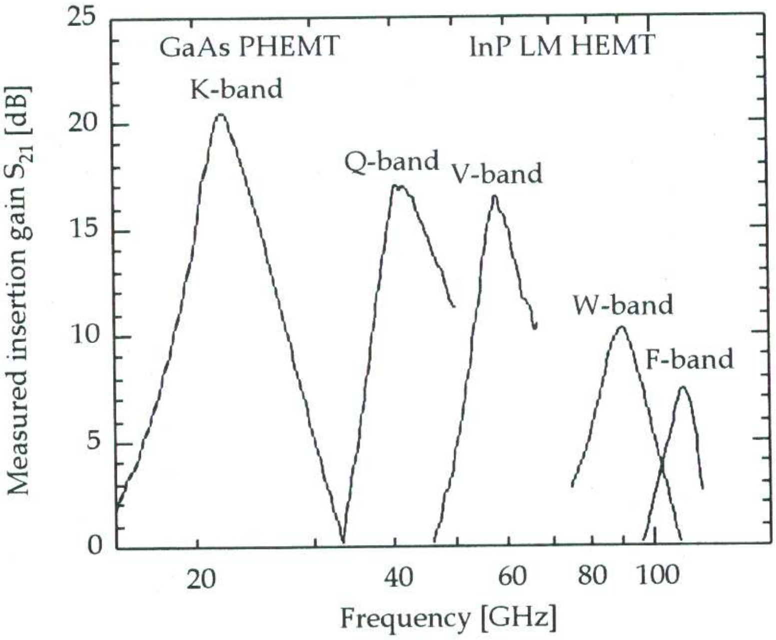

Figure 11: IMEC InP single stage (cascode) amplifiers

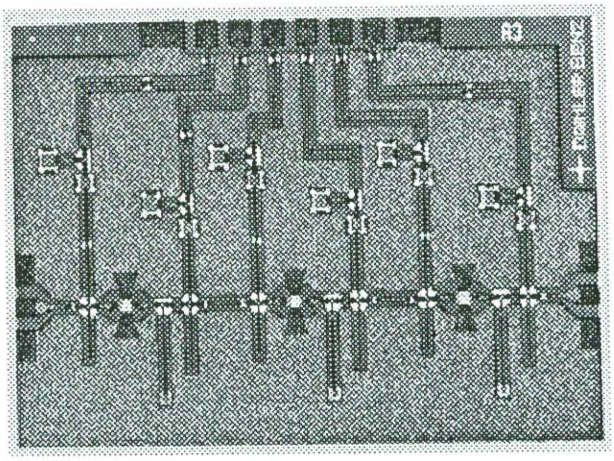

Figure 12: Daimler Benz Research InP 80 GHz amplifier

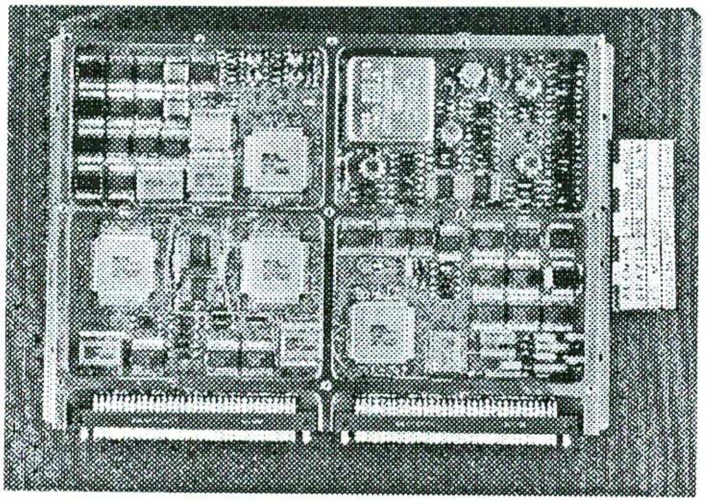

Figure 13:Alenia Aerospazio, Skyplex multiplexer card

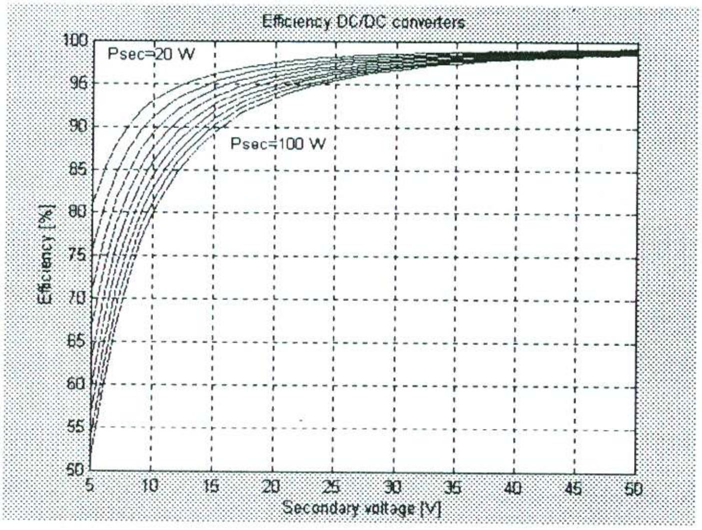

Figure 14: effect of secondary voltage on DC/DC converter efficiency