An overview of microwave component requirements for future space applications

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***Abstract* - New and emerging microwave component developments and their potential impact upon payload implementation for future European Space Agency (ESA) missions are discussed. Consideration is given to the use of indium antimonide (InSb), gallium nitride (GaN), RF CMOS along with MEMS and advanced packaging techniques.**

I. INTRODUCTION

Research activities at ESA can be divided into four primary themes; Telecommunications, Earth Observation, Navigation and Space Science. The mission characteristics and technical requirements in each of these areas can be significantly different due to aspects such as launch deadlines, commercial pressures, acceptable risk and the operational lifetime required. Earth Observation and Science missions typically strive for leading edge technical and scientific performance, hence they are characterised by a strong technology push in order to achieve the ultimate in sensor capability. A relatively high technical risk is accepted due to the potential for extremely high "knowledge payback" which is of benefit to the whole of mankind. On the other hand, space telecommunications is very much commercially driven, with strong competition between satellite manufacturers and operators. In recent years these environmental conditions have tended to push the telecommunications satellite industry towards being a more conservative "technology follower" rather than a "technology leader" to minimize risk and maximize revenue for investors. These operational differences result in differing technology requirements for each research area. Such factors will now be discussed along with the implications for future satellite payload architectures.

II. OVERVIEW OF MISSION REQUIREMENTS

A. *Telecommunications*

Over the last decade there has been a steady increase in the size of telecommunications payloads towards more transponders, greater capacity, higher EIRP and G/T. This is likely to increase in the future due to the emergence of multimedia, high definition TV and radio broadcast applications. The majority of current satellites operate in C and Ku band, however there is a trend towards moving to Ka-band operating frequencies (30GHz uplink/20GHz downlink) and possibly even V-band (40-50GHz) to overcome spectrum congestion and the bandwidth constraints of lower frequency systems. To allow acceptable gateway antenna size, while at the same time achieving wide-area coverage, it is necessary to use multiple, high gain, spot beams on board the satellite, as illustrated in figure 1.

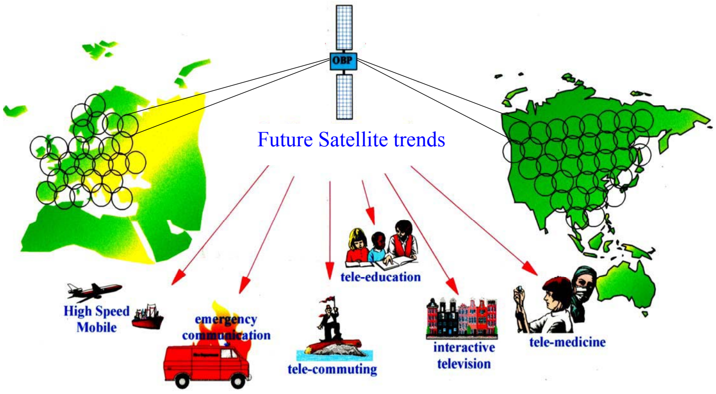

Fig.1. Evolution towards multi-beam Ka-band satellites

Another trend is towards increased use of on-board processing to generate a "clean-signal" prior to re-transmission and to manage smart "single-hop" switching between feeder links and multiple spot beams. Coupled with this are operator requirements for "future-proofing" so that satellite resources can be matched to evolving traffic patterns in the long term (>15 years mission lifetime). This will require the ability to adjust transmission bandwidth, power to beam and beam shape such that satellite resources are maximized. Moving to such an approach will mean using satellites with several hundreds of transponder channels rather than the several tens of transponders that are commonplace in today's C and Ku-band systems. This level of sophistication can only be achieved if active antenna approaches are used such as the direct radiating array (DRA) or the focal array fed reflector (FAFR), as illustrated in figure 2.

Studies have shown that the DRA gives the best flexibility in terms of beam agility and reconfigurability, however it needs a large number of radiating elements to achieve a wide field of view. This configuration has been adopted for the Boeing Spaceway downlink Tx antenna system [1].

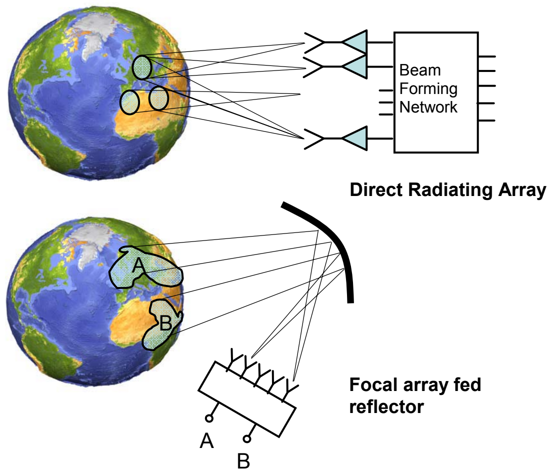

Fig. 2. Comparison of DRA and FAFR architectures

The focal array fed reflector is simpler to implement since it uses a smaller number of active elements, however beam steering and flexibility is not as good as for a DRA. For the DRA approach, SSPA's of moderate power level can be integrated directly with the antenna tile. Whereas the FAFR approach uses a smaller number of higher power transmit amplifiers (typically traveling wave tube amplifiers) that have to be physically set back from the feed antenna due to integration constraints. This introduces losses between the transmit amplifier and the feed antenna. With increasing frequency it becomes even more difficult to fit the required functions within the available aperture area favouring the use of a DRA active antenna solution using solid state power amplifiers.

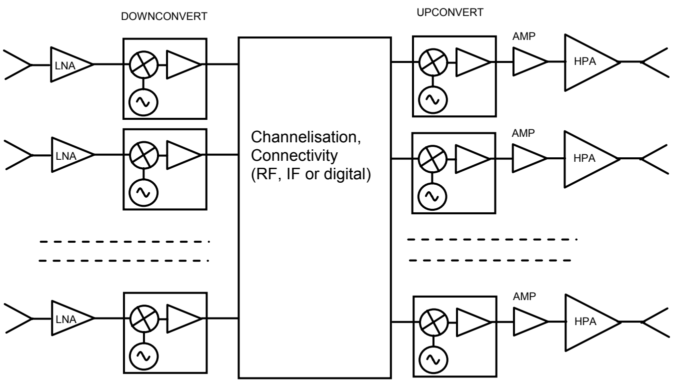

Fig. 3. Simplified transponder schematic

A simplified block diagram of a satellite transponder is shown in figure 3. Combinations of the following components will typically be required; input/output filters, low noise amplifiers (LNA), downconverters and upconverters, input and output multiplexers (IMUX/OMUX), routing switches (baseband, IF or microwave), channel amplifiers and high power amplifiers. For electronic beam steering, a beam forming network (BFN) incorporating phase shifters is also needed. To satisfy the needs of next generation multibeam Ka-band satellites, future transponders will require:

- Lightweight, small size, and wideband high power amplifiers. Simultaneous high power added efficiency (PAE) and linearity performance is also needed since each amplifier will be operating in a multi-carrier regime and hence the power amplifiers will have to be backed off to reduce intermodulation to an acceptable level.
- Low phase noise oscillators to minimize noise induced bit-errors, particularly if high order modulation schemes are adopted. Preferably, such functions should be integrated with the up and downconversion mixers to reduce component size.
- Low loss switches for redundancy chains and high order switch matrices.
- Accurate phase and amplitude tracking between transponder channels (requiring extensive use of multifunction MMIC technology).
- Microwave packaging and assembly techniques that allow low cost and highly integrated component functionality.
- High speed, low power consumption, digital processors for on board processing (OBP).

B. Earth Observation

Earth observation (EO) satellites are used for a wide variety of purposes such as monitoring weather and global climate change, terrain mapping, measuring ocean salinity, determining soil moisture conditions and monitoring changes in global water levels. Synthetic Aperture Radar (SAR) is typically used for ground terrain mapping [2]. Other instruments include microwave limb sounders/radiometers, for determining atmospheric composition, radar altimeters (Ku, Ka band) and 94GHz cloud radar profiling systems. Future EO missions will use a wide range of radiometer frequencies. Examples of planned missions include the European Global Precipitation Mission (EGPM) [3], and the Cloud Ice Water Sub-Millimetre Imaging Radiometer (CIWSIR) [4] operating at 18, 23, 89, 157 GHz and 183, 325, 448, 683, 874 GHz respectively.

Synthetic aperture radar: Current trends with SAR systems are to move towards baseline interferometer techniques by having two (or more) widely spaced antennas, such that better spatial resolution can be obtained. Key technology drivers for SAR systems are to achieve higher levels of integration and to reduce cost for the transmit/receive (T/R) modules. A major problem is removal of heat from the transmitter electronics which can limit the operational "on time" of many EO systems to only a few 10's of minutes [5]. Therefore efficient power amplifiers are needed, along with the ability to operate at higher temperatures. A bottleneck also occurs in the SAR data downlink. High speed (>1Gbps) satellite to earth downlinks are required to transmit this information while the satellite is passing over a ground station. Downlinks operating at Ka-band or higher frequencies (including optical links) are a possible option to improve downlink speed since a larger bandwidth is available for data transmission. However, a more radical way of overcoming the data link download issue, along with obtaining improved spatial resolution, improved access time and the potential for lower cost, is to operate a multi-static radar constellation of co-operating satellites [6] forming a wireless local area network (WLAN) in space. For this to become possible it will be necessary to develop microsatellites in the 50kg to 100kg range which in turn will require the development of highly miniaturised payload electronics.

Altimeter: Future pulsed FM radar altimeters require improvements in measurement accuracy (≤2cm height resolution), removal of the need for dual frequency schemes (used to correct for ionospheric delays) and development of miniaturised electronics for use onboard microsatellites. There is also a requirement to increase angular resolution in order to resolve height ambiguities over sloping ground (e.g. ice sheets). Some of these improvements can be obtained by operating at higher frequencies (Ka-band) since the wider bandwidth available for the transmit frequency chirp improves range resolution. Also, since smaller size components and antennas can be used a more compact altimeter system can be realised. In terms of microwave components, small size, solid state power amplifiers capable of delivering a few tens of Watts of output power are needed in Ka-band, along with low phase noise oscillators with highly linear frequency voltage tuning curves.

Radiometers: A typical radiometer front end consists of a high sensitivity receiver that can be operated either in a superheterodyne or direct detection configuration, as illustrated in figure 4.

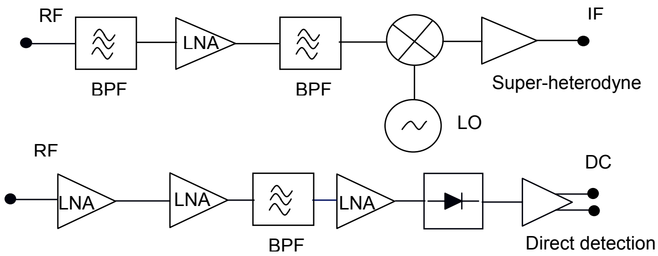

Fig. 4. Superheterodyne and direct detection radiometer architectures

The superheterodyne receiver uses a low noise amplifier (LNA) gain stage, a mixer, a local oscillator (LO) source and an IF gain block. The direct detection architecture typically consists of a high gain (≈50-60dB) low noise amplifier cascade, bandpass filtering (to limit out of band noise), a high sensitivity detector and DC electronics for noise voltage amplification. At lower frequencies, and where multiple receiver channels are used, the direct detection architecture is often preferred since the local oscillator and its associated distribution networks are no longer required. This eases radiometer implementation.

Primary factors determining sensitivity are given by the well known radiometer equation (1). For good thermal resolution it is essential to achieve a low system noise temperature (T_{sys}) which requires the use of high performance (sometimes cryogenically cooled) low noise amplifiers that have excellent gain stability over time and temperature ($\Delta G/G$).

$$\Delta T = T_{sys}\sqrt{1/B\tau + \left(\Delta G/G\right)^2} \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

The non-availability of low noise amplifiers is a limiting factor for realising ultra high frequency radiometers since the upper frequency limit of commercially available MMICs is ≈110GHz, whereas the frequency limit for research components is ≈200GHz [7]. Since direct amplification is not possible above 200GHz, superheterodyne approaches have to be adopted using Schottky diode based mixers driven by local oscillator multiplier chains. As a result, future radiometer developments will require:

- MMIC low noise amplifiers operating above 200GHz (preferably with low DC power dissipation to ease cryogenic cooling).
- High performance Schottky diodes capable of operating up to THz frequencies.
- High power sources operating at frequencies ≥500GHz for LO generation.

C. *Navigation and Science*

GALILEO is a major project that will provide Europe with its own global navigation satellite system using a constellation of 30 satellites in medium earth orbit (MEO). Each satellite will use a C-band navigation uplink, along with an L-band downlink for broadcast of navigation data. A critical requirement is the downlink transmit power amplifier where high efficiency SSPAs are needed capable of delivering >100W of RF power. This is currently at the limit of conventional solid state power amplifiers.

Many of the technology requirements and issues described earlier also apply for future Science missions. However, one of the critical differences is that extremely hostile environments often have to be encountered. One such example is the planned Solar Orbiter mission, which will be the first satellite to provide close-up views of the Sun's polar-regions. The Solar Orbiter satellite will carry its instruments to just one-fifth of the Earth's distance from the Sun where sunlight is 25 times more intense than on earth. The spacecraft must also endure powerful bursts of atomic particles from explosions in the solar atmosphere. Such missions will require microwave components to operate at high temperatures and be extremely resilient to high levels of radiation.

III. SEMICONDUCTOR TECHNOLOGY TRENDS AND SYSTEM APPLICATION BENEFITS

The performance of microwave and mm-wave systems is strongly linked to advances in semiconductor technology. Device applications can be generally classified into three areas, low noise amplification, power generation and mixed signal operation. Low noise and power amplifier functions have traditionally been dominated by III-V semiconductors, e.g. GaAs and InP. However, new materials such as indium antimonide (InSb) and gallium nitride (GaN) are emerging that have the potential to make a significant impact in specific application areas. In addition, advances in SiGe bipolar and RF CMOS technologies are starting to compete with GaAs up to frequencies as high as 40GHz due to dramatic reductions in device feature size. To illustrate some of these trends, data has been gathered on published results for the cut-off frequency (f_t), noise figure and output power density of emerging transistor technologies and a comparison made with GaAs and InP devices. This information is presented in figures 5, 6 and 7 respectively along with consideration of the system application benefits.

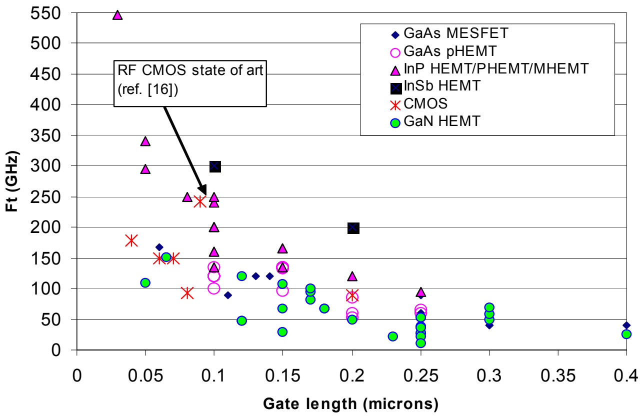

Fig. 5. Transistor cut-off frequency comparison for various device technologies

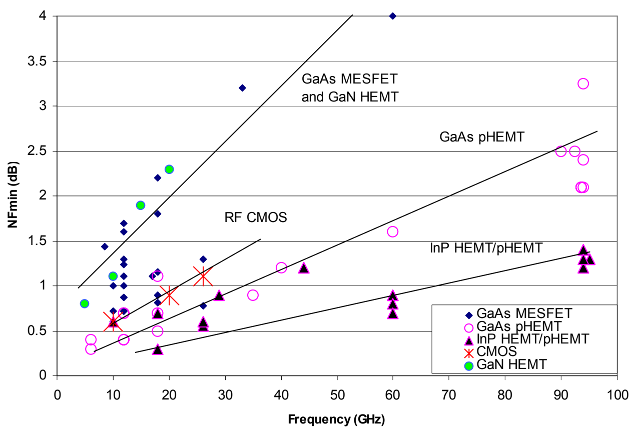

Fig. 6. NF_{min} comparison for various device technologies

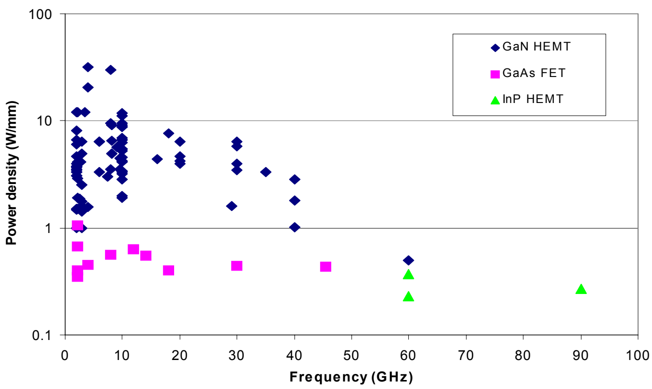

Fig. 7. Output power density capability for GaN, GaAs and InP FET technologies

Indium Antimonide: Ultra high frequency transistors have commonly been realised using InP pHEMT or MHEMT technology [8] as they provide excellent noise figure and gain performance. The incremental approach for achieving higher operating frequency has traditionally been a gradual reduction in gate length. However, for gate lengths below 70nm, the manufacturing limit is starting to be reached, in terms of yield and repeatability, so that it becomes necessary to move to higher performance materials to extend operating frequency. Indium antimonide (InSb) shows great promise as an ultra-fast, very low power consumption technology since it has the highest electron mobility and saturation velocity of any known semiconductor, as shown in table 1.

	Si	GaN	GaAs	$In_{0.53}Ga_{0.47}As$	InAs	InSb
Electron Mobility x10^3 ($cm^2V^{-1}s^{-1}$)	0.6	1.6	4.5	8	16	30
Electron Velocity (10^7 cm/s)	1.0 (sat.)	2.5 (sat.)	2.0 (sat.)	2.7 (peak)	4.0 (peak)	5.0 (peak)
Band-gap (eV)	1.1	3.4	1.43	0.72	0.36	0.18
Breakdown field (MV/cm)	0.6	3.5	0.6	0.4	0.1	0.01

Table 1. Common semiconductor material properties

The first demonstration of a high-speed InSb transistor has recently been reported in Europe and has shown that this material can be operated at room temperature using a minority carrier exclusion and extraction technique [9]. This approach mitigates the effect of the narrow band-gap on device leakage and breakdown and has allowed demonstration of a 300GHz f_t transistor, operating at Vds=0.3V, using a gate length of 0.1µm. A photograph of this device is shown in figure 8.

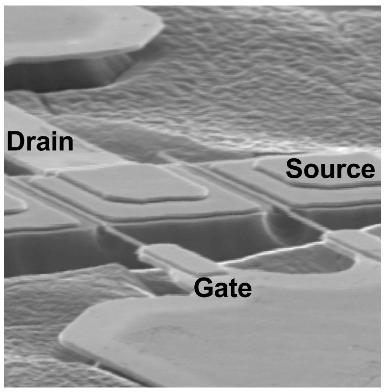

Fig. 8. SEM image of a two-finger InSb quantum well transistor (Courtesy of QinetiQ).

Figure 5 shows that for the same gate length, the operating frequency of InSb is capable of exceeding that achievable with InP. Additionally, a 5 fold reduction in DC power dissipation is obtained which is an advantage in cryogenic applications as cooling requirements can be simplified. Noise figure performance has not yet been reported, however it is likely to be comparable to InP. Therefore InSb transistor technology offers a potential way forward for realising MMIC based low noise amplifiers that can be used to extend the frequency operation of direct amplification radiometer systems to at least 500GHz. Antimonide heterostructure diodes are also likely to be useful for high frequency mixing and detector applications. Hughes Research Laboratory (HRL) has recently reported results on zero-bias square law detectors using epitaxial layers of InAs and GaAlSb [10]. Record voltage sensitivities have been demonstrated for 75 to 95 GHz detectors using these diodes, with typical values of ≈7,000mV/mW achieved for input power levels ranging from –50 to -30 dBm. High voltage sensitivity is important since it reduces the amount of RF amplification needed for direct detection radiometers. Also, since these diodes can be reproducibly manufactured it enables large-scale detector arrays utilizing zero bias direct detection circuitry to be realized. This is important for applications such as passive millimeter wave imagers, atmospheric radiometers, and radio astronomy receiver arrays.

Gallium Nitride: Wide band gap semiconductors (e.g SiC and GaN) have fundamental material properties that make them highly suited for a variety of RF and microwave applications. These electrical properties include a band gap that is much higher than for Si or GaAs (e.g. 3.4eV for GaN compared with 1.4eV for GaAs), a large breakdown field and a high saturated electron velocity. As a result, wide band gap devices offer the potential for realising microwave power amplifiers with an order of magnitude improvement in output power capability compared to GaAs. This is illustrated in figure 7, where it can be seen that the output power density of GaN is already far exceeding that reported for the best GaAs devices. Also, the high electron mobility of GaN means that it is suitable for high frequency operation with transistor cut-off frequencies as high as 150GHz recently reported [11]. This suggests that power amplifiers should be possible up to at least W-band operating frequencies. Another important advantage of wide band gap semiconductors is that they are radiation hard and have the ability to be operated at high junction temperatures. The potential benefits to space systems are simplified shielding requirements, reduced size and mass of cooling systems and improved survivability in harsh environments, e.g. as required for future Science missions.

A typical GaN power amplifier would be operated at a bias voltage of 30-50V, compared to 8V for a GaAs device. The higher operating voltage is closer to the satellite bus voltage such that power conditioning (EPC) requirements are eased. Also, a higher output impedance is obtained which simplifies matching over a wide frequency range and reduces the complexity (loss) of output manifold combining schemes. The higher output power density also enables smaller size power modules to be realised compared with using GaAs transistors. This is particularly important for Ka-band operating frequencies where antenna spacing restricts the available space to accommodate primary (and redundant) power amplifier chains. In terms of current state of art, impressive circuit results have been reported by Cree Inc. [12] demonstrating a 3-fold increase in output power compared with what is achievable with a single GaAs chip for a 38W power amplifier operating at 10GHz. As the technology matures it is clear that the GaN SSPA will become a serious competitor to the TWTA.

ESA has initiated a number of research activities to evaluate the capabilities of GaN technology for space application. One such activity is a programme of work to explore the microwave and mm-wave frequency potential of GaN semiconductors. This has culminated in the first European demonstration of a 2W Ka-band MMIC power amplifier, as illustrated in figure 9.

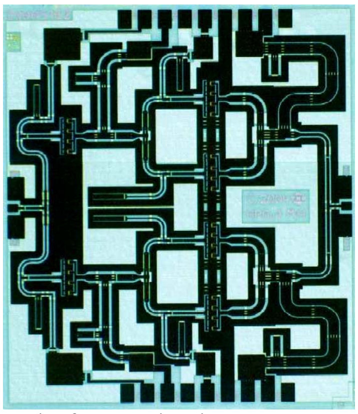

Fig. 9. Photograph of 2W Ka-band GaN MMIC power amplifier (Courtesy of TNO).

This result shows that Ka-band amplifiers capable of delivering ≥10W of output power from a single chip should be possible in the future. It is also interesting to see that the minimum noise figure (NF_{min}) for GaN HEMTs is comparable to that achievable using GaAs MESFETs, as shown in figure 6. This result is important since the combination of low noise figure and a high voltage withstand capability opens up the possibility for removing the limiter function in a typical SAR T/R module. The potential benefits are an overall reduction in system noise figure, due to reduced insertion loss in the receive path, along with reductions in module size, weight and cost.

Other applications being considered for GaN devices are for generation of mm-wave sources. One option is replacement of GaAs or InP Gunn diode oscillators with a low frequency solid-state oscillator, frequency multiplier and a mm-wave GaN power amplifier combination. This approach would allow wider operating bandwidths and an upgrade path for achieving higher output powers which are specifically needed in building THz receivers. Alternatively, some researchers have identified that the velocity-field characteristic of GaN exhibits a negative resistance that could be used to create high power Gunn diode fundamental sources [13-14] with two orders of magnitude higher output power than can be achieved using GaAs. Therefore this area is felt to be worthy of further investigation.

SiGe HBT and RF CMOS: Until recently the use of III-V semiconductors was the only means for realising microwave and mm-wave circuit functions operating above 20GHz. Rapid improvements in the frequency capability of silicon technologies have occurred such that it can now seriously be considered as a viable option to replace GaAs in some application areas. For example, silicon germanium (SiGe) heterojuncton bipolar transistors (HBT's) have recently been reported with simultaneous f_t and f_{max} values greater than 300GHz, with a minimum noise figure of 1.5dB and an associated gain of 8dB at 25GHz [15]. Figures 5 and 6 also illustrate that outstanding improvements in device f_t and NF_{min} are now being demonstrated for CMOS transistors. Current 90nm gate length nMOS devices are reported with f_t and f_{max} values of 243GHz and 208GHz respectively and a minimum noise figure of 1.1dB at 26GHz. However, such improvements in high frequency performance come at the cost of a reduction in breakdown voltage. This limits the majority of circuit applications to small signal functions.

Previously, the lack of a semi insulating substrate was one of the main drawbacks that prevented rapid introduction of high frequency silicon based MMICs above a few GHz as this resulted in lossy passive components. However, manufacturers have developed innovative approaches to get around this problem by using silicon on insulator (SOI) techniques in which transmission lines are raised above the lossy silicon substrate on an insulating SiO_2 layer. Measured results on long transmission lines indicate that a loss of ≈1.5dB/cm at 20 GHz can be achieved which is significantly better than obtained using bulk silicon. As a result of these innovations, impressive circuit performance has recently been reported for a SOI CMOS 26-42GHz LNA with a gain of 11.9dB and a noise figure of 3.6dB achieved [17]. Another noteworthy result is a 5 to 86GHz travelling wave amplifier with 9dB gain [18], as illustrated in figure 10. Similarly, SiGe HBT technology is being investigated by several researchers for realisation of a single chip 60GHz WLAN transceiver [19].

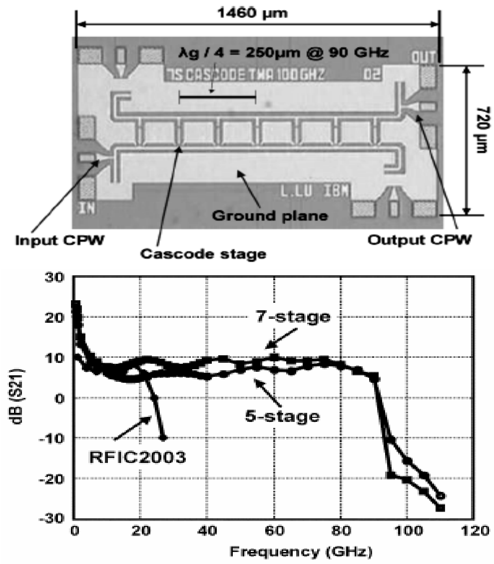

Fig. 10. CMOS 5-86GHz travelling wave amplifier (ref. [18]).

Multifunction, low cost, integrated circuit techniques will be essential for realisation of multiple transponder channels in future Ka-band telecommunications payloads, transmit receive functions in SAR phased array antennas and in the manufacture of low cost ground terminals for VSAT and navigation applications. Traditionally, many of these functions (gain blocks, phase shifters, attenuators, switches, mixers, oscillators) would have been realised using GaAs based MMICs and assembled into multi-chip modules (MCMs) or in waveguide packages with limited levels of integration. SiGe BiCMOS is an attractive alternative combining the best attributes of MOSFET technology (low power consumption logic, large-scale integration) and bipolar technology (low phase noise, low noise figure, threshold uniformity) resulting in the capability to produce a system on a chip (SoC). The primary function that is still missing in the silicon domain is the high frequency (≥5GHz) power amplifier. However, several workers are now beginning to demonstrate high power GaN/AlGaN HEMTs manufactured on silicon substrates such that this function may also become available in the near future.

One of the key issues for the space community will be maintaining access to sophisticated Si foundry process technology since the volume requirements are relatively small and the foundry cost is high. Possible ways around this problem may be to adopt a multi project wafer share approach for European space companies or to develop intellectual property (IP) blocks of common functions to reduce design and development costs.

IV. RF MEMS AND ADVANCED PACKAGING

Work is also being undertaken by ESA on the development of RF micro electro-mechanical systems (RF MEMS). Microwave applications of this technology include low loss switches for use in switch matrices, redundancy rings and tuneable filters. MEMS switches offer a much lower insertion loss and higher isolation compared to pin diode or GaAs FET equivalents, particularly over the 8 to 120GHz frequency range. An example of a 35GHz capacitive switch, developed under ESA funding, is shown in figure 11.

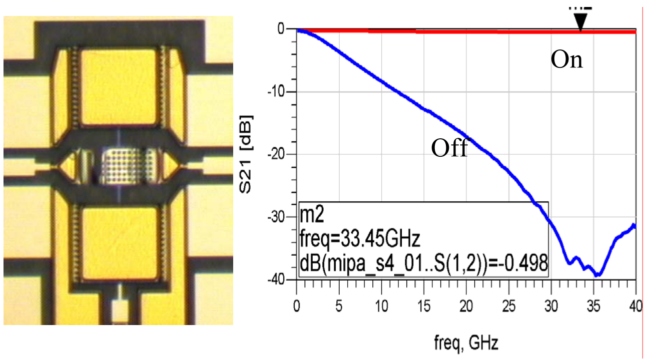

Fig. 11. RF MEMS capacitive switch (Courtesy of IMEC)

Typical measured insertion loss for this component was <0.5dB with an associated off-state isolation of >39dB. This exceeds the loss/isolation performance that is typically achieved using GaAs FET switches. At present, stiction remains one of the major problems that still needs to be resolved and therefore improvement of switch reliability is one of the key development activities currently ongoing at ESA.

Advanced packaging techniques are also essential for interfacing microwave components to the outside world and in the case of a space application to provide hermetic protection. The general trend is towards higher levels of integration, power and frequency with simplified assembly. The traditional approach of discrete packaged components mounted on a substrate has evolved with the availability of MMIC components towards using multi-layer low temperature cofired ceramic (LTCC) packages that integrate the RF feedthrough, microwave components and DC bias/control functions to form a multi chip module (MCM). ESA has a number of ongoing research activities that are aimed at developing low cost packaging techniques for microwave and mm-wave components. One example is the Microwave Multichip Hybrid Technology (MMHT) concept that is being developed by EADS [20]. This consists of a multilayer ceramic with a hermetic cavity on one side, used for attachment of active components, and a hybrid circuit on the other side used for attachment of passive components. The approach is innovative since commercially available broadband component functions (MMICs, ASICs, discrete transistors) are attached within the hermetic cavity using eutectic soldering, while on the rear side the passive surface mount components are used to tune the hybrid to its operating requirements (frequency, gain, bandwidth). This approach allows rapid design and manufacture of broadband RF blocks that are capable of re-use across many RF equipments. In contrast to the traditional approach of mounting microwave components front-face up and interfacing with gold bond wires, work is also being undertaken to investigate the suitability of flip-chip mounting of MMIC components for space applications. The primary advantages to be gained are improvements in the control of interface parasitics since bond wires are eliminated. This gives better repeatability and improved operation up into the mm-wave frequency range.

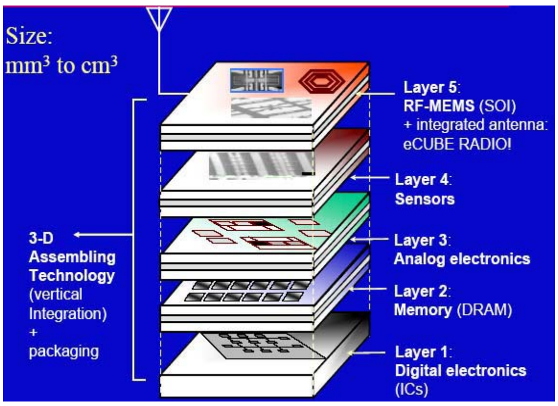

Fig. 12. 3-dimensional "e-cube" satellite on a chip (as proposed by H. Shea et. al. ref [22])

In the medium term, the move towards the system in a package (SIP) concept will continue and MCM techniques will be expanded to form a multi-layer 3-dimensional assembly [21]. However in the long term, elimination of the conventional package may occur with a move towards 3-dimensional electronics technology at the chip level. Ultimately this approach could result in a satellite payload on a chip, integrating such functions as silicon processors, microwave components, MEMS actuators, sensors and antenna functions into an "electronic cube", as illustrated in figure 12. The benefits for space systems will be the realization of low cost satellite swarms that can undertake a wide variety of operational tasks using distributed sensors.

V. CONCLUSIONS

New and emerging microwave component developments and their potential impact upon future European Space Agency missions have been considered. Rapid advances in state of art technologies such as indium antimonide (InSb), gallium nitride (GaN), RF CMOS, MEMS and advanced packaging techniques will have a significant impact in extending the frequency capability of radiometer systems, allow solid state replacement of TWTA's and enable 3-dimensional circuits to be realized that could revolutionise next generation systems. However, for this to become a reality, significant investment is still required in research and development to transition many of these technologies to manufacturing industry along with qualifying the technologies for space application.

VI. ACKNOWLEDGEMENT

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