Overview of Microwave Components Activities at the European Space Agency

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***Abstract*—A review of some of the activities of the European Space Agency in the area of Microwave Devices and Components for Space Application is presented. The activities discussed are in the areas of Solid State Devices and Technology, Travelling Wave Amplifiers, Microwave Filters and Time References. Each area is discussed in detail illustrating the achievements of on-going research and development programs involving European Industries and Research Centers. The growing importance of Microwave Technology for space applications is discussed and the future challenges outlined indicating how the European Space Industry is preparing for the future through the many R&D activities sponsored by the European Space Agency.**

I. Introduction

SINCE the beginning of the space era, the European microwave space industry has always played a key role in the successful launch of many experimental and commercial satellites. As long ago as 1978, the first communication satellite for the Fixed Satellite Service (FSS) to make extensive use of Ku-Band equipment, namely OTS, was launched under the auspices of the European Space Agency (ESA). Even by today's standards, the performance achieved by some units (e.g. the low noise amplifier with a noise figure less than 3 dB or the Travelling Wave Tube with 20 W RF and a dc to RF efficiency in excess of 40% etc.) was remarkable. In 1981, Marecs B, dedicated to the Mobile Satellite Service (MSS), was the first satellite to fly bipolar silicon Solid State Power Amplifiers at *L*-Band and, at the present time, all of its ten 10 W modules are still fully operational. The same basic technology of these forerunners was then subsequently used by many more national and regional satellites built in Europe.

For FSS and MSS, the general trend is toward Very Small Aperture Terminals (VSAT's) in the earth stations. This inevitably leads to high-gain spot beams in the spacecraft. Unfortunately, however, the evolution of the services in term of modulation, access, throughput, coverage etc . . . , are impossible to plan over the lifetime that operators expect from satellites (> 15 years). It is therefore essential that future payloads have the capability to change, in orbit, the position and the shape of various spot beams. In addition, dynamic allocation of traffic to beams will be essential in order to optimize the on-board power resources. Fig. 1 gives an example of a configuration presently studied in the European context. It is evident that such a level of sophistication is only achievable if active antennas can be deployed on board satellites which, in turn, implies extensive use of microwave solid state technology. Simpler configurations of spot beams, where flexibility requirements are less stringent, can be implemented with Travelling Wave Tube Amplifiers (TWTA) and associated circuits like, for example, a Butler matrix.

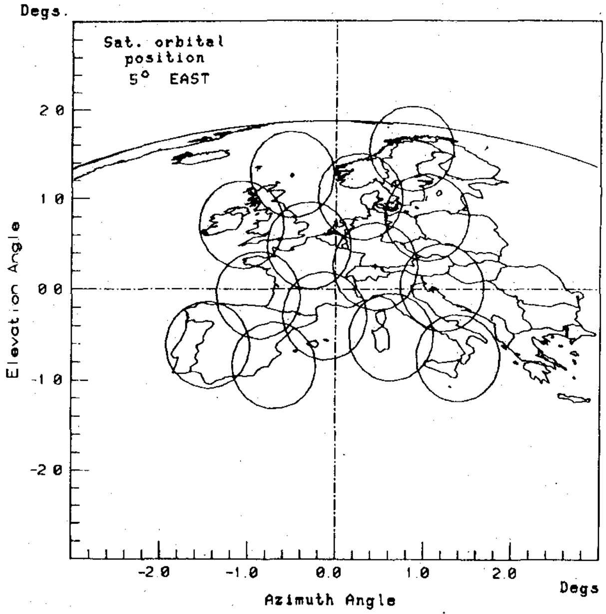

Fig. 1. Typical multiple spot beam converage of Europe.

Direct Broadcast Satellite (DBS) service is still under consideration in Europe, especially in view of the introduction of High Definition Television. The RF power to be radiated from the satellite will of the order of hundred of watts. The TWTA will, most probably, remain the most efficient way to obtain this power. However, frequency and power requirements are likely to be beyond the capability of the currently used helix type TWT and new interaction structures will have to be developed for the tubes.

The demand for earth observation at microwave frequencies is also expected to increase. In-orbit control of

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beam direction and swath size will be highly desirable. Active Synthetic Aperture Radars (ASAR) represents practically the only way to achieve this and, like future communication payloads, will depend on the successful development of microwave solid state technology.

In addition to efficient microwave equipment for their communication links, many of the scientific programs carried out by ESA require very precise clocks for which special technologies, such as atomic oscillators, must be developed.

This article presents and discusses current microwave technology and reviews how ESA promotes and coordinates the efforts of the European Industries and Research Centers to advance microwave techniques and technologies in view of future space programs.

II. Solid State Technology

Solid state technology brings indeed advantages in terms of mass, size and reliability but its main attractiveness, however, comes from its potential for the design of the complex payloads previously mentioned.

Silicon technology is well known, in fact Si bipolar transistors have already been manufactured, cost effectively, with good electrical performance up to about 2 GHz. At higher frequencies, GaAs technology has taken an indisputable advantage. With this material, active and passive devices can be manufactured with the same process. A high degree of integration can thus be obtained for various microwave functions. This enables multioctave wide-band performance, reproducible characteristics, flexible circuit topology and increased reliability to be achieved.

As already mentioned, ESA is developing active antennas. Typically, they consist of few hundreds of receive and transmit elements with very stringent requirements on gain and phase tracking performance (typically 0.5 dBpp and 5 deg.pp, respectively, over a dynamic range of 20 dB, and a temperature range of −15 to +55°C.) and of their Beam Forming Networks (BFN). It is clear that Monolithic Microwave Integrated Circuits (MMIC) will have an important role to play here [1], [2].

In order to properly assess the actual performance of the GaAs technology (and its evolution in the future), in an environment as close as possible to the one found in space application, ESA has awarded many development contacts, requesting the association of an equipment manufacturer, as designer, and foundries. The most significant achievements are reported in the following section, with special emphasis on MMIC and on Solid State Power Amplifiers.

A. Monolithic Microwave Integrated Circuits

The European GaAs technology has come now to age. At present three foundries offer commercial services in Europe: GEC-Marconi (ex Plessey) (UK), Philips Microwave Limeil (PML) (F) and Thomson (F). Very recently also AEG (D) has announced the operation of their foundry facilities on a commercial basis. The 0.5 μm MESFET process (identified as F20) from GEC is suitable for low noise and general purpose devices. PML have 3 different depletion mode MESFET processes: 0.7 μm (D07A) for analog IC's, 0.7 μm (D07M) for power MMIC's, and 0.5 μm (D05ML) for low noise circuits. A fourth 0.7 μm process (ED07AD) also includes enhancement mode devices, and has attractive features for combined analog/digital IC's. Thomson have two MESFET processes: 0.5 μm (LN05) for low noise applications and 0.7 μm (HP07) for high power applications. In addition Thomson provide second source of digital processes of the Vitesse (USA) foundry. Production of high volume GaAs discrete components and MMIC's is provided in Europe by Siemens (D), and many other companies (e.g. Telettra (I), Alenia (I), Fraunhofer Institute (D)) have internal facilities for producing GaAs MMIC's. In the immediate future European foundries will also have advanced processes such as 0.25 μm P-HEMT for extremely low noise applications, and power processes up to *Ku*-band.

B. MMIC activities at Ku-Band

At *Ku*-band, the main application is the active array. In fact, future communication satellites using an active array are expected to require few hundreds of transmit and receive elements.

For the receiver, a convincing demonstration of miniaturization achievable with MMIC has been given by Dassault Electronique (F) [3]. The front end amplifier, at 14 GHz, is a chip designed using the F20 process from GEC. The mixer, from 14 to 11 GHz, and the IF amplifier are two separate chips designed with the D05ML foundry process of PML. A standard chip from GEC has been used for the local oscillator amplifier. The complete assembly is compensated over temperature and has an RF to IF gain of 55 dB. The module, assembled in a kovar package, as shown on Fig. 2, has a total volume of 6 cm^3 and a weight less than 30 g. It is, however, planned to replace the front-end chip at 14 GHz by a discrete low noise transistor amplifier based on HEMT technology, already available in many places in Europe (Plessey, Thomson, PML, Siemens). It is even possible to consider a complete low noise amplifier and mixer on a single HEMT MMIC chip since this technology is now well advanced (it will be available soon from European Foundries).

The BFN is a key unit for the in-orbit control of a beam. Since multiple beams will be necessary, many BFN's will be required and their miniaturization is also essential. The main constituents of a BFN are power splitters, variable phase shifters and variable gain amplifiers, with Si-ASIC based control circuits. ESA is evaluating the technology with two industrial teams working on parallel contracts. An interesting aspect of this activity is that, in order to improve the reliability and reduce assembly costs, a multifunction chip with variable phase shifting over 360° and variable amplification over a range of 20 dB had to be

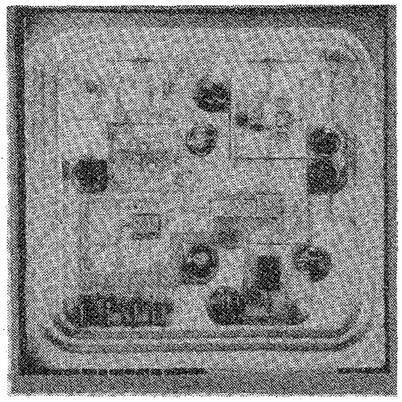
Fig. 2. 14/12 GHz miniaturized receiver.

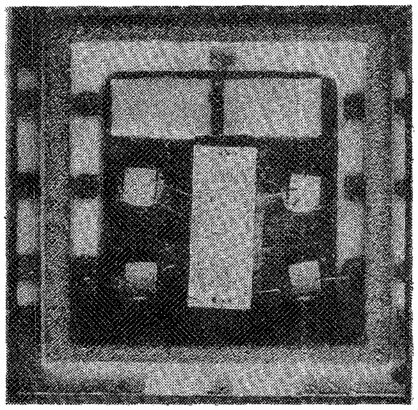
Fig. 3. *C*-band switching element.

developed in both cases. One team, GEC (F20 process) and MBB, has proposed a concept based on an active 5 bit phase shifter. The dc power consumption of the microwave part is dominant but the ASIC is rather simple. The second team, Alcatel Espace (F) and Philips Microwave (D05ML process), has proposed a passive 5 bit phase shifter concept. In this case, the power consumption is dominant for the ASIC and minimal for the microwave part.

On the transmit side, it is not believed that the power stage could be efficiently realized on a MMIC chip, but rather with hybrid technology and a discrete power transistor. However, the driver is well within the reach of MMIC. A development contract is presently running with GEC. The objective is an amplifier operating in a multicarrier mode, delivering 1 W RF power with a C/I better than 38 dBc (2 carriers) and a dc to RF efficiency in excess of 20%. A three stage design has been proposed. The two first consist of 2 MMIC chips (F20 process), one of them having a gain control function for temperature compensation. The last stage is manufactured on an ion-implanted wafer, with optimized implantation profile, and employs a bathtub structure for best thermal performance [4].

C. MMIC activites at C-Band

The main applications at *C*-band, for the time being, are the Data Relay Satellite (DRS) and the Synthetic Aperture radar (SAR) payloads.

Two developments explore the advantages of the MMIC technology for the intermediate frequency of DRS from 5.3 to 5.7 GHz:

An 8 by 8 switching matrix is being developed by ANT (D). Very high isolation, >60 db, is obtained using a switchable amplifier configuration. The MMIC chip design and manufacturing is done by GEC (F20 foundry) [5]. Fig. 3 shows one of the switching elements.

Many IF amplifiers (20 to 30) are necessary and miniaturization of this equipment is quite attractive. This type of equipment is being developed by FEL-TNO (NL) using the PML D05ML MMIC process.

For the SAR, the operating frequency is 5.5 GHz. Initial studies suggest that the antenna should consist of more than 700 Transmit/Receive modules, for a total dimension of 10 m by 1.3 m. Each module should provide about 10 W peak RF power (7.5% duty cycle) and less than 3 dB noise figure. MMIC will be widely used although the output stage is likely to utilize discrete devices or MMIC's using off-chip matching circuits. Alcatel Espace are carrying out a breadboard-model development, with the transmit signal switchable to two orthogonal polarizations and simultaneous reception in both polarizations. The module makes use of MMIC devices from different foundries. An interesting feature of the module being developed is that the RF signals and the Telecommand and Telemetry signals are provided by an optical interface with a central control unit.

D. Other MMIC Activities

Two industrial teams, namely BAE (UK) associated with the PML foundry and Alcatel Espace associated with the GEC foundry, are studying MMIC devices for other common applications in the microwave spectrum. Typical examples are: frequency conversion, linear phase modulation, medium power amplification etc. . . . In addition, the implementation of GaAs, or even Si, standard MMIC chips for mobile terminal (at *L*-Band) will be the subject of a forthcoming contract to be awarded by ESA. Other activities are planned in 1992 for developing standard components for VSAT's at *Ku*-band.

The qualification of the MMIC technology for space application is the subject of many ESA sponsored activities in the various European foundries [6], [7] and semiconductor manufacturers like Telettra (I), for power MESFET's. The approach followed is the one of Capability Approval that is applicable to all technologies (e.g., ASIC on Si, MMIC on GaAs) where a fixed foundry process can produce a whole range of products. This approach differs significantly from the standard qualification of a single component and will lead to schedule and cost advantage. In a Capability Approval a process is at first reviewed by analyzing the manufacturer data, also through construction analysis of samples. Following this first phase the manufacturer is evaluated considering both the adequacy of its Quality Assurance (QA) system and its technological process to determine failure modes and reliability features. At this point the Capability Approval testing is started on dedicate testing vehicles, which fully characterize the technological domain of interest. Once this phase is successfully completed a Capability Approval is granted by ESA for that process. The qualification of a particular MMIC function is then only subjected to the successful performance of a Type Approval test.

In addition to supervising R&D contracts in the industry, ESA is carrying out its own research program in MMIC at ESTEC. Computer facilities and software are used for the design of MMIC chips in all of the commercial foundries in Europe developing layout macro instructions, linear and nonlinear modeling etc. . . Once manufactured the MMIC chips, Fig. 4 is one example, are dc and RF characterized on wafer and in various test jigs. Quite often young graduate trainees as well as students from various European Universities are involved in this research program.

E. Solid State Power Amplification

Solid State Power Amplifiers are already used in many satellite repeaters when they can represent an alternative to TWTA's [8], [9]. They are, however, essential in active array antennas where a large number of linear units is required. One attractive feature of an SSPA is that it operates with low dc bias and this simplifies considerably the dc power conditioner. The main application at *L*-Band is the MSS. For the Inmarsat 3 repeater, built by Matra Marconi Space (UK), as many as 22 amplifiers per spacecraft will be integrated. The qualified bipolar transistors, manufactured by Philips Components (F), are used with a (patented) Dynamically Electronic Biasing System (DEBS), which maintains good linearity and efficiency over a large input dynamic range. The RF output power is about 20 W, with an associated dc to RF efficiency better than 30% and a C/I of 16 dB.

With the same type of bipolar devices, MBB (D) are developing a different method to improve the linearity. The concept: Power Amplifier Module for High Efficient and Linear Amplification (PAMELA) (an MBB patent [10]) is based on adaptive loading techniques. A breadboard has been manufactured utilizing bipolar transistors from Philips Components (F) (see Fig. 5). At 20W RF output power, a noise power ratio of 19 dB has been measured. The associated dc to RF efficiency is better than 27% and remains also good in back-off conditions. The gain and phase stay constant within 0.5 dBpp and 4 deg.pp, respectively, over 25 dB input signal dynamic range. The PAMELA technique is now being applied by MBB (D) at *Ku*-band using power MESFET's from Thomson (F).

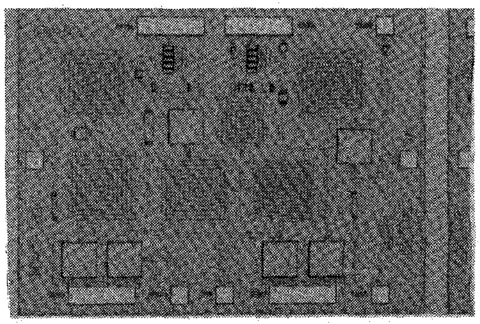

Fig. 4. MMIC *S*-band amplifier designed at ESTEC.

At *S*-Band, the main application is for inter-satellites links between LEO vehicle (Colombus, Hermes) and the DRS. Fiar have developed a 30 W RF amplifier [11], with a MESFET device. The dc to RF efficiency is 31% (including the DC power conditioner) over the full temperature range (−20 to + 60°). The linearity achieved is such that the single carrier QPSK transmitted has its first side lobe at −25 dBc, which avoids excessive sprectrum spreading.

At *Ku*-Band, a demonstrator amplifier is being developed with discrete GaAs MESFET's for the evaluation of this device in a phased aray configuration. 37 SSPA's have been manufactured by Mier Communicationes (E) [12], [13]. With two carriers in the 12.5 to 12.75 GHz band, 3 W RF have been obtained using Fujitsu devices. The dc to RF efficiency is close to 20% and the C/I better than 20 dB. Over the input dynamic range, the peak-to-peak gain and phase tracking between all 37 amplifiers is expected to be better than 0.5 dB and 5°, respectively, without any special linearization. When better linearity is necessary, a linearizer in front of a standard SSPA, can further improve the overall performance. Better efficiency at a required C/I, reduction of gain and phase variation and thus better tracking over the dynamic range, have been demonstrated by ANT (D) with the development of a linearizer based on the predistortion principle (see Fig. 6).

At 20 GHz, DRS has a special need for a SSPA. The RF power required is 5 W and it is obtained by combining six devices (from Thomson). Low loss (<0.1 dB) and compact three- and two-way waveguide combiners have been designed by Siemens Telecommunicazioni (I) [14] with an electromagnetic simulator (ANAPLAN) developed at the University of Pavia (I). Fig. 7 shows the combining network. The target is an overall efficiency of 20% and a C/I of 20 dB with two carriers.

ESA sponsors other developments to improve SSPA's characteristics. In particular, class-B operation with MESFET has been evaluated by the University of Lille (F) [15], distributed power amplifier by ERA (GB) [16], memory-less biasing circuits by Hirschmann (A) [17] and improved modeling of Lange coupler for SSPA by the "Politecnico di Milano" (I) [18].

If most of the present realizations with GaAs are based on MESFET structures, new devices are being studied which look very promising in terms of RF output power, associated gain, efficiency and also reliability. This is the case of Pseudomorphic High Electron Mobility Transistor (P-HEMT) and Heterojunction Bipolar Transistor (HBT) under development at the Daimler-Benz Research Centre

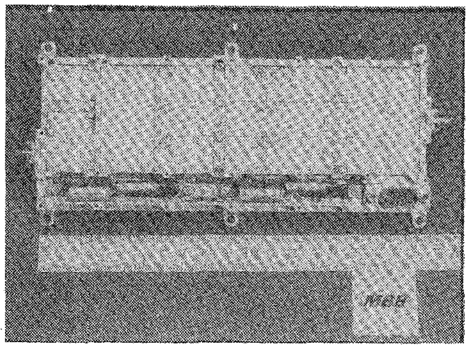

Fig. 5. Breadboard Model of "PAMELA" *L*-band SSPA.

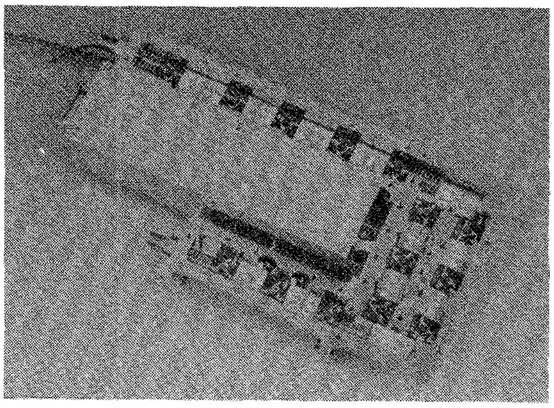

Fig. 6. 12 GHz linearizer.

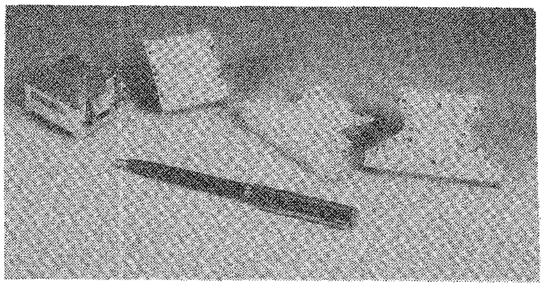

Fig. 7. 20 GHz three way wave-guide coupler.

(D), at Thomson (F), and at GEC (UK). The application of HBT devices to space has been studied under an ESA contract by the University of Darmstadt (D) [19].

F. Other Solid State Technologies

Microwave technology in the millimeter wave range is also being investigated by ESA for possible applications in inter-satellite links, radiometers etc. . . At 60 GHz, VTT (SF) are developing a low noise amplifier using Pseudomorphic HEMT devices from Daimler (D), and STI (I) the frequency mixer to 4 GHz. ANT (D) and Elektronic Centralen (DK) are using GaAs FET devices from Thomson (F) to replace Gunn diodes for direct frequency generation at 36 and 45 GHz using whispering-gallery Dielectric Resonators to stabilize the frequency.

III. TRAVELLING WAVE TUBES

The Travelling Wave Tube, (TWT), together with its Electronic Power Conditioner, (EPC), form a Travelling Wave Tube Amplifier (TWTA). If SSPA's are particularly suited for active element phased array payloads, the TWTA is still the most commonly used equipment when high RF power generation is requested on board space platform or when extensive on board beam reconfiguration is not necessary. ESA has dedicated much effort in bringing the European TWTA technology to a mature state. This support has mainly been directed at the *Ku*-Band (10.7–12.75 GHz) for FSS and DBS, with RF output powers in the range of 50 to 130 W. These development and qualification activities have been carried out with TTE (F) and AEG (D) for the TWT, and with ANT (D) and FIAR (I) for the EPC. The TWTA's have a instanteneous power capabilities over the entire 10.7 to 12.75 frequency range, thus allowing greater flexibility in channel allocation and redundancy scheme. TWT efficiency has been significantly improved by new helix tapering concepts and collector design from some 40% a few years ago (OTS) to over 60% now. Standardization of design and modular manufacturing concepts have allowed cost reduction and reduced delivery schedule times. TWTS's of this generation have an efficiency of 60% and a mass of 750 g for an output power of 50 W. At 130 W the efficiency is 61% and the mass 950 g. The EPC has an efficiency in excess of 90%, a mass of 1600 g for the 50 W TWT and 1900 g for the 130 W TWT. They have been successfully selected for a number of commercial programs, for instance Intelsat VII, Telecom 2, Eutelsat 2, Hispasat, Telestar etc. . .

Work is now in hand for the development of higher frequency *K*- and *Ka*-band TWTA's, namely: 45 W at 17 GHz, 30 W at 23 GHz and at 27 GHz, for DRS applications. The good design practices learned during the *Ku*-Band developments are again applied and will result in optimized performance. TWT efficiency of around 48% at 27 GHz, for 30 W, with a mass around 850 g is expected.

The presently operating European DBS satellites (TDF, TVSAT, Tele-X, Olympus) all use 230 W *Ku*-Band TWTA's. The DBS satellites being now under design (Hispasat, Europesat. .) require about 120 W, still at *Ku*-Band. Future concepts, with High Definition Television, will broadcast at higher frequencies and higher powers. As an example some studies are considering 250 W and 23 GHz. This would exceed the power capabilities of helix TWT's and some initial development on coupled cavity TWT is therefore foreseen. As an alternative method of obtaining higher RF output power, a Butler matrix configuration [20] paralleling a number of lower power TWT's is also investigated. This approach is also considered for spot beam generation when few beams are necessary and less stringent flexibility is required.

The recent significant improvement is the performance of TWTA's (for efficiency in particular) is due to the increased understanding of electron bunching and interaction in the TWT. This outlines the essential importance of the theoretical design capabilities program of ESA. For example, the work carried out by the University of Lancaster (UK) has brought new capabilities for the accurate modeling of higher efficiency collectors having asymmetrical designs using a three dimensional depressed collector computer modeling code [21].

Although the efficiency of a TWTA is very high at saturation, its linearity may not be acceptable. Operating the TWT in back off would improve this linearity but degrade the efficiency. Like SSPA's, a predistortion circuit in front of the tube would bring an excellent compromise, admittedly with a mass penalty. ANT have demonstrated good performance for a broad-band linearizer [22].

Finally, it is ESA's aim to continuously try to improve the reliability of flight hardware. To this end, a "TWTA Working Group" has generated a "TWTA Procurement Requirement Specification" This document includes not only formal qualification and flight acceptance testing requirements but also design requirements for both TWT and EPC. It is foreseen that it will become a mandatory requirement for all ESA programs. It is also being widely discussed with the international community in view of becoming in the future an international standard for space TWTA procurement.

IV. MICROWAVE FILTERS

Microwave filters are to be found in all satellite payloads. Miniaturization, while maintaining or even improving electrical performance, has therefore been the subject of many research and development activities.

Recently, dielectric materials with very low losses have become available, in particular in Europe at Tekelec (F), which has manufactured a dielectric "pill" resonating from 6 to 8 GHz with a quality factor Q*F of 10^5. To take advantage of these new materials, ESA has sponsored the following activities on the utilization of dielectrics for the miniaturization of waveguide filters.

Alenia and Cselt (I) have developed an IMUX channel filter with 72 MHz bandwidth at 11 GHz [23]. The insertion loss is 1.5 dB and power utilization is being considered.

ComDev (UK) are developing various types of filters at different frequencies with the following target performances:

1. A directional five channel multiplexer at 12 GHz [24]. Four have a channel bandwidth of 36 MHZ, with and target insertion loss of 0.8 dB. The last filter has a bandwidth of 72 MHz and target insertion loss of 0.5 dB. Fig. 8 shows details of this filter.
2. A diplexer at *Ku*-Band: one (receive) band from 14.0 to 14,5 GHz, the other (transmit) band from 12.5 to 12.75 GHz. In both bands the target insertion loss is less than 0.2 dB and the transmit filter will be designed to resist multipaction and Passive Intermodulation Products (PIMP) generation.
3. An *L*-Band diplexer: 1530–1555 MHz transmit and 1626.5–1660.5 MHz receive with target insertion loss of less than 0.3 dB, also multipaction and PIMP free.

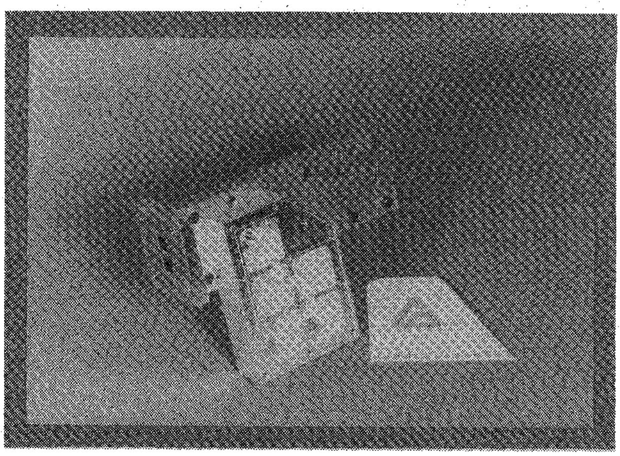

Fig. 8. Detail of multiplexer filter being developed by Com Dev Europe (UK).

ANT (D) are developing a diplexer at *S*-Band [25]. It operates at 2.2 to 2.3 GHz for receive and 2.025 to 2.120 GHz for transmit, with an insertion loss less than 0.4 dB.

Furthermore, studies are being carried out by the University of Limoges (F) on the degradation of unloaded Q of dielectric resonators cut by metallic planes [26]. This is of interest because if the Q factor can be kept at an acceptable high level, the "image resonator" concept can further reduce the size and mass of the filters.

To improve spectrum utilization, ANT (D) have developed a 12 contiguous-channel manifold multiplexer [27]. Each individual filter is in circular waveguide, see Fig. 9. The channels bandwidth is 27 MHz for eight channels and 52 MHz for the other four. Insertion loss is 1.0 dB and 0.65 dB, respectively.

With the fast development of solid state technology, it is essential that suitable filters are developed on planar structures. In spite of high insertion loss, Surface Acoustic Wave technology is attractive at frequencies below 1 GHz for narrow-band channel filters as required for the MSS, for example. Manifolding of SAW filters is possible with rather good performance. The use of Magnetostatic Waves (MSW) devices is also being investigated by ESA with the CNR (I) [28]. Preliminary results see (Fig. 10) show a variable bandwidth, between 20 and 200 MHz at a centre frequency tunable between 2 and 20 GHz.

Active filters on substrates compatible with GaAs MMIC are being studied by the Universities of Limoges [29] (see Fig. 11) and Duisburg (D), and by King's College London (UK).

For millimeter wave applications, Non Radiating Dielectric waveguide (NRD) structures are being evaluated with the University of Rome "La Sapienza" (I). In the initial phase, a ring type resonator has been studied to determine its electrical characteristics [30], [31] (see Fig. 12).

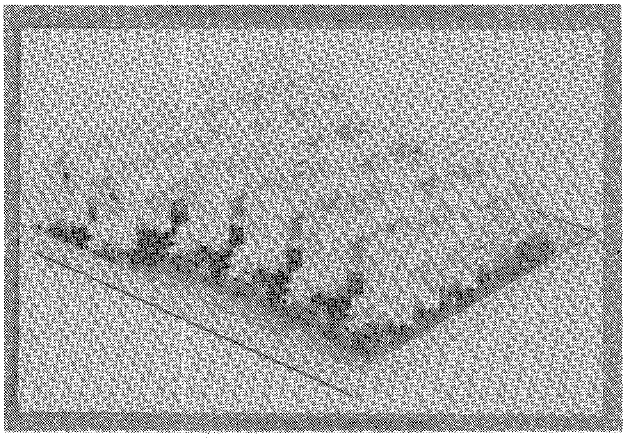

Fig. 9. Twelve channel contiguous multiplexer developed by ANT (D).

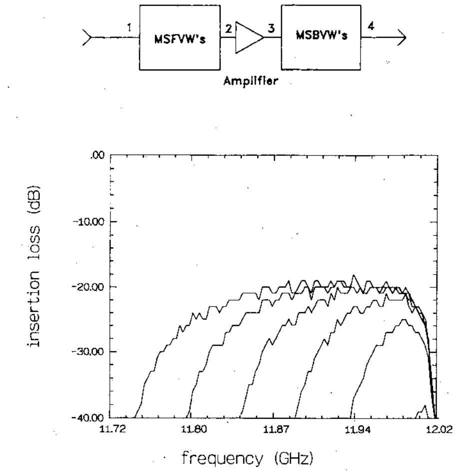

Fig. 10. Topology and simulated behavior of MSW variable filter, CNR Rome (I).

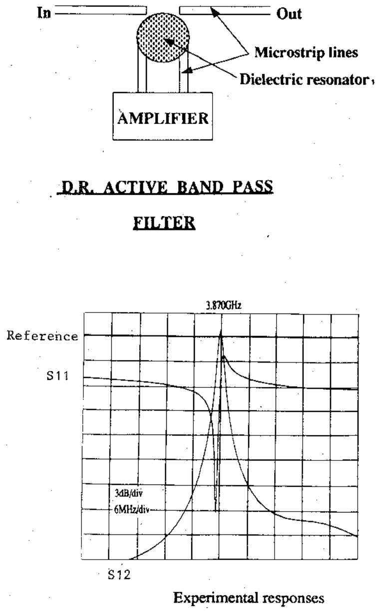

Fig. 11. Typical active filter topology investigated by the University of Limoges (F).

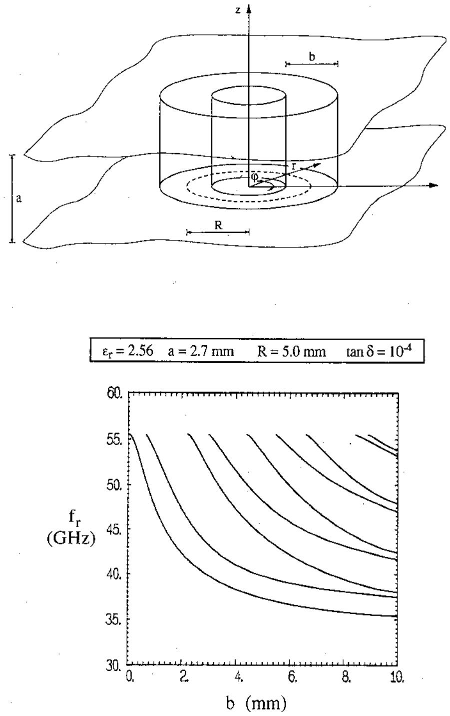

Fig. 12. Structure and mode chart of NRD ring resonator, University of Rome "La Sapienza" (I).

ESTEC carries also its own R&D program in filters. The main activities are in the area of modeling of discontinuities [32], [33], planar transmission lines analysis, enclosure effects and dual-mode microstrip filters [34], [35].

V. ACTIVITIES IN TIME AND FREQUENCY

The fact that time can be measured so precisely, far better than any other physical parameter, represents a technological asset of great importance. Nearly all ESA programs including both the ground and space segments, require some form of stable timing for successful operation. Typical examples are digital network synchronization, spread spectrum communication, range and range rate determination, navigation and position, very long baseline interferometry, scientific research (gravity and relativity experiments), time transfer by satellites etc.

Oscillators based on quartz have been used for the majority of space missions to date. Good initial performance is achievable but as averaging time increases towards one day, some degradation appears. When applications require stability over longer periods, e.g. GPS (global Positioning System), Ultra Stable Oscillator (USO) must be implemented using, for instance, atomic clocks.

The three main atomic oscillators in use today are based on the atoms of rubidium, hydrogen and cesium. The basic principle of operation is the same for each. A voltage controlled crystal oscillator is locked to a highly stable frequency reference generated by a microwave transition in the atom of interest. The rubidium USO utilizes the ground state hyperfine transition of the rubidium atom at 6834682111 Hz. The device offers the unique combination of very high long term frequency stability, typically

5×10^{-12} over 1 s, low dc power consumption and miniaturization potential. A miniature engineering model of rubidium USO is being developed by the Observatoire de Neuchatel, ON, (CH). The hydrogen maser is an active oscillator with an output derived from the quantum transition between two hyperfine ground state levels corresponding to the well 21 cm line or 1420405751 Hz. Masers are the most accurate commercially available clocks over the medium to long term with stabilities better than 5×10^{-15} over 1000 s. Other activities, still with the ON, aim at the development of ground and space masers capable of achieving long term stabilities better than 3×10^{-16} over 1000 s. The major advantage of the cesium clock is its long term stability: typically 10^{-13} per year. This stability arises because cesium tubes use collision-free atomic beams rather than a confined/buffer gas, as for example rubidium. ON is presently considering the introduction of optical pumping in order to reduce the device mass by eliminating the state selection magnets and their supporting structure used in classical models. The main barrier to progress is currently the frequency stability of the laser diode used to pump the cesium atoms.

Finally, ESA has entrusted the ON with the task of maintaining capabilities to perform high precision frequency stability measurements. In particular, a system to perform close to carrier phase noise and short term stability of the USO mentioned previously is under development. The test set has been specially designed to be portable for use at remote locations at the request of users.

VI. CONCLUSION

More than ever, the next generation of application and scientific satellite payloads will depend on microwave technology for their successful implementation. Microwaves will be the cornerstone of sophisticated concepts previously considered as dreams and now urgently needed by satellite operators in quest for in-orbit flexibility. In this context, the European industry, already in the forefront of TWT achievement, very active in solid state, microwave filters and time-reference developments is certainly up to the challenge as already demonstrated in many of the R&D activities sponsored by the European Space Agency.

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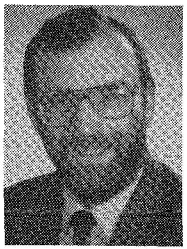

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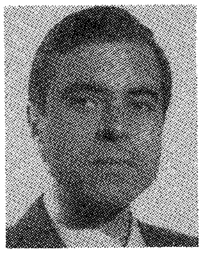
Dr. Feltham is a member of the Institute of Physics.



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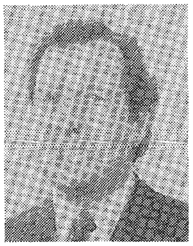

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