*FUSE*

**APPLICATION EXPERIMENT**

**DEMONSTRATOR DOCUMENT**

**I-1953**

# MEDIUM POWER MONOLITHIC AMPLIFIER FOR ROAD TO VEHICLE TRANSMITTER

**March 1999**

**rev-03**

**Abstract**

Micrel is an Italian company that designs and produces components and subsystem devices for telecommunication . The company has 22 employees, 4 are involved in electronic system design .

Intent of the project was the implementation of a GaAs medium power amplifier (MPA) single chip to be used in the new generation of ground station transceiver for Road-Vehicle communication data link. GaAs medium power amplifier in monolithic form will replace the old discrete components. The new technology will ensure increased security and reliability of the data exchange to mobile vehicles (in the range of some tens of metres) by using microwave carrier and digital modulations. Moreover it allowed to increase the product performance and to reduce its cost.

The presented one is the only solution to address large volume production market with a competitive price strategy. The new product will open to the company the promising market of the service areas (application to automatic debiting systems, city downtown entrance control...)
The experiment had a duration of 24 months and a budget of 119KECU. The anticipated pay-back period is less than 2 years.

The new MPA presents performance improvements due to higher output power (+1 dBm) , better ON/OFF ratio (+ 6 dB), wide bandwidth (5,7-6,1 Ghz) and higher reliability.
Assembling and testing operations are reduced by the replacement of many discrete components with a single monolithic module, with a process yield improvement and a cost reduction of about 250 ECU for each transmitter module in a mass production.

At the end of the AE , beyond the developed module and its commercial benefits, the company has acquired new design skills and management experiences. These additional benefits encompass the non linear design techniques, now applied in many other developments, and the capabilities of issuing proper technical specifications and interacting with consultants and external services.

The Targeted Industries belong to industrial sector of electronic components and subsystems in the telecommunication field.

## 1. Company name and address

Alenia Difesa - Divisione Sistemi Avionici ed Equipaggiamenti
Unità Officine Galileo
Microelettronica
Via Einstein, 35
I - 50013 Campi Bisenzio FI
Italy

Former Company Name :
Micrel S.p.A.
Via Einstein, 26
I - 50013 Campi Bisenzio FI
Italy

## 2. Company size

Number of people involved in the microelectronics field is 19. Basic knowledge is in the microwave and millimetre wave frequency range, even if a market niche has been successfully established in Radar Pulse compressor Surface Acoustic Wave modules. The Company's design personnel have been developing suitable components and subassemblies for Radar-Telecommunications (i.e. Radio Link and Ground Based satellite transceiver) applications. CAD modelling and simulation of hybrid circuit with accurate microwave and millimetre wave testing and mechanical design capability represent the basic skills of designers.

On the other hand, since 1984 the company has been developing an appropriate competence in hybrid thin-film technology. Processes like substrate metallisation and etching, hybrid assembling and hermetic sealing of components and subassemblies, represent the major technological tools of the Company design and production facility.
Personnel involved in the program included 2 microwave senior designer engineers and 1 senior engineer as programme manager. ( Only From May 1996 to March 1997)
Since August 1996 Micrel S.p.A. has been incorporated by Alenia Difesa-Divisione Sistemi Avionici ed Equipaggiamenti - Unità Officine Galileo.

## 3. Company business description

Microwave and millimetre-wave hybrid integrated circuits, SAW devices and integrated subassemblies.

Micrel was founded in 1984 as an independent company in order to satisfy the advanced technological exigencies, required by the Italian and foreigner high-tech military and civil market, through custom designed component and subassemblies production and manufacturing.

Micrel's mission has been dedicated to operate as a design and technological facility for the market of "system companies" which make use of hybrid microwave and millimetre wave technology sensors. According to custom system-specifications, Micrel designs and produces components and subsystems by using proprietary CAD software and a mature hybrid thin-film technology for application such as airborne and ground based radar system, telecommunication transceiver, automotive and satellite data link.. Since 1994, the company belongs to the FINMECCANICA Group

Present Micrel product lines include SAW (Surface Acoustic Wave) pulse compression modules, hybrid MIC (Microwave integrated circuit) and MMW (MilliMeter Wave) components, and integrated subsystems from some tens of MHz up to 40GHz.

In the field of **SAW** components, Micrel has been a partner of advanced research projects under National Research Program grants. The Company has achieved a national and world-wide leadership with state of the art performance level in the field of SAW Compression Modules and SAW-Based Chirp transformer. Airborne and ground radar systems, real time spectral analysis and electronic warfare are the main application fields of Micrel Surface Acoustic Wave products (SAWs).

Hybrid microwave integrated circuit (**MIC**), operating from 1 to 30GHz have been mainly designed and produced by Micrel as "building-blocks" for custom-designed microwave integrated subassemblies. Micrel component typology includes Gallium Arsenide (GaAS) Hemt and GaAs Fet low noise amplifiers, solid state transmitters, up and down balanced converters, pin-diode switches and attenuators, and a variety of microwave oscillators as DROs, synthesisers, and VCOs. Preferred propagation structures are microstrip lines on alumina thin film and soft substrates. Typical radar hybrid subassembly production includes X-band front-end for early-warning radar, C-Band microstrip down converters for radar-altimeter, different typology of high performance monopulse X-band multichannel radar front-end and up converters for fighter aircraft.

Micrel professional and civil market of hybrid microwave integrated subassemblies is mainly dedicated to ground stations for satellite communications and microwave transmitters and receivers for highway automatic tolling systems. Ku-band RTX with solid state transmitters, low-noise down converters and agile synthesisers for SCPC ground based stations have been produced by Micrel for Nuova Telespazio (IRI/STET Telecom Group). Since 1992, Micrel is operating on TELEPASS™ (the Italian automatic debiting system developed by Società Autostrade) ground based transceiver . More than 500 hybrid units have been designed and produced for the first generation of road terminals.

Since 1988, Micrel has established a research group in the field of MilliMeter wave (**MMW**) components. The group has developed a proprietary CAD software, based on in house modelling of devices and discontinuities; this has been intensively used in a "design-loop configuration" based on a HP8510B millimetre-wave vector analyser and a couple of UNIX workstation. By using this loop for measurements acquisition and modelling verifications, Micrel has achieved a full design and production capabilities of MMW components. Preferred propagation structures are symmetrical stripline and microstrip but also standard waveguide is included. Typical applications include components and subassemblies for radiometers, short-wavelength radars and telecommunication equipment. Up and down converters have been designed and produced for ITALSAT Alenia Spazio (IRI/Finmeccanica Group) ground station. A pulsed Ka band radar-front end has been designed and successfully tested for automotive collision avoidance radar; the transmit/receiver units have been manufactured in a rugged and compact size in order to withstand typical automotive environment and high volume production. Recently, extending microstrip technology to the field of millimetre frequencies, Micrel has developed components for application in the telecommunications band of 37 ÷ 39.5GHz..

TECHNOLOGY:

More than 250 squared meters of 10.000 to 100.000 class clean room (according to MIL-STD 209) for thin-film process including mask fabrication, film-deposition, spinning and multimask exposition, chemical etching, sealing and measurements control, represent Micrel's technological tools. The hybrid assembling process is carried out with pick and place units, thermosonic, thermocompression or ball-wire and ribbon bonding machines. The facilities include a "yellow" (class 10.000) room for thin film and photoetching processes, a "red" room for MIC/MMW mask generation, two assembling areas (class 100.000) for assembling, sputtering and sealing.

QUALITY:

The company is endowed with a Quality System not only to compliance with the usual equation "Quality = Conformity" but also to implement an industrial process capable to develop a quality product with the minimum cost. Since 1987 the company is equipped with Configuration Management and Control Procedures, Process, Manufacturing and Production Control Procedure including Suppliers Qualification, Incoming inspection, Quality Design Review and Production Screening, according to Nato AQAP-1.
On 1989, the Company was certified by the Aeritalia Company, now Alenia Group, in compliance with Nato AQAP-1 Quality System. Since August 1996, the Microelectronics Unit Quality System is under Officine Galileo Quality System responsibility.

## 4. Company markets and competitive position at the start of the AE

Micrel is pursuing two different market niches: the first-one is represented by the Italian System Companies which are manufacturing Radar Systems (airborne, ground-based, mobile). Some contract have been obtained also from EEC and South American companies.

The second sector is represented by the Telecommunications System area in which Micrel addresses the Radio-Link producers (ground-based telecommunication radio link or ground to vehicle data communication like the Società Autostrade Telepass System). In this market region, Micrel has been involved in ground based satellite transceiver design and manufacturing (for Eutelsat and Italsat birds), and telecommunications equipment for Siemens.

The Micrel market has been initially dedicated to military applications only; after the drop of the late 80's (in which the company trade was already 50% devoted to non military applications), military niches are now the backbone of the actual Company's revenues. Yet, the telecommunication market addressed by Micrel (radio-link and satellite hardware) is expanding on the wave of the employment of many new sites on the European territory. But the highest grow-up is expected in the mobile communication area where, **automatic debiting system** (highway, bridge and tunnel-toll, parking and restricted area access) and **city-downtown entrance control** represent very promising service areas for the world wide community.

The company is one of the two Italian firms operating in the field of ground based microwave stations for automatic debiting systems. Its market share was , at the beginning of the AE, 25%. The Competitor's share was, at the beginning of the AE, almost 75% of the Italian market. Their product still has the same performances and makes use of the same technology of the old Micrel product, but the competitor's market share was increasing, due to both their quality, reliability, cost and to their effective marketing operations.

For Micrel, the only way to recover and possibly increase its market share was both a technical improvement of the existing product and a deep commercial activity.

The commercial operation consisted in the search for new customers, as a possible alternative to the state-owned Società Autostrade. This activity has been successfully carried out and now Micrel has a new, private-owned customer , Tecnotel s.r.l. -Via Lazio, 25 - Zola Predosa (BO), Italy . This new partner deals both in Italy and in other countries. Therefore, Micrel's product is now planned to be installed outside Italy too. New market prospects include traffic, access and parking control devices and both higher and lower data-rate road-to-vehicle communications transceivers.

The technical operation consisted in an accurate analysis of the cost of the existing product, its performances and its use in the actual and future versions of the ground-based terminal for road-to-vehicle radio link.

The conclusions of the technical investigation can be summarised in the urgent need of a significant unit cost reduction. As a matter of fact, the excellent electrical performances were achieved at very high costs; the source of these costs consisted in the very expensive hybrid technology and in severe reliability problems. The solution was possible only with the introduction of a new technology

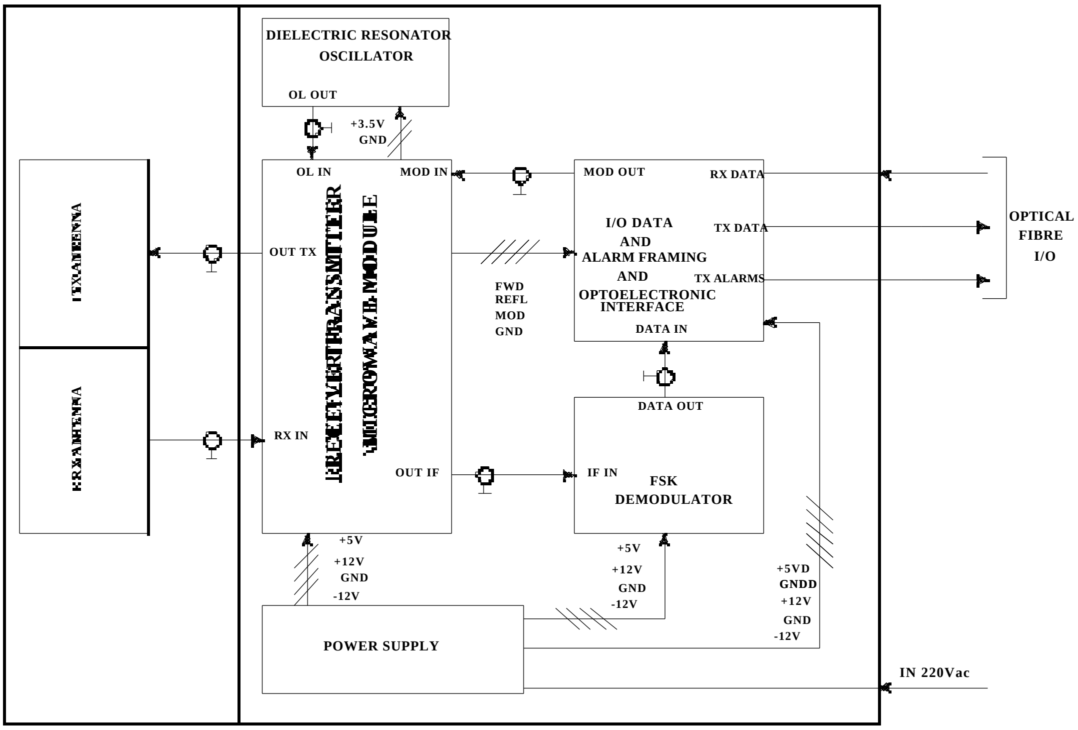
The reliability problem in the old product was caused mainly by the high power oscillator (DRO); the cost was related to the assembling and tuning of the DRO / Transmitter pathway.

The required cost reduction relevant to the microwave transceiver of the ground station was estimated in the order of 500 ECU compared to the old product, 200/300 of which associated with the TX/modulator components.

## 5. Product to be improved and its industrial sectors

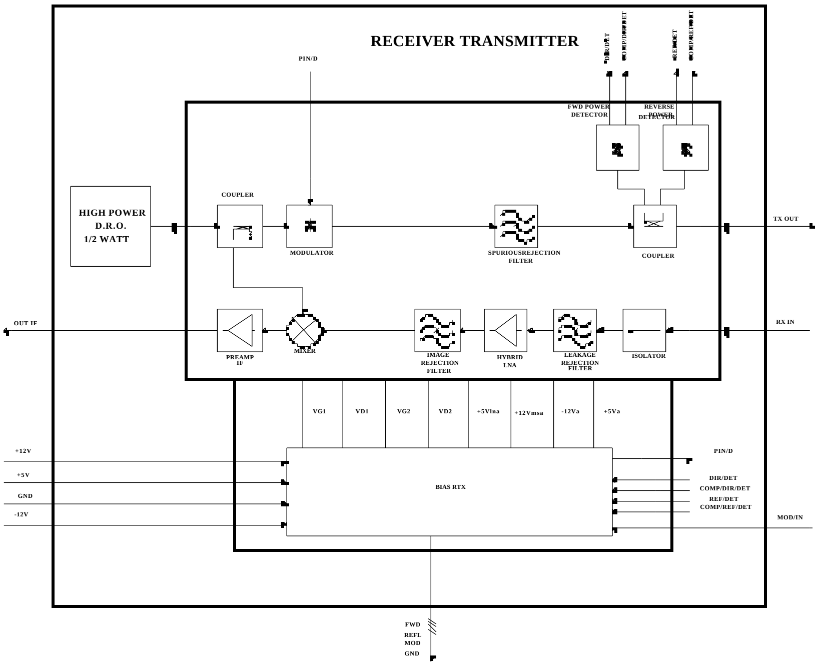
A ground station for road-to-vehicle communication radio link is shown in the following block diagram.
Many of its parts have been designed in order to reduce their cost as much as possible. This optimisation process has been carried out by using surface mount technology for both passive components and active silicon devices. Yet, the most expensive block (at the beginning of the AE), was the Receiver-Transmitter (RTX) microwave module.

**AUTOMATIC DEBITING SYSTEM GROUND STATION**




This unit must be designed by using a specialised microwave CAD and must be produced by making use of the suitable microwave technology. It is the most expensive block of the whole system, due to the very long time it takes to design, the expensive components which operate at the specified super high frequency, the expensive microwave circuit technology and the very long test and assembly time, not to mention the time required for adjusting all the circuits inside it.

A more detailed block diagram of the old microwave RTX module is shown below .




Many critical and expensive blocks were considered.

The first critical block is the 5.8 GHz medium power dielectric resonator oscillator. It delivered a relatively high power (in excess of half a Watt) , compared to commercially available oscillators, whose output power is seldom greater than 30 mW. The specified medium power (0.5 Watts) could be achieved by means of a very powerful and therefore expensive GaAs FET.

Moreover, this oscillator required a very careful mounting and trimming procedure, and only very specialised and skilled technicians were able to produce such oscillators; furthermore, this production required a very long time. Despite a long, difficult and boring trimming procedure, many of these oscillators had also serious yield problems

Instead, a low power active device, specialised for very low phase noise oscillators , represents the optimum solution. Micrel had already developed and produced more than a hundred pieces of a generation of low cost, low power dielectric resonator oscillators which had never given any yield problem. Such oscillators could and can still be produced very quickly, by means of very cheap (low power) components. They do not need any adjusting and have a guaranteed operation in the temperature range from -40 to + 85 °C. Taking into account the minimum time required for their production and test, the cost of these high reliability oscillators is less one fifth of the old high power units. The trade-off related to their use was represented by their poor output power.

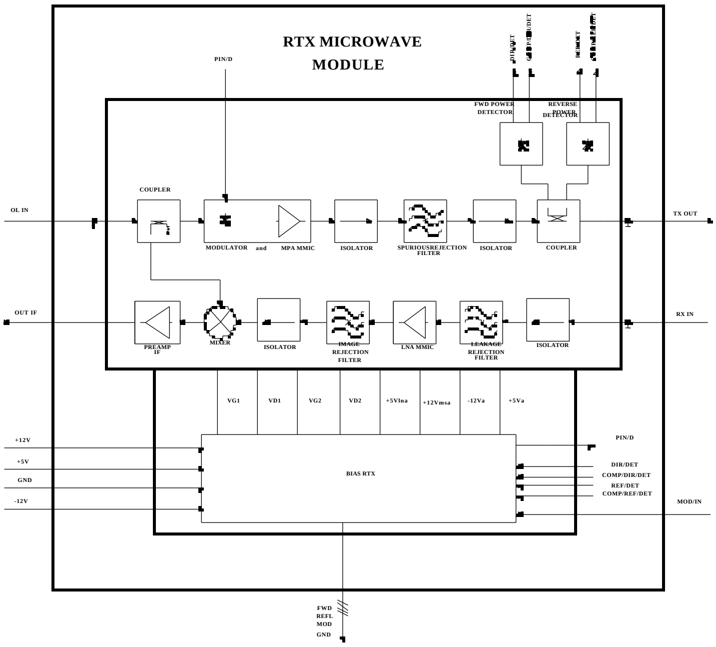
The achievement of the same output power of the old product was therefore possible by introducing a medium power amplifier in the TX pathway of the RTX microwave module.

A second source of problems was the modulator, which operated as an on-off switch with high power handling capability. Again, high power means a special device, whose housing must be able to sink the heat which is generated by such operation. This special device was very expensive. At the beginning of the AE, it was even becoming obsolete and therefore difficult to find.

A third critical block was the low noise amplifier, which also required a very long trimming time. Even this amplifier had its cost, due to the above mentioned trimming time and also to its performances which had to be very challenging.

It was evident that these critical blocks had to be replaced by cheaper and simpler ones, and a new architecture (block diagram) of the RTX microwave module was needed.

This new block diagram is shown below.




As far as the replacement of the low noise high output power amplifier (in the RX pathway) was concerned, Micrel had already developed a monolithic microwave integrated circuit.

It is interesting to mention that, for the low power modulator and the medium power amplifier, a preliminary hybrid version of such cascaded components was developed during the AE.

This new version of the RTX module was, even in this hybrid version, very cost effective, but all the main sources of the high cost of the microwave module could have been avoided by extensively using **monolithic** microwave technology, instead of the expensive **hybrid** technology.

This approach could only be implemented by using a modulator- amplifier block in monolithic form in order to maintain small transceiver dimensions and reduce production costs.

A Medium Power Monolithic Amplifier could only be designed and produced by using efficient Power Level GaAs technology. Alenia GaAs Foundry, part of "*Consorzio Roma Ricerche",* had already developed a technology process, named AL.04, suitable for microwave power and control volume applications at convenient unit cost.

The abolition of any trimming requirement, the large amount of circuit that can be processed at the same time and the consequent cut-back in production unit cost represent unique advantages of this technology over the old state of hybrid process.

At the same time, the introduction of an integrated half-watt microwave amplifier could have allowed the development of new generation of more powerful road to vehicle data-link transceivers, with higher level of integration in the same overall dimension and at a reduced cost.

The introduction of a new technology , like Medium Power monolithic integrated GaAs circuits would have allowed Micrel to pursue new volume productions (especially for traffic control of city downtown), not affordable with microwave transceiver in hybrid-form. Moreover, manufacturing cost reduction and improved performances and reliability represented the key benefits that could have improved the competitiveness of the transceiver unit over larger application areas.

By means of this monolithic microwave technology and this simpler and cheaper arrangement of the various blocks, the overall cost of the RTX microwave module could have been dramatically reduced to almost half of the old version.

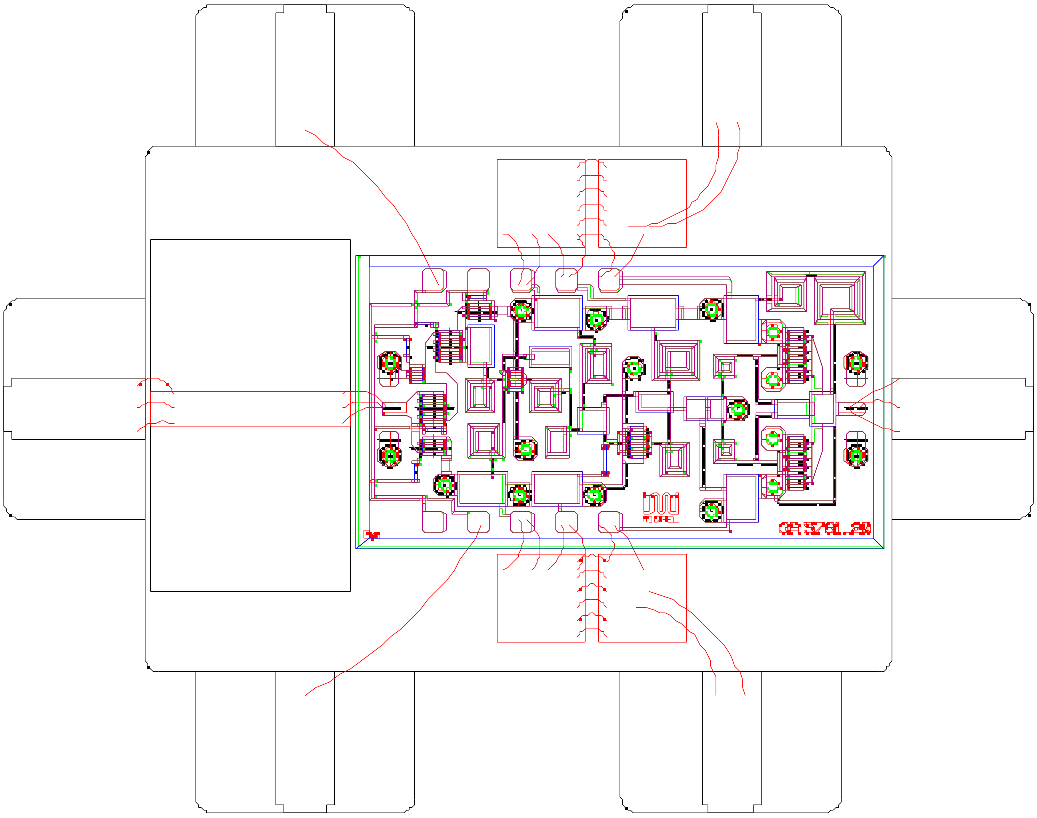
This would have allowed our Company to recover a significant share of this competitive market.

## 6. Description of the technical product improvements

The monolithic integrated circuit ,as previously stated, is realised on a Gallium Arsenide substrate. The process is named AL04 and this process is specialised for power and control.

The size of the chip is 3.2X1.6 squared millimetres and the size of the packaged monolithic modulator-amplifier is less than 10X8.8 squared millimetres.

In the following picture it is possible to observe all the internal connections of the packaged device.



The **measured** main features of this component can be summarised looking at the performance of the new transceiver, which employs the monolithic technology both in the Receive pathway and in the Transmit pathway , compared to the old one which uses hybrid technology:

| **RX pathway** | **Specification** | | **New RTX** | **Old RTX** |
|---|---|---|---|---|
| noise figure [dB] | 4.5 | max | 3.2 | 3.5 |
| conversion gain [dB] | 16 | min | 24 | 17 |
| rf input VSWR | 2:1 | max | 1.5:1 | 1.5:1 |
| if output VSWR | 2:1 | max | 1.5:1 | 2:1 |
| **TX pathway** | | | | |
| output power [dBm] | 22 | min | 25 | 24 |
| frequency pulling [KHz] | 300 | max | 100 | 200 |

| | | | | |
|---|---|---|---|---|
| ON / OFF ratio [dB] | 20 | min | 30 | 24 |

As far as phase noise performance is concerned, the improvement is of the order of 10 dBc at 100 KHz offset from carrier, but this improvement is due to the special design of the dielectric resonator oscillator.

Small signal gain is in excess of 15 dB and output power at 1 dB gain compression point in greater than 26 dBm. Another important feature is the bandwidth ( in excess than 5.7 to 6.1 GHz )

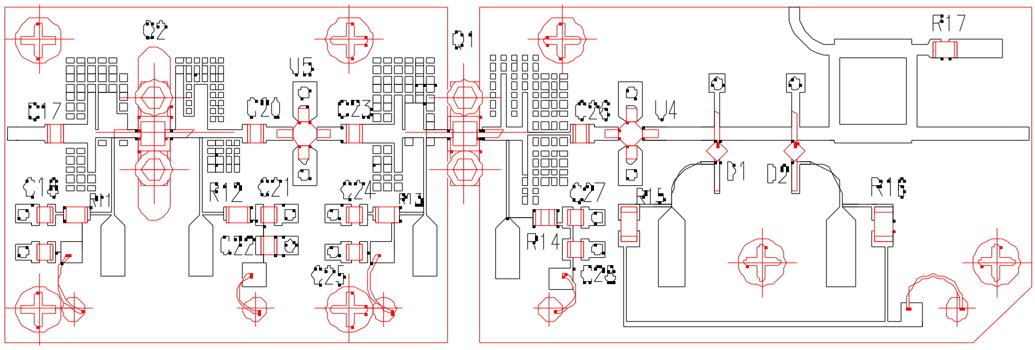
All these **measured** parameters are in compliance with the required specifications.

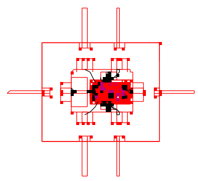
Thanks to these performances this circuit can be successfully used to accomplish the same operations of the hybrid version of the modulator and medium power amplifier, but it does not require any time for trimming and testing.

The benefits can be summarised as :

- Manufacturing cost reduction . The time needed for the assembly of the new MMIC is less than 1/20 of the time required for the hybrid version . Its cost is less than the cost of the discrete components which have been replaced.
- Manufacturing test cost reduction. No time for trimming and test, compared to more than one hour of specialised personnel labour.
- Process yield improvement . The hybrid modulator-amplifier consisted of more than 30 discrete components. Now, it has been replaced by only **one** integrated circuit, which is tested at the foundry. Thus, the yield has significantly increased.
- Product performance improvement, mainly due to its output power, its wide bandwidth, its reliability. Another interesting advantage is its very small size and weight, compared to the hybrid version. Even if space (and weight) is not a problem in the whole ground station, this reduced size is suitable for future and even lower cost versions of the whole ground station.
- In the following figure we can appreciate the dramatic difference in dimensions (about 10 times less), compared to the hybrid version (the monolithic MPA size is 10x8.8 mm).

HYBRID CIRCUIT



PACKAGED MONOLITHIC CIRCUIT

- Reliability improvement. Obviously, a single MMIC, instead of 30 components, means an increased reliability.

All these benefits have contributed to decrease the overall cost of the RTX module.

Taking into account the overall assembly, test, adjusting time which can be saved and the increased yield in the production of the new generation of ground stations, the aimed target cost ( half the cost of the old version) can be achieved.

For all the applications already mentioned at section 4, such as the mobile communication area, especially automatic debiting system (highway, bridge and tunnel-toll, parking and restricted area access) and city-downtown entrance control, this new generation of ground stations, which make use of monolithic microwave integrated circuits, represent very promising service at an affordable price.

## 7. Choices and rationale for the selected technologies, tools and methodologies

Following the decision on the new transmitter architecture with the need of a Medium Power Amplifier, it was necessary to select the proper technology for carrying out the component.

Considering the specific product, the choice was between the Hybrid and Monolithic technologies. As already repeated, thin film hybrid integrated assembly, was no longer suitable for larger and more performing production phases. The use of monolithic component is convenient, in our case, mainly for:
- higher reliability
- Improved reproduceability
- component cost reduction for large production volume ( today the quantity of convenience is lowering, tanks to the technology improvement)

The second step in the choice was among the various kind of semiconductors employed for the monolithic circuit implementation:

- Si : was becoming obsolete (mainly employed for digital applications)
- SiGe : not mature for industrialisation
- InP : very expensive, recommended for millimetric wave (above 30 Ghz)
- GaAs : currently used in industry for medium power applications up to 40 Ghz (and above)

A GaAs medium power amplifier in **monolithic** form, represented the **only** solution to address major volume production market with a competitive price strategy.

Alenia AL-04 process of GaAs semiconductor substrate ion implantation creates the proper active layer of each active element and the structural elements such as MIM capacitors, thin-film resistors, inductors and transmission lines.

The project started with the investigation of High Level GaAs technology in order to learn and to discover the proper cost-effective methodology to implement this proposed experiment and future projects.

Basic S parameters of Alenia interdigitated 0.7um gate length (or similar) FET were recovered and analysed; load-pull techniques have been used in order to optimise output power performances. The proper FET geometry was then selected according to different stage output power requirement.

A three stages configuration was simulated as a suitable approach to the required specifications. A proper feedback was set-up on each stage in order to guarantee the proper performance and maintain overall stability. Matching networks were implemented by using lumped element in place of distributed microstrip lines.

On wafer testing was a straightforward method for measuring and evaluating low level GaAs MMIC like small signal gain and VSWRs, but in order to assess the proper power performances a series of custom-designed test-jigs were designed and a specific hardware was implemented for the test bench set-up. Power dissipation was also guaranteed by the test fixtures.

The prototype was produced on a 3 inches multiproject wafer.

## 8. Expertise and experience in microelectronics of the company and the staff allocated to the project

As mentioned in section 2, Micrel's design engineers had already been developing a suitable microwave component and subassemblies expertise for Radar-Telecommunications (i.e. Radio Link and Ground Based satellite transceiver) applications. CAD modelling and simulation of hybrid circuit, with accurate microwave and millimetre wave testing and mechanical design aptitudes represented , even prior to the AE, the basic skills of designers.

On the other hand, from a technological point of view, the company had been developing an appropriate competence in hybrid thin-film technology; processes like substrate metallisation and etching, hybrid assembling and hermetically sealing of components and subassemblies, represented the major technological tools of the Company design and production facility.

Design engineers involved in the AE had also taken in a specific knowledge in monolithic circuits design, based on GaAs substrate, after the successful design, development and production of a low noise high dynamic range monolithic amplifier, which is the basic building block of the receiving pathway of the new RTX microwave module. This design technique is based on **linear** circuit analysis.

Therefore, GaAs itself did not represent a new technology for Micrel, since a **low noise** process had already been designed and used. For a low noise design, a linear circuit analysis software is a suitable tool.

Instead, a **power** GaAs process had never been used before the AE. When power electronics is involved in the design of an amplifier, linear circuit analysis is not sufficient to properly predict the behaviour of such circuit.

For this reason, **non-linear** analysis and synthesis techniques were needed. An important specific knowledge had to be assimilated, in combination with a specific non-linear software tool and with an accurate set of non-linear models of the active devices which had to be used for the new design.

## 9. Workplan and rationale

The original workplan was divided into 5 Workpackages. These packages are described below.

- Workpackage 1 : management;
- Workpackage 2 : specification;
- Workpackage 3 : training;
- Workpackage 4 : design;
- Workpackage 5 : evaluation.

Each package was subdivided into various tasks.
The scheduled activity is summarised in the following table.

| Activities | Month | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| **Management** | | | | | | | | | | | | | | | | | | |
| Project management | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Dissemination | | | | | | | | | | | | | | | | | | X |
| Reporting | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Specification** | | | | | | | | | | | | | | | | | | |
| System specification | X | X | X | | | | | | | | | | | | | | | |
| Technical specification | X | X | X | | | | | | | | | | | | | | | |
| **Training** | | | | | | | | | | | | | | | | | | |
| Specification training | X | X | X | | | | | | | | | | | | | | | |
| CAD training | X | X | X | X | | | | | | | | | | | | | | |
| Design training | | | | X | X | X | X | X | | | | | | | | | | |
| Evaluation training | | | | | | | | X | | | | | | | | | | |
| **Design** | | | | | | | | | | | | | | | | | | |
| Subsystem level design | | | | X | X | X | X | X | | | | | | | | | | |
| **Evaluation** | | | | | | | | | | | | | | | | | | |
| Prototype production | | | | | | | | | X | X | X | X | X | X | X | | | |
| Test set-up | | | | | | | | | X | X | X | X | X | X | X | | | |
| Prototype testing | | | | | | | | | | | | | | | X | X | X | |
| Field testing | | | | | | | | | | | | | | | | X | X | |

The objectives related to **Workpackage 1** consisted in the run of the experiment, the management of the project, the control of the service providers (especially the GaAs foundry), the interface with the TTN, and the reporting and dissemination activities. Due to its intrinsic nature, this activity had to be carried out throughout the whole duration of the project.

The three tasks the workpackage was divided into are:

- - Project management
- - Dissemination
- - Reporting.

Two major events during the development of the first task (Project management) happened.

The first significant event was the assignment of Micrel S.p.A. activities to Officine Galileo, another Finmeccanica Group Company. The transfer was due to a new strategic organisation within the Finmeccanica Group. Since August 1st, 1996 all the design and production activities of Micrel S.p.A. are being carried out by the same people and at the same former location, as an individual Microelectronics Unit within Officine Galileo.

The second event has been the staff variation. The program manager, who had started the AE, resigned on March 1997 and since that date one of the two senior engineers , already involved in the project, had to carry out also this activity. The biggest problem he had to face was the increasing delay of the delivery of the prototype. This inconvenient was due to circumstances absolutely out of control of the FU, since the delay of the prototype was due to the delay of the GaAs foundry service (responsible of the prototype production) . The decisions which had to be taken to circumvent this problem will be described in the following part of this section.

The second (Dissemination) and the third (Reporting) tasks have been carried out without particular difficulties, thanks to the continuous assistance of the TTN.

The objectives related to **Workpackage 2** (Specification) were the final component specification, the proper design strategy, according to the medium power FETs model which was available at that time and the issue of the preliminary component simulation.

Since the functional specification of the whole ground based transceiver had already been determined, the activity related to this workpackage was devoted to the GaAs integrated medium power amplifier definition. The configuration of the amplifier had to be studied and its preliminary behaviour had to be predicted. The construction of some hybrid versions of the amplifier was planned and the related test fixtures and housings had to be designed.

The two tasks the workpackage was divided into were :

- \- System specification of component,
- \- Technical specification of the component.

The first task was carried out in co-operation with the external GaAs foundry's technical personnel. Its was agreed a three-stage configuration. This activity was completed in time.

The second task was also completed in accordance with the scheduled plan. At the end of this task, the feasibility study had been completed and at least two possible versions of the amplifier were predicted. As a matter of fact, two possible output power stages were possible. These two versions would have permitted a double approach to the design .

**Workpackage 3** ( Training) had two objectives . The first was the increase of the aptitude of FU on medium power design and modelling ;the second was the enhancement of FU expertise on chip design, with a special focus on medium power amplifier physical layout.

Basically, the first objective had to be carried out by the Electrical Department of University Tor Vergata - Rome, whose people have a special expertise on this field, while the second objective was the main task of external foundry service's staff, who has been designing monolithic microwave integrated circuits for a very long time.

This workpackage was divided into 4 tasks:

- \- Specification training,
- \- CAD training,
- \- Design training,
- \- Evaluation training.

Specification training was devoted to the enhancement of the FU's capability to the definition of the proper requirements for the medium power amplifier. This task had also the aim to detail the feasibility study of the component.

CAD training was aimed at the training of the FU on the usage of non-linear model and algorithms. The key improvement of the expertise of First User's designers was their familiarity with models and algorithms which predict the behaviour of a medium power amplifier and allow the design of the circuit layout of such amplifiers. For this purpose, the special training, which was carried out by the staff of Tor Vergata University, Rome, was essential. Another important tool was the new MMIC CAD software from HP-EEsof. This software was delivered at the beginning of the 6th month of the AE.

Design training consisted in the training of the FU in efficient medium power GaAs monolithic integrated circuit design, with special attention to the design of the physical layout of the chip. This task was successfully carried out by the external foundry's staff. Design strategies, methods, amplifier circuit configurations and physical layout suggestions were the key features of such action. A very good relationship was established between external foundry personnel and FU's personnel. It is important to remember that this training consisted also in the feasibility study of the component ( see Workpackage n. 2). The cost of this training was included in the overall Foundry costs.

Evaluation training was the evaluation of the obtained design and skill capabilities, which have been certified by both the University and the Foundry.

At the end of this Workpackage the two engineers of the FU were familiar with the new design tools and were able to face the fourth Workpackage, which consisted in the design of the medium power amplifier, which had been specified at the end of Workpackage 2.

All the Workpackage 3 was carried out in time. More than expected man power was necessary to complete this Workpackage. This difference is due to the intrinsic difficulty of non-linear models of active devices, and to the new approach to the new MMIC CAD. As far as durable equipment cost is concerned, the required investment was less than expected, due to the decrease of the cost of the MMIC CAD, compared to the cost of the same package at the beginning of the AE.

As already reported, **Workpackage 4** consisted in the design of the medium power amplifier integrated circuit. More in detail, it was aimed at the identification of a medium power amplifier configuration which had to satisfy the technical specifications issued at the end of Workpackage 2. As it was expected in the original workplan, part of this design work was conducted during the training tasks.

This workpackage consisted of one task:

· - Subsystem level design.

This task was the application of the design method and skills which had been taken in by the design engineers of the FU. This activity concerned the identification of the most suitable MPA configuration in order to assess the best compromise between power gain and output power, over the required frequency bandwidth. Practical usage of the new MMIC CAD which had been purchased in the meanwhile and of the non-linear model which had developed by University of Rome - Tor Vergata was involved. At the end of this task, three different versions of the three-stage amplifier were ready for prototype production. Also a replica of the first two stages, which are common to all the three-stage versions, was designed as a stand-alone amplifier. This two stage release was also needed for on-wafer measurements, since such operation is not possible on a three-stage amplifier, whose third ( output) stage has a power consumption such to ensure safe measurements only on a specialised housing. Moreover, a reduced output power release of an amplifier could be used in future applications of the ground station which require a lower output power.

This design experience has proved very useful for FU's engineers and has given the possibility to develop other designs, based on the same technique.

Workpackage 4 was completed more than one month later ( month n.10), compared to the original workplan (month n. 8). The main reason of this delay was due to the three versions (actually 4 versions, including the two-stage), instead of the only version which had been budgeted before the AE had started.

Another important difference which must be considered is the labour cost which has been above budget, due to the extensive design activity.

**Workpackage 5** ( Evaluation) had, as main objective, the production of some prototypes of the monolithic amplifier. An extensive set of measurements was expected, in order to compare the measured performances with the simulated performances. A version of the new receiver-transmitter unit had to be designed .

The workpackage included some tasks (the prototype production, the design of the test fixtures, the prototype test ) which had to be carried out by the external Foundry service.

Workpackage 5 was divided into 4 tasks :

· - Prototype production,
· - Test set-up,
· - Prototype testing,
· - Field testing.

The objective of the first task was the physical fabrication of some monolithic microwave medium power amplifier prototype demonstrators. This Task, which had to be carried out by the external foundry's staff, included mask fabrication, wafer production, PCM (Process Control Monitor) and on-wafer testing, dice sorting and chip packaging. Moreover, another service which had already been supplied by external foundry service consisted in the specific training of Micrel personnel. As above mentioned in Workpackages 3 and 4, the new design criteria focused on physical chip layout design, layout rules, active device cell libraries and power dissipation had been successfully taken in by Micrel designers.

The selected Alenia process was the AL.04 Ion Implanted, specific for **power** GaAs MMICs. This technology is based on interdigitated 0.7 micrometers gate length depletion mode MESFET on a 120 micrometers thick semiconductor substrate with via-holes.

The end of this task was scheduled by end of the 15th month, but unfortunately lasted much longer. After external foundry service people confirmed a delay of more than three months, Micrel asked, on October 9th, 1997, a first extension of the program. The purpose was to obtain the sufficient time to finish the AE. Since no relevant technical activity had been carried out by Micrel's staff during the prototype production period, no increase in the overall cost of the experiment was expected. This delay was due to the external Foundry service and, therefore, it was entirely out of control of Micrel. The reasons of this delay were essentially the late delivery of the masks, which the external foundry service had received very late (from their usual supplier) and the missing delivery of the gold salts, which were needed to complete the last step of the prototype production process. A two months program's extension was estimated by the staff of the Foundry. Eventually, the process finished by end of 19th month.

Test set-up had the objective of the test bench design for prototype testing. This was a side activity which was carried out during the prototype fabrication process. This task was finished at the end of the 21st month.

The third task (Prototype testing) consisted in the evaluation of prototype performances. Its duration was expected between the 15th and the 17th months, but it started at the beginning of the 20th month. After the prototype production was completed, a preliminary **on-wafer** verification started. The result was that all the two-stage versions had a small-signal gain below any acceptable value. It is very important to take note that only the two-stage (and low dc power consumption) amplifiers could be measured on-wafer without thermal damage. After an accurate technical and technological inspection had been carried out, two possible sources of malfunction had to be investigated .

The first supposed source of malfunction was the bias network of the first stage. A poor design of this network was guessed. The correction consisted in the attachment of the amplifier chips on their housings, containing further bypass capacitors which obviously could not have been used during on-wafer measurements. This action had an expected time duration of one month. If this correction had not proved sufficient, a second one would have taken place. As a matter of fact, the source of malfunction could have been a mistake in the production process. A second foundry run would have been needed. This drastic action would have taken an estimated additional time of four months. For these further inconvenient, a second extension of the program was asked for on December 15th, 1997. It was pointed out that the time extension would not increase the cost of the AE.

To avoid the risk of the failure of the AE, the staff of the Foundry decided to produce a second wafer. This activity was carried out in parallel to the dice selection and attachment; it lasted up to the end of the AE, without any additional cost for the FU. For this reason, Task 1 finished at the end of the project (24th month).

The selection of the dice which could have been attached to the housing led to a preliminary operation of mapping on the whole wafer. The mapping consisted in the on wafer measurements of the power three-stages, under bias conditions which allowed fast measurements at a reduced dc power consumption. More in detail, a biasing of the gates of each active device(MESFET) at the nominal voltage, and a biasing of each drain at a reduced voltage , reduces the power consumption of the power amplifier and , of course, decreases the gain performance of the amplifier chip, but allows accurate input matching and bandwidth measurements. The measured results gave the possibility to detect the amplifier chips which could have been mounted on their housings. These measurements, which were carried out very extensively and accurately, showed furthermore that the source of malfunction was not the bias network of the first stage, as it had been previously supposed. This more detailed inspection showed that the reason of the lower than calculated small-signal gain was the pinch-off voltage of the MESFETs in the modulator stage. The fabrication process ended up with a value of -7 Volts, instead of the expected -5 Volts. After having increased the test voltage of the modulator stage to the value of -7 Volts, even the two-stage amplifiers showed acceptable values of small-signal gain.

According to the selection criterion of the lower pinch-off voltage of the modulator stage, the proper samples of each three-stage medium power amplifier were selected.

Small signal gain, S-parameters and output 1 dB compression points were measured.

The average measured performances of the three versions of the amplifiers can be summarised in the following table.

| AMPLIFIER RELEASE | **GA 5761_20** | **PW 5761_01** | **PW 5761_02** |
|---|---|---|---|
| output 1 dB compression point [ dBm ] | 26.5 | 26.5 | 24.5 |
| small signal gain [ dB ] | 15.0 | 13.0 | 15.0 |
| gain ripple [ dB ] | +/- 1.0 | +/- 1.0 | +/- 1.0 |
| bandwidth [ GHz ] | 5.7 - 6.1 | 5.7 - 6.1 | 5.7 - 6.1 |
| input VSWR | 2:1 | 2:1 | 2:1 |
| ON / OFF ratio [ dB ] | 30 | 30 | 30 |

A comparison of these figures shows that the release GA 5761_20 best meets the required performances.

Looking back at the block diagram of the new RTX microwave module (chapter 5), provided that the input power, which is delivered by the new dielectric resonator oscillator, is always in excess of 15 dBm, a 3 dB power divider is at the input of the modulator- medium power amplifier monolithic circuit. This means that the input power of the new MMIC is always more than 12 dBm.

Since the small signal gain is 15 dB (15 dB is the average measured value) , the power at the output of the medium power amplifier MMIC is 26 dBm ( 1 dB less than 27 dBm due to the 1 dB gain reduction). This signal is fed to the output spurious rejection filter and to the output detector stage. The loss of these circuits is less than 1 dB.

Therefore, the overall output power of the Receiver-Transmitter microwave module is more than 25 dBm. This value is 1 dB higher than the output power of the old version of the receiver-transmitter microwave module.

Taking into account the overall system requirements considered in the next Task (number 5) we can conclude that the AE has been successfully completed.

The last task (Field testing) consisted in the review of the performances of the Receiver-Transmitter microwave module, which now makes use of the monolithic medium power amplifier and the already developed low noise amplifier . A design of the new module has been completed and the measured performances of such new module are reported in chapter 6

A last figure which must be considered is the overall price of the receiver-transmitter microwave module.

This analysis is carried out in the 16th Chapter. The conclusion is that, for quantities above 500, even taking into account the industrialisation and engineering costs, the price is 20% lower than the price of the old module. For some thousands, this **price** is **half** the price of the old module.

At the end of the AE, the actual workplan is shown in the following table.

| **Activities** | **Month** | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| **Management** | | | | | | | | | | | | | | | | | | | | | | | | |
| Project management | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Dissemination | | | | | | | | | | | | | | | | | | | | | | | | X |
| Reporting | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Specification** | | | | | | | | | | | | | | | | | | | | | | | | |
| System specification | X | X | X | | | | | | | | | | | | | | | | | | | | | |
| Technical specification | X | X | X | | | | | | | | | | | | | | | | | | | | | |
| **Training** | | | | | | | | | | | | | | | | | | | | | | | | |
| Specification training | X | X | X | | | | | | | | | | | | | | | | | | | | | |
| CAD training | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| Design training | | | | X | X | X | X | X | | | | | | | | | | | | | | | | |
| Evaluation training | | | | | | | | X | | | | | | | | | | | | | | | | |
| **Design** | | | | | | | | | | | | | | | | | | | | | | | | |
| Subsystem level design | | | | X | X | X | X | X | X | X | | | | | | | | | | | | | | |
| **Evaluation** | | | | | | | | | | | | | | | | | | | | | | | | |
| Prototype production | | | | | | | | | | | X | X | X | X | X | X | X | X | X | | X | X | X | X |
| Test set-up | | | | | | | | | | | X | X | X | X | X | X | X | X | X | X | X | | | |
| Prototype testing | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X |
| Field testing | | | | | | | | | | | | | | | | | | | | | | | | X |

The shaded cells represent the deviations from the original workplan.

Despite a longer than expected duration of the AE, the overall cost has not changed. The most significant variations have been the number of worked hours. This number is significantly higher than the budgeted value, due to the considerable time required to complete the Workpackages 3,4,5. Yet, the overall cost has not changed since less than expected investments have been necessary. Another cost which has been less than expected is referred to in the item Travel. Consumables have also been less than expected. The budgeted cost at the beginning of the AE and the actual cost are summarised below.

| Workpackages | Cost | Budgeted | | | Actual | | | Deviations | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | hours | Amount ITL | Amount ECU | hours | Amount ITL | Amount ECU | hours | Amount ITL | Amount ECU |
| 1) management | **Cost personnel** | 386 | 20.458.000 | 10.491 | 553 | 33.655.162 | 17.259 | 167 | 13.197.162 | 6.768 |
| 2) specification | **Cost personnel** | 55 | 2.915.000 | 1.495 | 50 | 2.234.350 | 1.146 | -5 | -680.650 | -349 |
| 3) Training | **Cost personnel** | 236 | 12.481.500 | 6.401 | 324 | 14.890.882 | 7.636 | 88 | 2.409.382 | 1.236 |
| 4) Design | **Cost personnel** | 425 | 22.525.000 | 11.551 | 694 | 31.616.587 | 16.214 | 269 | 9.091.587 | 4.662 |
| 5) Evaluation | **Cost personnel** | 550 | 29.150.000 | 14.949 | 790 | 36.719.756 | 18.831 | 240 | 7.569.756 | 3.882 |
| | **Tot. cost personn.** | **1.652** | **87.529.500** | **44.887** | **2.410** | **119.116.737** | **61.086** | **758** | **31.587.237** | **16.199** |
| | Durable Equipm. | | 30.000.000 | 15.385 | | 15.530.822 | 7.965 | | -14.469.178 | -7.420 |
| | Third Party assist. | | 75.000.000 | 38.462 | | 75.000.000 | 38.462 | | 0 | 0 |
| | Travel | | 15.036.000 | 7.711 | | 9.852.125 | 5.052 | | -5.183.875 | -2.658 |
| | Consumables | | 16.000.000 | 8.205 | | 5.677.760 | 2.912 | | -10.322.240 | -5.293 |
| | Other | | 30.000.000 | 15.385 | | 30.000.000 | 15.385 | | 0 | 0 |
| **TOTAL** | | **1.652** | **253.565.500** | **130.034** | **2.410** | **255.177.444** | **130.860** | **758** | **1.611.944** | **827** |

All the scheduled deliverables were delivered substantially in time.

## 10. Subcontractor information

As already mentioned in Chapter 8, the experience that Micrel mainly lacked was represented by the modelling of power microwave devices and power integrated circuits design. Indeed, the technology which was not (and still is not) available in Micrel is the foundry service for the production of MMICs.

The subcontractor for the modelling activity was the University of Rome ‘ Tor Vergata ‘, Department of Electronic Engineering.

The basic expertise of this subcontractor consists in Gallium Arsenide technology for advanced components, combined with design of hybrid and monolithic integrated circuits up to 40 GHz .

Experience in modelling of linear and non linear active devices, microwave component design, testing of components and circuits up to 40 GHz in fixture and on wafer, with network analyser, spectrum analyser and noise figure meter had been proved by their wide scientific production.

The personnel involved in the activity consisted of :

- 2 Senior Engineers;
- 1 Junior Engineer;
- 1 Technician.

The activity was divided into two tasks :

- Non-linear modelling of active microwave devices
- Training of Micrel’s microwave design engineers.

Due to the very good relationship between people belonging to both the FU and the Subcontractor, no inconveniences happened during the time the activity was carried out. Yet, a contract with a University must include very clear conditions and specifications about :

- subject of the contract
- activity workplan
- terms of payment
- economic and scientific roles and responsibilities
- bonus and penalty clauses
- non-disclosure agreement ( very important when a Subcontractor is a University ).

The tasks were carried out successfully and in the expected time.

An acknowledgement has to be done to the very good level of experience and professionality of the staff of the University of Rome ' Tor Vergata', their scientific background and the deep knowledge of the subject they have dealt with.

The other external service involved in the AE is the Alenia GaAs Foundry, which is located in Rome, Via Tiburtina.

Their technical expertise cannot be shortly summarised, since they have been working in the microwave field for almost 50 years.

As far as the monolithic microwave integrated circuits are concerned, they had already established a very good relationship with the designers of Micrel. The above mentioned low noise monolithic microwave amplifier had proved an interesting technical and human experience for Micrel's engineers.

During that experience, Alenia Foundry service had already shown its impressive design, development and reliable production capability. A wide range of applications for their circuits had been shown, combined with a complete set of measurement equipment. This special expertise in the monolithic microwave integrated circuits area of application was established more than fifteen years ago.

Despite all of that, Micrel had asked a quotation for the development of the new medium power MMIC to many European possible suppliers.

In order to keep the cost of the prototype production at an affordable value, a multiproject approach was chosen.

Only two Foundry services provided a good quotation. Even if Alenia's Competitor offered almost the same price, Micrel choose Alenia, since their offer included not only the production of the wafer, but also on-wafer measurements, the packaging of a significant number of samples and an extensive **training** of Micrel's engineers on the topics of non-linear power circuit design.

Another very important factor which was considered in the decision of this external service was the co-operation which was already well assessed between the Foundry and the University of Rome. This well established co-operation was essential in terms of the time needed for the management of the AE.

Foundry's personnel involved in the activity consisted of :

- 1 Technical Manager;
- 2 Senior Engineers;
- 2 Technicians, specialised in on-wafer measurements;
- 2 Technicians, specialised in dice sorting and packaging.

The contract with the foundry had essentially the same contents of the contract with the University; a special attention was devoted to the **non disclosure agreement** between the two contractors, but did not contain any bonus or penalty clause. These clauses cannot be easily specified in case of a multiproject approach, since there is section of the wafer which is out of control of the FU.

Moreover, GaAs technology is not widely used as Silicon and therefore it is very difficult to find a partner who enables a FU to finish this essential task in the expected time.

A possible suggestion is, in case of GaAs technology, the budget of a longer time which could be allowed to a FU , just to take into account such inconveniences.

## 11. Barriers perceived by the company in the first use of the AE technology

The AE was aimed at an innovated existing product. As described, the old product already used GaAs technology, but only on conventional hybrid circuits.

The deep innovation consisted primarily in the replacement of a hybrid microwave circuit with its monolithic version.

This is only possible when the expected number of such circuits is of the order of some hundreds pieces.

In the specialised field of microwave circuit design and production, a hybrid version of a specified circuit always represents the first and more immediate solution.

Instead, the development of a monolithic version depends on the number of produced equipment.

Micrel's ground station for automatic debiting system followed these development steps, and the **main barrier** which prevented the company from adopting the new monolithic technology was represented by the relatively low number of pieces which were under production.

Instead, knowledge barriers consisted mainly in the lack of experience in power microwave circuit design. No specialised software tool was available, no model had been developed for non-linear circuit design and this cultural lack was reflected by the poor quality of the old product. On the contrary, the Company's design engineers had already developed a useful experience in linear microwave circuit design, mainly in the field of hybrid circuits, but also in the field of linear (low noise) monolithic circuits.

This lack of specialised non-linear design techniques for medium power amplifiers could have been filled only by people who had been involved for a long time in such experience.

And yet, despite a relatively wide literary production, a deep knowledge of non-linear design techniques cannot be assimilated in a reasonable time without the contribution of both University's and Industry's experienced personnel.

The choice of the proper partners from both a scientific and a technological point of view has been another barrier, which has proved very difficult to circumvent.

## 12. Steps taken to overcome the barriers and arrive at an improved product

Since the main barrier was represented by the relatively low number of pieces under production, the circumvention of this obstacle consisted in an effective marketing operation, aimed at an increased number produced pieces. After an accurate analysis of the Italian market, the critical number of 500 pieces per year was budgeted. The number of 500 pieces was considered critical, since a deep innovation of the product, which was essential for further increase of the market share, could have been achieved only by means of the introduction of the new technology and the payback period would have been less than one year.

An extensive commercial initiative consisted in the search for new customers, in order to further increase the number of pieces produced per year.

Another kind of search had started . The aim was to find the best subcontractors and external Foundry services. This action was essential also from the point of view of the knowledge that had to be taken in by Micrel's designers.

University of Rome - Tor vergata - was naturally selected for non linear modelling, thanks to their well known competence and the relationship with Micrel.

For the component realisation two foundry services were investigated: Plessey and CETME (Alenia).

- Both are involved in medium power process ( for Alenia, AL.04 process is developed for power and control applications up to Ku-band; employs 0,7 um gate length, depletion mode MESFETon 120 um thick semi-insulating substrates with via-hole)
- Plessey supplies the process and the components, but does not support in testing
- CETME gives the total service
- The prices offered were the same

Micrel selected CETME for :

- The offered complete service
- The more easily interface with an Italian company
- The previous experiences carried out with AL.02 process (developed for low noise , linear design techniques).

The transfer of knowledge represented the first steps of the AE ( See Workpackages 2) and was practically verified during the development of Workpackage number 4.

The two above mentioned technical and commercial search for the proper partners proved much more important than expected, since, in the meanwhile, a dramatic change in the scenario of the market of equipment for automatic debiting system had happened.

As a matter of fact, the market share of Micrel was contracting, due to the unexpected decrease in the demand for ground stations. At the beginning of the AE, Micrel had relied on the demand of only one customer (Società Autostrade). Unfortunately, throughout the year 1997, this customer ordered only the ground stations which were produced by Micrel's competitor.

Thanks to the agreement with a new customer (Tecnotel - Via Lazio, 25 - Zola Predosa - BO - Italy) the new generation of ground station has still become a possible development, since this new customer is not only active in the domestic (Italian) market, but has been trading outside Italy for many years. For this reason, the critical number of 500 (or even more) units can still be budgeted and, taking into account the delayed conclusion of the AE, a payback period of less than one year is still an actual estimation, as it can be seen in Chapter 16.

Yet, during the year 1997, this new customer immediately needed some prototypes of the new equipment.

Since the monolithic integrated circuits were under production and, as already reported, their delivery was delayed, a very useful solution was the development of a new hybrid medium power amplifier and modulator. The design approach was represented by the new acquired design capability, which used the new non-linear specialised software and the non-linear techniques which the designers of Micrel had learned in the meanwhile. This solution has proved a key aspect of the knowledge transfer. The result has been very challenging, since only one deign step has been needed. (In microwave circuit design, two or more steps are often required to satisfy the specifications ).

The new scenario of the ground stations market is shown in Chapter 16.

## 13. Knowledge and experience acquired

As already reported in almost all the previous chapters, the knowledge transfer consisted mainly in a technical transfer. Now, non-linear design techniques have been taken in by Micrel's engineers involved in the AE.

The new design skills and commercial benefits can be summarised as follows :

Investigation of new technology process ( for Micrel) and related aspects, such as :

- non linear simulation and design;
- specific CAD routine experience;
- power dissipation and related materials;
- large signal testing;
- extended Micrel hybrid design, integration level and production capabilities.
- increased Micrel penetration in Automatic Tolling Transceiver market.

As far as other knowledge issues are concerned, (for example learning how to plan and manage microelectronics, preparation of technical specifications, interaction with consultants and external services) it is important to remember that microelectronics is the business of Micrel. Therefore, all the mentioned issues did not represent skill shortages.

As a proof of the transferred knowledge, the non linear design techniques have been successfully used by the engineers in the development of the hybrid preliminary version of the medium power amplifier. This success has started a very encouraging commercial partnership with a private-owned customer.

But, as mentioned in chapter 3, Micrel is involved in the design and development of microwave integrated circuits for both commercial and military applications.

For example, another design, which involves medium power amplifiers, has been carried out by Micrel's engineers. This amplifier is one of the most important building blocks of a frequency synthesiser for airborne application.

This increase in the expertise of the company represents a key aspect of the whole AE.

A summary of the required investment is summarised by the following figures:

- Durable equipment : 7760 ECU
- Third part assistance : 15000 ECU

Therefore, the investment related to the acquisition of the suitable skills has been 22760 ECU.

## 14. Lessons learned

The problem that Micrel had to face during the AE consisted mainly in the late delivery of the prototype. This inconvenience depended on the activity of the external foundry service and therefore was out of control of the FU.

As already repeated, no trouble was caused by the introduction of the new technology, due to the business area of Micrel.

This problem could have been very severe , since the company had to put the new product on the market as soon as possible.

If the new integrated circuit had had to be developed on a Silicon substrate, a wider choice of suppliers would have been available and in that environment bonus or penalty clauses could have been accepted by any supplier.

But GaAs power technology is not so widely used in the electronic market and this process, at the time the AE started, was only supplied by two Foundries. Moreover, to achieve the expected results at a reasonable price, a multiproject solution was chosen. For these reason, bonus or penalty clauses were not applicable.

The best solution has already been explained in the previous ( number 13 ) chapter.

As a matter of fact, the new learned design techniques have successfully helped the Company to overcome the late delivery of the prototypes.

As a general concept, when GaAs technology is the only way to achieve the needed improvements, the transfer of know-how must be carefully followed by any FU.

The technical staff must take in the new design rules and a specialised software is always essential and must be learned in deep detail. This gives the FU the possibility to interact with any external service and sub-contractor and control their activity, but basically gives to the FU the possibility to face any other new development.

From the point of view of non technical experiences gained as FU the project management and the relationship with the TTN have been the main means to improve the chances of success. Planning techniques and the capability to face unexpected event are fundamental when a new technology is introduced in the company. The role of TTN has been of primary importance for interfacing with E.C. in all the phases of the A.E and for the help in the selection of the technology and of the subcontractors.

Small and medium companies which are involved in the microwave applications can have benefit in following a similar approach for upgrading of their products or for new ones.

Even if the microelectronic components will assure quality and competitive cost, care must be taken in the possible delay of the first prototypes. While costs can be correctly foreseen, many events out of our direct control can delay the process which is complex and time consuming by itself. When time on market is a requirement, an early action is fundamental.

## 15. Resulting product, its industrialisation and internal replication

The new product at the end of the AE has already been tested and its performances are summarised in chapter 9. In fact, the measured performances of a new receiver-transmitter which uses the new MMIC is the last Task of the Workpackage number 5.

Due to the peculiar nature of microwave products, which cannot be developed as wired breadboards (as it happens in case of digital design), all the circuits, which are needed for the production of a subsystem, must be accurately designed, assembled and tested, using the same components and mechanical housings which are used for a massive production.

For this reason, the prototype of the whole RTX microwave module and the industrialised final product do not present any differences. No further industrialisation cost is expected for the new RTX microwave module, except for the MMIC which has been successfully developed at the end of the AE.

The total non recurring cost incurred for the development of new RTX, including the industrialisation is 280 KECU, 77% of which devoted to the MPA (216 KECU). The FUSE funding has been 119 KECU.

The most significant step in the industrialisation process of such MMIC will be the production of a new wafer, that must contain only the version of the amplifier which was previously named **GA 5761_20** . As already mentioned in chapter 9, three different versions of the MMIC were designed and produced, together with a two-stage (and therefore lower output power) version.

The number of MMICs which can be supplied at the end of the AE takes into account the effective useful fraction of the wafer, the yield of the process and the number of produced wafers.

The surface of the wafer devoted to the version GA 5761_20 is 1/8 of the available space. In fact, Micrel purchased half the wafer (a multiproject approach was chosen) and one fourth of this available space is occupied by the right version, which is one among four versions. Since the dimensions of the MMIC are 3.2X1.6 squared millimetres , on a 3 inches diameter wafer, the theoretical number of produced amplifiers is almost 100 per wafer. The yield of the process is between 60% and 70% and the number of produced wafers is 2. Therefore, the expected number of MMICs is more than 120. As it can be seen in the following chapter, this number is only sufficient for the needs related to the year 1998.

The cost of the external Foundry service, for the development and production of the prototype ( see table at chapter 9 ) , has been 37,500 ECU. This cost includes the training activity of Micrel's technical staff.

A projection for future production does not certainly include any cost for training and any cost for new design. The only engineering cost is the rearrangement of the wafer, which obviously will be devoted **only** to the production of the GA 5761_20 chip. Taking into account the cost of the package and of packaging and screening, the final cost of a packaged MMIC medium power amplifier has a target value of 150 ECU, for quantities above 500. This price should decrease to 100 ECU for larger quantities ( thousand pieces).

The complete industrialisation process is still in progress and it can be summarised by the following workplan.

The number of pieces involved is accurately described in the following (number 16) chapter.

| NEW RTX INDUSTRIALISATION PLAN | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | 1997 | | | | 1998 | | | | 1999 | | | |
| ACTIVITY | 1st quart. | 2nd quart. | 3rd quart. | 4th quart. | 1st quart. | 2nd quart. | 3rd quart. | 4th quart. | 1st quart. | 2nd quart. | 3rd quart. | 4th quart. |
| Design new MMIC | XXXXXXX | | | | | | | | | | | |
| Development hybrid RTX microwave module | | | | XXXXXXX | | | | | | | | |
| New MMIC prototype production | | XXXXXXX | XXXXXXX | XXXXXXX | | | | | | | | |
| New MMIC prototype evaluation | | | | | XXXXXXX | | | | | | | |
| Development MONOLITHIC RTX module | | | | | XXXXXX | XXXX | | | | | | |
| Field testing Monolithic RTX module | | | | | | XXXXXXXXXX | | | | | | |
| Ground Station Qualification Test | | | | | | | XXXXXXXXXXXXXXX | | | | | |
| Production 1st lot Monolithic RTX modules | | | | | | | | | XXXXXXXXXXXXXXXXXX | | | |
| Industrialisation wafer for mass production | | | | | | | | | XXXXXXX | | | |
| Production 2nd lot of MMICs | | | | | | | | | | XXXXXXXXXXXXXX | | |
| Production 2nd lot Monolithic RTX modules | | | | | | | | | | | XXX | XXXXXXX |

The activities 1 to 6 of the workplan have already been finished with good results.

The production of the first lot of RTX modules is expected to start by the 1st quarter of 1999, after the qualification of the Ground Station product. The qualification of the product is one of the cause of the program delay. This problem is due to the present lack of clearness about the correct CE Standard to be applied.

For this first lot (120 pieces), the MMICs, which represent the outcome of the AE, will be used.

The industrialisation of the new wafer should start in the first quarter of 1999, thus allowing the production of a second lot of RTX microwave modules by the year 1999. The quantity of transceivers to be produced for that year is now estimated in the order of 300 pieces.

Beyond the specific program the acquired know how has been very useful. Even though in non monolithic process the use of non-linear design techniques and the knowledge of material and process have been and will be used for the design of:

- Hybrid intermediate TRX for Ground Station (output stage)
- Xband frequency agile synthesiser (R.F. channel final stage)
- Xband TWT driver (output stage)

Future MMIC developments are foreseen for radar seeker and radar altimeter applications, even if at different R.F. band

## 16. Economic impact and improvement in competitive position

At the beginning of the AE, the expected impact of the new technology was summarised in the following table.

| **Old product** | | **1995** | **1996** | **1997** | **1998** |
|---|---|---|---|---|---|
| | Turnover current product (KECU) | 500 | 800 | | |
| | Cost old product (KECU) | 375 | 600 | | |
| | Profit old product (KECU) | 125 | 200 | | |
| | Number of old products sold | 500 | * 400 | | |
| | Market share old product | 25% | 25% | | |
| | | | | | |
| **New product** | | | | | |
| | Turnover new product (KECU) | | | 800 | 1600 |
| | Cost new product (KECU) | | | 560 | 1120 |
| | Profit new product (KECU) | | | 240 | 480 |
| | Number of new products sold | | | 500 | ** 1000 |
| | Market share new product | | | 40% | 50% |

* The cost of the old product was increased due to the obsolescence of some raw materials. The quality of the product was decreasing.
** In 1998 a strong market expansion for Italy was expected.

Turnover data were referred to global production data.

If the new product units had presented a significant cost reduction the number of sold systems would have increased (see 1997) and the share of the market niche would also have increased.

From this table and from the budgeted overall cost (119 KECU) of the AE (See table at the end of Chapter 9)
a payback period of less than one year was calculated.

At the end of development phase some conclusions can be done

- The new product has now the expected technical characteristics and the performances are even better than the original requirements.
- The recurring costs , projected in the mass production, match with the expectation, making the price competitive in the market and giving value to the statement that the sales are possible only with the new product

The cost reduction of the new microwave transceiver is of the order of 500 ECU for mass production (+300/year).

The MPA alone, compared to the equivalent hybrid circuit, gives a cost saving of 250 ECU. Taking into account the relevant non recurring cost of 216 KECU and the FUSE funding of 119 KECU the breakeven will be reached after 400 TRX (monolithic) produced.

As mentioned before, a dramatic change in the market has occurred. Despite all expectations, a sudden contraction of the domestic (Italian) demand has led to the following sales figures, as far as the **old** product is concerned:

| | | Year | | |
|---|---|---|---|---|
| **Old product** | | **1995** | **1996** | **1997** |
| | Turnover (KECU) | 500 | 200 | N/A |
| | Number of product sold | 500 | 100 | N/A |
| | Market share | 25% | 5% | N/A |

Note the increase of unit price, due mainly to two circumstances: the low number (100 instead of 500) of produced pieces and the obsolescence of some raw electrical materials.

A comparison with the budgeted figures at the beginning of the AE ( see chapter 5 ) shows the dramatic restriction of the whole market and the loss of market share of Micrel.

In this scenario, a table showing projections for the sales of the old product for the 3 years following the AE is not available, since that product has become obsolete from a technological point of view and moreover no longer competitive, due to its cost.

The new private-owned customer (Tecnotel) has changed this depressing situation. The key to their success is their commercial activity in Italy and abroad. The new product, which was under development at the beginning of the partnership, had a challenging expected price and **only** for this reason the co-operation between Micrel (now Officine Galileo) and Tecnotel has been possible.

On the other hand, it is very important to point out that the cost of the new equipment has been made possible only by the deep innovation of the product.

The demand of Tecnotel for new ground based stations for road to vehicle radio link is represented below.

| **YEAR** | **Number of stations** | **application / Country** |
|---|---|---|
| 1997 | 30 | field testing / Italy |
| 1998/99 | 120 | installation / Italy |
| 1999 | >200 | installation / Italy and field testing Spain, Turkey, Brazil |
| 2000 | >500 | installation Italy, Spain, Turkey, Brazil and field testing Asian market |

Projections for the sales figures of the improved product for the three years (and more) after the introduction of the innovated product are shown below. The figure reported in the table are referred only to the transceiver module of the Ground Station.

| **New product** | | **Year** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** |
|---|---|---|---|---|---|---|---|---|
| | Number of sold units | | | 30 (*) | | 320 (**) | 500 | 500 |
| | Turnover | (KECU) | | 67,5 | | 430,0 | 625,0 | 625 |
| | Cost | (KECU) | | 60,0 | | 331,0 | 499,0 | 499 |
| | Profit | (KECU) | | 7,5 | 0,0 | 99,0 | 126,0 | 126,0 |
| | Engineering cost | (KECU) | 35 | 100,0 | 95,0 | 50,0 | | |
| | FUSE Financing | (KECU) | 30 | 47,0 | 31,0 | 11,0 | | |
| | Cash Flow | (KECU) | -5 | -45,5 | -64 | 60 | 126 | 126 |
| | Market share | | | 5% | | 20% | 40% | 40% |
| (*) Equipped with hybrid medium power amplifier version | | | | | | | | |
| (**) 120 equipped with 1st MPA lot | | | | | | | | |

From this table the payback year is the 2000 (two years after the end of AE), with an IRR of more than 40% at the end of the 2001. The delay of the program is caused by the length of prototyping phase, the problem of qualifications and by the delayed market demand.

The benefits of the introduction of the new technology are evident in terms of turnover and market share.

## 17. Target audience for dissemination throughout Europe

A collection of possible Companies which could be interested in the new product include :

- Industries involved in microwave component and subsystems design, development and production;
- Industries involved in radio-links ;
- Industries involved in road to vehicle communications systems;
- Highway authorities;
- City Councils ( for city downtown entrance control );
- Small and medium engineering companies ( for specialised microwave design).
- The experience of Micrel AE can help the SME whether in diffusion of GaAs technology and in management of electronic project.

The target industrial sector identified is the Electronic Components (code 321) and Communication Equipment (code322).

The experience of Micrel can be very useful for more of SME belonging to these sectors especially because the particular features of technology applied by Micrel, GaAs technology utilised by not linear algorithms.

It has to be underlined that most of the companies (mainly in the Italian region) in the targeted sector use low level electronic technologies. As only 5% of firms belonging sector coded 321 and coded 322 use ASIC mixed technology, the Micrel. AE will be used to stimulate high technological upgrade. Moreover the large range of problems experienced and overcame during the project realisation could be a positively used as guide on how to avoid or bypass problems for all the ASIC projects.